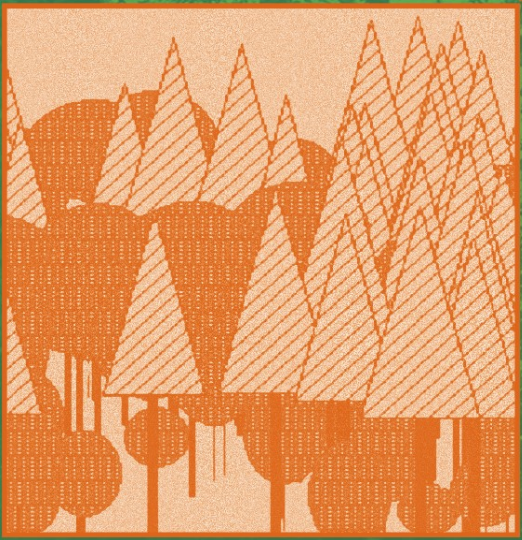
H. Hasenauer (Ed.)

Sustainable Forest Management

Growth Models for Europe



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With 110 Figures, 30 in color, and 44 Tables

Springer

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Preface and Acknowledgements

Given the change in silvicultural management from being mainly clear-cut-driven to an uneven-aged mixed small-scale and/or individual tree-driven forest management system, existing yield tables will become increasingly unreliable. As a potential alternative, tree growth models have been developed in order to forecast the growth of each tree within a stand independent of tree age, species mixture and silvicultural management, allowing increased flexibility, which is necessary for modeling such managed forests.

The work presented in this book summarizes a joint effort among European tree growth modeling experts, forest policy decision-makers and forest companies to further enhance modeling theories and to investigate problem-solving methods for silvicultural decision-making. From February 2001 to January 2004, a group of 45 individuals worked within the ITM consortium (Implementing Tree Growth Models for Forest Management), an EU-funded effort to enhance and promote tree growth modeling theories within Europe. For our work, a number of tree growth models were selected. After extending the models and research gaps related to tree growth modeling theory (Chaps. 1–8), the following application examples (Chaps. 9–17) were selected by our company representatives to demonstrate the problem-solving potential:

1. Regeneration in uneven-aged mixed-species stands.
2. Timber-harvesting scenarios.
3. Incorporation of tree growth models in information systems.
4. Using tree growth models beyond the calibration area.
5. Assisting forest policy decision-makers.
6. Tree growth models as a decision support system component.
7. Optimizing cork production in southern Europe.
8. Converting even-aged pure stands into uneven-aged mixed species stands.
9. Modeling coppice forests in Greece.

Many individuals contributed to the success of our work. We are very grateful to our 12 company representatives: Thomas Böckmann, Germany; Miguel Teles Branco, Portugal; Morten Elback Jorgensen, Denmark; Gerhard Fischer, Germany; Josef Gasch, Austria; Stephan Göd, Austria; Ivan Herich, Slovakia; Theodoros Kostantinidis, Greece; Jens Briand Petersen, Denmark; Wolf Dieter Radike, Germany; Hermann Spellman, Germany; and Johannes Wohlmacher, Austria – as well as the five members of our quality assurance panel – Marijan Kota, Slovenia; Emilia Pinto Preuhsler, Portugal; Janna Maria Puumalainen; Finland; Konstantin von Teuffel, Germany; and Peter Weinfurter, Austria. Their participation in all the meetings and the fruitful discussions are greatly appreciated.

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Hubert Hasenauer
November 2005

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Concepts Within Tree Growth Modeling

Hubert Hasenauer

Abstract. Given the change in silvicultural management from being mainly clearcut-driven to an uneven-aged mixed small-scale and/or individual tree-driven forest management system, existing yield tables will become increasingly unreliable as the main forest management tool to ensure sustainable harvesting. As a potential alternative, tree growth models have been developed to forecast the growth of each tree within a stand independent of tree age, species mixture and silvicultural management option. This allows the flexibility needed for managing uneven-aged mixed species forests. The purpose of this chapter is to introduce the conceptual differences as they are currently implemented within tree growth models.

1.1 Introduction

Forest inventories assess the current forest conditions either by individual stand enumeration or by a random point sampling procedure using permanent or temporary inventory plots. This information in combination with forest growth models is important to forecast future stand development (e.g. volume increment) in order to avoid overcutting and thereby ensure sustainable forest management.

Traditionally, yield tables have been used to predict future forest stand development. Depending on site conditions such tables forecast mean stand development (mean diameter at breast height, tree height) and the stocking (basal area, volume and the stem number) per hectare for pure even-aged forests. Different site conditions are handled by using mean dominant tree height as an estimate of site quality. Conceptually, yield tables are based on a "reference stand" for each species and site index. The site index, defined as the mean total height attained at a particular age, is used to assign each forest to a fully stocked "reference stand" of a given yield table. Yield tables have been developed for a number of tree species and regions across Europe (see Guttenberg 1896; Wiedemann 1949; Assmann and Franz 1963; Bradley et al. 1966; Marschall 1975; Schober 1975; etc.)

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and some of these yield tables (e.g. Marschall 1975) assume a treatment from below or allow the selection of a limited number of thinning treatments (e.g. Lembcke et al. 1975).

Yield tables operate at the stand level and therefore only stand level information is provided. Thus an important restriction is that conceptually they are only applicable to even-aged, pure forests. If they are used within mixed forests, the existing species mixture is conceptually split into pure forests, which ignores competition effects among species. Next the "reference stand" for each species within such a mixed forest is selected and the values taken from the yield tables are weighted according to the basal area proportion by species in order to forecast the mixed species stand development (Fig. 1.1).

1.2
Tree Growth Models

With the shift from even-aged pure forests toward uneven-aged and mixed species managed forests new forest growth models are needed to ensure sustainable forest management. Tree growth models are considered a potential alterna-

Fig. 1.1. A typical even-aged pure Norway spruce forest managed using a clearcut system (*left*) vs. an uneven-aged mixed species forest with selective cuttings (*right*). If no thinning or only thinning from below is applied the forest to the left would be a typical stand for which a yield table would be the appropriate estimator of stand volume increment. However, if we have a stand situation, such as given to the right, yield tables become unreliable because a more flexible forest projection system is required.

tive because conceptually they predict the development of each tree within a forest. The level of resolution is the tree with its specific competition situation and this allows the required flexibility in forecasting tree growth regardless of species mixture, age distribution or applicable silvicultural system.

The transition from a stand-level-based growth projection system as implemented in yield tables to tree growth models can be considered as a fundamental change within forest growth modeling because no predefined limits in species mixture, silvicultural treatment and/or tree age exist. Historically speaking the first tree growth models were developed in North America (see Newnham 1964; Stage 1973; Monserud 1975; Wykoff et al. 1982; van Deusen and Biging 1985; Wensel and Koehler 1985; Burkhart et al. 1987). For Scandinavia and central Europe, the main tree growth modeling concepts were developed during the early 1990s; for details see Sterba (1983), Pukkala (1988, 1989), Pretzsch (1992, 2001), Hasenauer (1994, 2000), Nagel (1995), Sterba et al. (1995), Monserud and Sterba (1996), Kahn and Pretzsch (1997), Nagel et al. (2002) and Pretzsch et al. (2002). These models basically extended the previous model approaches to all major species in Europe. For further details see also von Gadow and Hui (1999) and Pretzsch (2001).

1.3

General Structure of a Tree Growth Model

Tree growth models consist of diameter and height increment functions to predict growth and a mortality equation to predict the probability of mortality for each tree over a given time interval (usually 5 years). In addition, a regeneration or ingrowth routine to recruit new trees is needed to ensure consistent simulation output. Several tree growth simulators also include form factor functions and assortment tables to predict volume and/or merchantable volume development over time.

Many tree growth models are designed to forecast tree growth within uneven-aged forests. Thus stand age, one of the key driving variables within yield tables, cannot be used and all functions must be age independent. Sub models are included to assess the competition situation of each tree within the stand. Because crown length or crown ratio is a key driver within growth and mortality functions, tree growth models include an equation to update the crown length or crown ratio.

Important competition variables are (1) crown length or crown ratio to assess the competition that a tree experienced in the past and (2) the current competition index for addressing the competition for each tree within the stand. Some tree growth models explicitly include the change in the competition situation before and after crown release to address the fact that depending on the tree species, lower or higher increment rates may be possible immediately after crown release versus a tree, which is experiencing the same competition level but without crown release. Typical examples are the acceleration of growth in diameter increment of common beech and the decline in height increment for Norway spruce during the first 5 years after crown release (Hasenauer 1994). Models that explicitly include crown release as part of the growth functions are FOREST (Monserud 1975), SILVA (Pretzsch et al. 2002) and MOSES (Hasenauer 1994).

1.3.1
Increment Functions

Two conceptual approaches are possible for predicting the 5-year diameter increment and height increment for each tree within a stand: (1) potential dependent or (2) potential independent growth functions.

Potential dependent diameter and height increment predictions were first proposed by Newnham (1964) and assume an upper limit or a limited growth. This upper limit or growth potential is species and site specific. Models based on this concept must first define species- and site-specific diameter and height increment potentials. These potentials are then reduced for each tree within a stand according to the specific competition situation of each tree and can be derived using crown length and competition indices. It is worth noting that a similar "potential growth" concept has been implemented within gap modeling (see Botkin et al. 1972) by defining a species-specific potential. Actual growth rates within a gap model are then derived using this species-specific potential and so-called response functions (between 0 and 1) for light, water, temperature and nutrients to reduce the growth potential to the actual growth according to varying site conditions and the competitive status of each tree within the stand.

Tree growth models based on the potential growth concept may have the following form:

$$inc = potinc \cdot CR^{a} \cdot (1-e\ (^{b \cdot COMP}) + \varepsilon$$

where *inc* is the actual 5-year increment for each tree, *potinc* the predefined 5-year potential increment by species and site conditions, *CR* the crown ration, *COMP* the competition indices, a and b_i the parameter estimates and ε the remaining error components.

Considering the general model formulation, we see that realistic definitions of potential periodical diameter and height increments are essential because these numbers define the upper limit or maximum possible growth within the model. Increment predictions converge to upper and lower asymptotes depending on the competition situation. The 5-year height increment is often developed by site- and species-specific mean dominant tree height development that is derived from site index functions. After rearranging these equations, the "calculatory" age of each tree can be defined according to site index and actual tree height. Adding 5 years to the "calculated tree age" and assuming a dominant tree, the difference between this calculated tree height and the actual tree height gives the species- and site-specific height increment potential. Some authors have extended this procedure by deriving the potential tree height functions using site parameters (see Kahn and Dursky 1999). Note that dominant tree height growth is site specific and thus site variations are addressed at this point within the model.

The potential diameter increment functions may be defined by so-called open grown tree dimensions. It is believed that such open grown trees have never experienced any competition and thus the tree dimensions may be considered as the maximum or potential dimensions that a tree may have. Simple allometric functions such as those given in Hasenauer (1997) allow us to calculate for each tree height the potential breast height diameter a tree would have, if open grown. Typical examples for models following this approach are SILVA (Pretzsch 1992; Pretzsch et al. 2002), MOSES (Hasenauer 1994) and B-WIN (Nagel 1995).

The second important approach used within tree growth modeling does not define a growth potential. The actual growth increments of diameter and height increment rates are estimated directly from the available data and are only based on a set of independent variables. No upper limits or maximum growth increment rates are defined. Site variations as they may affect tree growth are part of the dependent variables. The general relationship may have the following form:

$$\mathrm{In}(inc) = a + b \cdot (tree) + c \cdot (comp) + d \cdot (site) + \varepsilon$$

where $\ln(inc)$ is the logarithm of the growth (diameter/height), *tree* is the set of tree variables, *comp* the variables assessing the competition situation of each tree within the stand, *site* the variable for defining the site variations, *a, b, c* and *d* the species-specific coefficient estimates and ε the remaining error component. PROGNOSIS (Stage 1973; Wykoff 1990) and PROGNAUS (Monserud and Sterba 1996) are typical examples of this type of tree growth model.

1.3.2
Competition Indices

One of the main achievements of tree growth models is that tree growth can be assessed for each tree within the stand according to its unique competitive situation. Much effort has been put into researching and testing a variety of different individual tree competition indices that can be used to predict tree growth (see Biging and Dobbertin 1995).

The basic principle for most of the competition indices is that they assume a certain minimum distance between neighboring trees before competition occurs. Since the study by Krajicek et al. (1961) this minimum distance is often derived by the radius of the crown area of an open grown tree. This open grown crown radius for a given tree can be easily calculated using allometric functions of open grown crown tree dimensions (Hasenauer 1997) using actual diameter at breast height or the tree height of two neighboring trees. If the crowns of open grown trees begin to overlap, tree competition is evident and will affect tree growth (see Fig. 1.2). This concept was proposed by Bella (1971) and many existing competition indices are considered to be variants or extensions of this original idea.

An interesting extension of this approach is the competition index proposed by Pretzsch (1992). This index assumes a potential cone to define the growing zone for a tree without competition. This three-dimensional index assesses the competition of two neighboring trees by their overlap of the neighboring tree in-

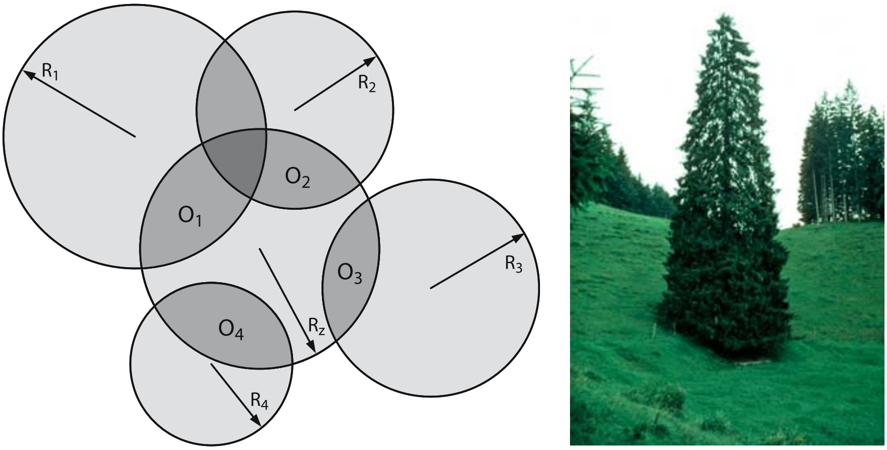

Fig. 1.2. Example of open-grown Norway spruce (*right*). Open-grown trees are trees that have grown without neighboring competition. Their crown and breast height diameter are supposed to be the maximum possible or potential values. *Left* A typical example for assessing tree competition within a stand, where *R* is potential crown radius a given tree would have if open grown. This value can be easily derived from actual tree height or breast height diameter using published material as given in Hasenauer (1997). *O* is the resulting crown overlap and indicates that a competition-induced reduction of growth may be expected. The *numbers* indicate the trees

to the potential space of the first tree according to the size of the potential cone of the first tree. If cones overlap competition is evident in a manner similar to the two-dimensional concept explained previously.

Although a large number of indices have been developed and tested they can be separated into two groups: (1) distance-dependent indices, where the position of each tree and thus the distance between neighbors is known, and (2) distance-independent indices, which assume a mean distance between each tree on a given plot.

Distance-dependent competition indices have been developed and used within growth increment functions to increase the accuracy of the predictions and to address spatial and structural issues. If a distance-dependent approach is used, data with recorded x and y coordinates must be available for calibrating the increment and mortality functions. However, for model applications the position of each tree may be derived form distribution routines which have been developed to generate realistic stand situations at the beginning of a simulation period. Examples are the STRUGEN (Pretzsch 1993; Pommerening 2000), the Gibbs process model (Degenhardt 1998), an index-based algorithm proposed by Lewandowski and von Gadow (1997), and the Stand generation program STANDGEN (Kittenberger 2003). It is important to note that within a distance-dependent approach the tree location does not change throughout the simulation run. This may be important if structural, textural or mixture effects need to be assessed.

Models using a distance-independent competition index assume a mean distance between trees on a given plot regardless of the actual stand situation or the stand treatment scenario applied. The advantage in using such competition indices is that no tree coordinates are needed during the calibration process and for running the model. On the other hand the trade-off is that a mean distance between the trees growing at a given plot is assumed. This suggests that within the modeling system trees are not fixed because at the beginning of each simulation run an evenly distributed stand situation is assumed regardless of the actual structure of the forest. If the plot is small this may be negligible, but if the plot size increases and/or certain silvicultural scenarios are to be applied, the modeled stand situation may diverge from the real situation.

1.3.3
Crown Models

Within tree modeling, measuring crown length, crown width or crown ratio are considered to be methods to assess the competition a tree has experienced in the past. They are also measures of tree vitality and as such surrogates for leaf area index, a key component to measure the uptake of photosynthates and thus volume growth. Because crown length or crown surface area is used as a key driving variable within the growth and mortality functions, models for updating crown length have been developed. The following approaches may be distinguished:

1. Crown ratio models (see Hasenauer and Monserud 1996) which predict the crown ratio at a given time as a function of tree, competition and site variables.
2. Height to the live crown base models (Pretzsch 1992; Nagel 1995) which estimate the clear bole length at a given time as a function of tree and competition measures. Calculating the difference between the tree height and the height to the base of the live crown gives the necessary crown length or crown ratio for each tree at the beginning of a simulation period.
3. Changes in the height of the live crown base (Short and Burkhart 1992; Hasenauer 1994). This approach may be considered a dynamic crown model because the change in the clear bole length as it depends on tree, competition and site variables is derived for a given time interval. Note that this approach requires repeated observations of height to the live crown for model calibration.

1.3.4
Mortality Models

Tree growth models predict the mortality for each tree by calculating the probability of mortality depending on tree competition and site variables. Because the dependent variable is binary (dead or alive – 0 or 1), LOGIT models are a common method (Neter and Maynes 1970) to derive the parameter coefficients using maximum likelihood procedures (Monserud and Sterba 1999; Hasenauer

2000). A possible alternative may be neural networks (Hasenauer et al. 2001). A typical formulation for a mortality model has the following form:

$$p = \frac{1}{1 + e^{(a+b_i \cdot x_i)}} + \varepsilon$$

where p is the probability of mortality, x_i the set of parameters selected and a and b_i the estimated coefficients using maximum likelihood procedures. This results in a probability of mortality for each tree and growing period. The final decision whether a tree dies within a given 5-year growth period and thus has to be removed from the tree list is made by comparing the estimated probability of mortality with a uniformly distributed random number.

One of the difficulties in calibrating mortality models is that mortality is a rather rare event. Depending on the stand, the average 5-year mortality rate of the total stem number per hectare may vary from about 10% in very young stands to less than 1% per 5 years in old forests. In addition, tree mortality is often affected by external impacts such as drought stress, etc. Consequently, for a given competitive situation, tree mortality may be quite variable and this makes the collection of data for developing tree mortality models difficult and expensive. Note that individual tree mortality predictions may be considered as one of the most difficult tasks within tree growth modeling.

1.3.5
Regeneration Models

Estimating the recruitment or ingrowth of tees following the death or cutting of an overstory tree is crucial to ensure sustainability in uneven-age mixed species stands. Usually, trees below a defined tree height or breast height diameter are considered as regeneration while all other trees belong to the overstory population. These thresholds mainly depend on the data monitoring program. For example, while on long-term research plots it is common that all trees taller than 1.3 m belong to the overstory population, forest inventories often use a certain minimum diameter at breast height (DBH) (e.g. 5.5 cm, FBVA 1994) to reduce the data monitoring costs.

One option to recruit trees entering the overstory population is the calibration of ingrowth models (Ledermann 2002). Based on representative forest inventories the probability that trees will pass a predefined threshold (5.5 cm) within 5 years can be predicted. Such models do not explicitly assess regeneration establishment and juvenile tree growth.

Since several silvicultural systems focus on the initiation and/or promotion of regeneration processes, recent approaches have split the recruitment of juvenile tees into different steps by explicitly taking into account regeneration establishment (Pukkala and Kolström 1992; Ribbens et al. 1994; Schweiger and Sterba 1997; Hasenauer et al. 2000; Biber and Herling 2002; Hasenauer and Kindermann 2002) and juvenile tree growth (Monserund and Ek 1977; Golser and Hasenauer 1997; Biber and Herling 2002; Kindermann et al. 2002). Regeneration establishment and juvenile tree growth may vary strongly due to climate and micro site conditions as well as random impacts such as flowering, fructification, etc. This makes the calibration of regeneration models more difficult.

An important concern in developing regeneration models is the availability of data. Some forest inventories record regeneration information only if a certain minimum threshold in the number of juveniles per unit area is available (see FBVA 1994). This may lead to biased results because situations with no or with a very small number of juvenile trees are excluded from the data. From a practical management point of view these situations are of high relevance because it would be important to understand why no or only little regeneration occurs. As a result growth models that explicitly address the regeneration process might follow the following procedure (see Kindermann et al. 2002):

1. Predicting the probability of regeneration within a given 5-year growth period.
2. Predicting the species distribution.
3. Estimating regeneration density.
4. Determining juvenile tree growth depending on the overstory, inter- and intra-specific competition as well as compensatory effects due to edge effected incidence of light.
5. Determining juvenile tree mortality.

1.4
Data Needed for Calibrating Tree Growth Models

Tree growth models predict the change in diameter and height increment for a given time interval (e.g. 5 years) which may depend on tree, competition and site descriptors. By adding the predicted periodic changes to the tree dimensions at the beginning of the growth period (e.g. DBH, height and height to the live crown base) the tree dimensions at the end of the growing period are calculated. Consequently tree growth models are dynamic because they focus on assessing the change in diameter and height increment. This is one of the important conceptual features of tree growth models and it provides the flexibility needed to be independent from age, stand structure, mixture, etc. This is also a very substantial difference from that of other population models such as gap models (Botkin et al. 1972).

Calibrating dynamic growth models requires repeated tree observations. If repeated diameter, height and if possible height to the live crown measures are available the benefits of tree growth models versus yield tables can be fully utilized. An important precondition to having repeated measurements available is that permanent plots with marked trees are available so that the repeated observations are always taken on the same trees. This avoids sampling error and provides time series. Another important constraint is that data including a variety of stand densities, mixture types and ages as well as different treatment intensities should be available to cover the full range of possible growth responses expected from different stand treatments.

In general we may distinguish between inventory data which are representative for a given forest area and permanent sample plots which commonly cover the variation in different stand treatments, site conditions, age structure and species mixture. While inventories are commonly established to gain an overview of the forest-covered land area, permanent research plots are normally established to study forest growth response to different silvicultural treatments.

For model calibration it would be desirable to use data sets consisting of both types of data sources because forest inventories may not cover the full range of important silvicultural management systems which are important for ensuring reliable predictions if a wide range of scenarios occurs. On the other hand permanent plot data may not be representative of the forest land of a particular region and may not include conceptually important growth situations.

Data with very high stand densities are mainly available from untreated forests, while the other extreme, very low densities, growing under almost open grown tree conditions or very intensive treatments are very uncommon because such management options are usually not applied in practice. However, from a conceptual modeling point of view such data are extremely important because they would help us to understand growth response to different levels of treatments as they are important for silvicultural scenario analysis (Pretzsch 1995).

This difference in the data source for model calibration is also important for relating site variation to affects of tree growth. While a data source based on a systematic grid (see forest inventory data) allows us to test for possible site variations that are measured by site descriptors (see humus, soil, vegetation type, etc. within PROGNOSIS or PROGNAUS), tree growth models based on permanent research plots often use the potential height development which is estimated from site index functions in order to incorporate productivity differences (e.g. SILVA MOSES BWIN). The underlying assumption here is that once the relative proportion for reducing a potential tree growth to the actual increment values is defined it is proportional in its mechanism regardless of the site quality.

Commonly tree growth models assume constant site conditions since they are not intended to be sensitive to changing climate. Therefore it is important that the data used for model calibration do not include periodic changes in the weather conditions because this may strongly affect tree increment rates. Data sources for calibration should come from different 5-year growth periods so that under- or overestimation in the resulting growth predictions due to changes in annual climate can be avoided.

1.4.1
The Heuristic Transformation of Input Data

One constraint in the availability of data for modeling may be that very often we have repeated observations for DBH but only a limited number of repeated height and height to the live crown measurements due to the high cost of such measurements. Common practice in this situation is that missing tree heights are derived from the DBH using heuristic functions. Similar procedures are used for estimating the missing total height and the height of the live crown base in order to estimate crown ratio. Several growth models have used height increment functions based on such smoothed data (e.g. Monserud 1975; Nagel 1995).

All these examples exhibit surprisingly high coefficients of determination relative to increment models that use a complete sample of repeated tree height observations (e.g. 15% for spruce within Austria). The explanation for this phenomenon is that existing variation is excluded from such smoothed "height increment data" because the random variation for height diameter functions of about ±2.5 m is ignored and this heuristic data transformation may even lead to biased and inconsistent height increment predictions (see Hasenauer and Monserud 1997).

A simple calculation may demonstrate the problem: assuming a measurement error of ± 0.5 m for height measurements at the beginning and end of the growth period, the measurement error for height increment would be ± 0.7 ($0.5 \times \sqrt{2}=0.7$). If we assume that the average 5-year height increment for a given species may be 1.2 m, of which approximately 59% is expected to be the unexplainable measurement error, then according to these numbers a height increment model based on repeated height measurements can only explain 41% of the existing variation. If we assume an R^2 value of 15% the variation explained by the model is approximately one-third of the explainable variation.

A similar problem is evident if heuristic functions are used to generate missing total height to the live crown measurements. This suggests that the reliability of published R^2 values for increment models strongly varies depending on whether repeated observations or heuristic data transformation procedures have been applied. The latter method has removed much variation due to the data smoothing procedures applied (see Hasenauer and Monserud 1997).

1.5
Summary and Conclusion

Sustainable forest management tools must provide reliable predictions for uneven-aged mixed species stands to ensure sustainable harvesting. The change of the silvicultural system from a mainly clear-cut-driven to an uneven-aged mixed small-scale and/or individual tree harvesting system (e.g. target diameter cutting, etc.) makes monitoring and forecasting more complex. This increase in complexity requires the adaptation and/or introduction of new forest management tools such as tree growth models to provide a conceptual framework and controlling instrument for forest companies to ensure sustainable forest management in their day-to-day work.

Models have to address conflicting interests such as simplicity, observability and biological realism (Pacala et al. 1996). Within tree growth modeling this is extremely important because one of the main constraints is that the application should be based on routine inventory data. Thus, research efforts have focused on understanding the theoretical relationships between tree growth and competition but also on how information can be derived without and/or with only small changes in the design so that existing forest monitoring systems can be utilized. This constraint is important for ensuring the practicability and implementation of tree growth modeling theory as a potential alternative vs. yield tables.

Tree growth models require repeated observations (DBH, height and if possible height to the live crown base) covering the full range of expected stand situations ranging from pure even-aged to uneven-aged mixed and heavily unmanaged forests in order to fully utilize the conceptual benefits (Pretzsch 1993; Spellmann et al. 1996). They predict periodical increment and mortality rates for individual species, competitive situation and site conditions. This is clearly a dynamic approach because it allows us to address growth variations according to different competitive situations. The height and diameter increment models are derived independently, and assess changes in the allocation patterns due to crown release (e.g. thinning, etc.). This possibility addresses changes in the height:diameter ratio due to stand density and is one of the main differences vs. other population models such as gap size or gap phase approaches (Botkin et al. 1972). Note that this makes tree growth models independent of silvicultural management regimes, a precondition for testing different forest management practices.

A relatively complex and new field is that of regeneration modeling. Unfortunately most regeneration surveys visually assess the regeneration situation, which usually results in strongly subjective or even biased data (Wildt 1995). In recent years regeneration inventories have been established based on reproducible measures such as counting juvenile trees or measuring the mean height. Although these first steps are very promising we still lack information on repeated regeneration enumerations which are important to further test the impact of silvicultural management regimes on regeneration establishment and juvenile tree growth.

One of the challenging issues to make tree growth modeling theory available to the end user is its link with decision support systems (DSS) and/or adoption of the various theories to specific forest company situations. In this context the documentation and user-friendly implementation in a computer software or demo package is of interest because growth models are not just an important tool for ensuring sustainable forest management; they are also important for training and education so that the end users gain a comprehensive understanding of the range of possible silvicultural management options.

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End User Needs and Requirements

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Abstract. Forest practice is about making decisions concerning forest management that will have consequences for a long time. Models of forest growth and yield were first used as simple abstractions of stand development. They were then adapted to specific management objectives. Now changing user needs are shifting the preferences of forest practice for forest models from pure to mixed forests, from stand to individual tree-based silvicultural measures and from even aged to uneven aged management methods. In addition, changing growth conditions call for even more customisable models. Tree models try to transcend the limitations of earlier forest growth modelling approaches by predicting individual tree growth with respect to competition with surrounding neighbours, the local canopy structure and species composition, instead of delivering mean stand values. This remarkable scientific development leads to more complex models with more detailed predictions. To focus on the needs of forest practice – especially in the field of forest planning, silvicultural programmes and multicriterial decision support – the following essential attributes of tree models are proposed: a clear purpose specification, a reasonable accuracy of the predicted values, an easy integration into the enterprise information flow and communicability of model results. A clear documentation of the model limits, the comprehensibility of the simulation process and user-friendly handling improve the trustworthiness of the models. A successful evolution of tree models will avoid using growth simulators as all-purpose tools, but ensure the participative development of purpose-related components and the definition of practice-relevant simulation scenarios.

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Sustainable Forest Management
Growth Models for Europe

2.1
Historic Development

Foresters need model approaches to support their decision-making. A model in this context is defined as a simplified picture of real systems, which includes the crucial elements and interactions of the system (Bossel 1994). Forestry as a profession emerged some 200–300 years ago, when in vast areas throughout Europe forests were excessively overused and devastated. In order to rebuild and manage forests, decisions had to be made based on reliable sources of information and predictions of growth and yield provided by models.

One of the first model approaches used was that of yield regulation by volume ("Massenfachwerk") developed by G.L. Hartig in 1795 (Hartig 1795). He divided the rotation time into 20-year periods. Stands were allocated to the periods according to their individual age, thus striving for an equal distribution of allowable cut. The potential cutting volume was estimated stand by stand. The theoretical model behind this regulation method was the idea of a so-called normal forest or ideal forest, later developed by Hundeshagen 1826 (Speidel 1972). A normal forest is characterized by pure even-aged stands of equal area (e.g. 1 ha) from an age of one to the end of the rotation period. All stands grow with the same yield class and a stand density index of one. There are no disturbances such as storms, snow, etc. The sustainable annual allowable cut is realized by clear cutting the stand, when it has fulfilled its rotation time.

H. Cotta in 1804 introduced a yield regulation method by area ("Flächenfachwerk"). Areas of the same size were allocated to periods. Due to uneven stand age and density, sustainability of cuttings was theoretically only achieved after the second rotation. One advantage of the method was the establishment of a structure of the forest in permanent compartments. Subsequently, the two methods were combined in the yield regulation system by age classes ("Alterklassenmethode"). It differs from the regulation system by area through the stand-related planning of production and utilization.

2.2
Yield Tables

The method of yield regulation by age class has dominated forest management planning for more than 100 years. It was crucially supported by the development of yield tables. Yield tables can also be considered as models predicting the growth of forests as they simulate the development of a stand over time. So far, they represent a theory of stand growth, mostly pure stands of a certain tree species, site class and yield level (Kurth 1994). They depend on a certain treatment of a stand throughout its development over time. Yield tables come in tabular or graphic form. They usually show the development of the following elements:

- stand stem number;
- stand basal area;
- stand mean diameter;
- average or top height;

- form factor; and
- stand volume.

Additionally they depict:

- expected thinning volume over the next 10-year period;
- annual increment of basal area;
- current annual increment, mean volume increment, etc. (Prodan 1965).

Yield tables originally represented the average development of a "normal" or "ideal" even aged pure stand. Later they were constructed under certain treatment scenarios. The first yield tables were developed in the 19th and early 20th centuries by Hundeshagen, Schwappach, Gehrhardt and Wiedemann, later followed by Assmann, Franz, Schober and Bradley, among others. They are for the most part based on numerous and repeated measurements of experimental plots (time series). This fact shows how costly it is to develop and construct adequate tables.

If they are based on data derived from large areas (common yield tables) a disadvantage may be that they do not apply to certain regions due to different yield levels in different sites, growth zones, etc. (Prodan 1965). Contrarily, regional tables may suffer from a lack of statistical accuracy, as the number of plots is limited and the variance between the plots is very high.

Yield tables are still applied throughout Europe, and are mainly used for securing sustainability. They are usually applied as an instrument to simulate the development of stands during the process of working out a forest management plan normally for a period of ten or more years. Yield tables are generally divided into different tables for each site class for different tree species, often in a compendium of tables applied by a certain forest owner or forest administration (MLR 1993a).

The limitations of yield tables are obvious. Not only are they tree species specific and only constructed for a certain period of time during the life cycle of a stand, but also they often do not refer to the actual state of the stand they are applied to. Furthermore, they do not depict different treatment alternatives. Several authors have recently questioned the usefulness of yield tables (Pretzsch 1992; Schöpfer et al. 1994, 1997; Spiecker et al. 1996).

2.3
Changing User Needs

For a long time, yield tables were appropriate instruments for the simulation of forest stands. However, during recent decades, the needs of users have changed. Four main elements have triggered this development:

- a substantial shift from the preference of pure to mixed stands;
- a changing treatment of stands which differs significantly to the treatment most yield tables are based on;
- a change from even aged to uneven aged management methods;
- changing growth conditions in Europe.

These changes have led to a redefinition and enlargement of the concept of sustainability as described by the criteria and indicators, nowadays widely accepted as the basis of forest certification (MCPFE 2003). These changes are also reflected in the modern forest management programmes of large forest enterprises (e.g. Otto 1990; Niedersächsische Landesforsten 1992).

2.3.1
Preference of Mixed Stands

Experience over recent decades has shown that in various cases, pure stands do not fulfil the needs of forest owners and society any more (Spiecker et al. 2004). The major assumption is that they are subject to higher ecological vulnerability and higher economic risk. The following statements summarise the main reasons for the rising preference of mixed stands.

Among the ecological reasons is the concern that:

- the establishment of pure tree species stands in general may increase the risk of insect infestation and fungi attacks (Führer 1996; Baier et al. 2000);
- pure conifer stands often are supposed to be more susceptible to high atmospheric deposition. Evidence of accelerated soil acidification and soil nutrient losses endanger tree species enrichment (Augusto et al. 2002).

Mixed forests lead to:

- a more balanced input–output budget of nutrients within an ecosystem as the litter of deciduous forests is decomposed more quickly than litter of coniferous trees; organic residues are not accumulated at soil surfaces and release of nutrients is faster (Klimo et al. 1995);
- nitrogen losses with seepage water are reduced especially in N-saturated ecosystems and acidification of surface waters is reduced (Heitz 2000);
- there is an improvement in microclimate;
- biological diversity provides arguments for a tree species enrichment as the fauna and flora composition are more diverse (Jedicke 1996; Matthes 1998).

This improves the adaptability of ecosystems to the occurrence of climatic extremes and thus reduces the risk for wood production. Increasing concerns about biodiversity and appreciation of the recreational values of forests have led to an increased public and private interest in mixed forests (Schraml and Volz 2004). However, some ecological effects either are not yet well understood or do not fully support the advantages of mixed or broadleaved forests (Kulhavy et al. 2004).

An economic argument for enrichment with other species is the risk of high salvage cuttings of pure stands often consisting of Norway spruce or Scots pine on various sites. Pure forests established on inappropriate sites with high standing volume often face increased salvage cuttings with increased age caused by storm (Drouineau et al. 2000). This is especially true for sites that do not allow the development of a deep root system. Even though case studies show a reduced profitability of forests during their phase of conversion from even aged conifer stands to uneven aged mixed stands of Norway spruce and European beech (Jacobsen et al. 2004), an economic preference is often given to mixed forests due to their expected higher flexibility in reacting to sudden changes in wood supply. Nevertheless, little research is available on the degree of flexibility and its consequence for business economy, as flexibility may depend on the tree species and their shares in mixed forests (Jacobsen et al. 2004).

The application of yield tables to mixed stands has some disadvantages since they are mostly constructed for the purposes of pure stands. One important problem is that competition between different trees and tree species is not properly dealt with. The first mixed stand yield tables were developed early last century (Bonnemann 1939; Wiedemann 1942), but were rejected by forest practice, as foresters did not find their specific mixtures sufficiently represented in the yield table settings.

2.3.2
Changing Treatment

Early so-called normal yield tables assumed no silvicultural treatment at all (e.g. Hartig 1795). When yield tables were first constructed, there was a common understanding of one main treatment alternative for a specific tree species, at least in a certain region where the yield table was supposed to be applied. This is not necessarily the case any more. Different owner preferences and market conditions, different sites and so on do not allow for one single treatment strategy of a tree species any more. The application of models has to react to these changing needs.

For example, there is a tremendous difference between treatments aimed at maximising biomass production and one preferring the production of high value timber. Of course, there are various nuances between these two extreme alternatives. One of the vastly applied treatments to many stands is a so-called crop tree treatment (Abetz 1980; Klädtke 1992; Abetz and Klädtke 2002). It favours the optimal development of a future crop tree early in a stand's age, and thus requires high thinning throughout a longer time frame during stand development. Other treatment programmes favour low thinnings. These different treatments cannot be represented in one yield table. When compared with older yield tables it can be stated that modern stand treatment allows for an earlier age of final harvesting. Trees reach their target diameter earlier than represented in older yield tables. There are certainly modern yield tables (e.g. Assmann and Franz 1963; Wenk et al. 1985; Lockow 1995, 1998) for regions and tree species that depict stand growth properly, but with changing treatments according to the management objectives of forest owners, their flexibility is limited.

2.3.3
Change from Even-Aged to Uneven-Aged Management Methods

Several aspects of multifunctional forestry suggest a shift from even-aged to uneven-aged management methods. Under natural conditions, without the interference of man, many forests in Europe, especially central Europe, would comprise of a patchwork of small groups of more or less one age (Remmert 1991; Mayer 1992; Korpel 1995). This refers to the dynamics of natural regeneration of forests in this region. Big catastrophes are rather seldom within European forest conditions, aside from the special situation of the boreal forests in Scandinavia (Korpilahti 2002). A close-to-nature approach broadly accepted among foresters in central Europe copies the natural regeneration patterns and integrates it actively into forest management.

Another reason for the change to a more uneven aged management is stand stability. Stand stability here is meant as the ability of stands to withstand the forces of wind and to defy insect infestations, etc. A higher within-stand diversity in tree size reduces the risk of large-scale sanitary cuts after bark beetle outbreaks. Of course, other catastrophic events such as storms do not leave uneven aged forests undamaged, but they are believed to be more stable because a windthrow event cannot blow over vast areas of uneven aged stands. Their effects are interrupted as a result of the patchwork stand structure. Experiments with Forest GALES wind risk models and sitka spruce stands as described by Mason (2002) have recently supported the experience of forest owners that on moderately wind-exposed sites, irregular stands are more wind stable than conventionally thinned regular stands. However, on sheltered and heavily wind-exposed sites no difference was found.

Uneven aged forests carry the economic option of allowing each single tree to reach its individual maturity. This results in a higher rate of return. Nevertheless, a reduced profitability of forests at the transition phase between even aged and uneven aged structures has to be taken into account (Jacobsen et al. 2004).

Clearly, there is a higher biodiversity in stands with more structural elements. An extensive description of the impact of the conversion towards uneven aged management methods on diversity aspects is given by various authors in a list compiled by Spiecker et al. (2004).

It is impossible to fully describe uneven aged stands using yield tables. By definition, yield tables are constructed to show average values such as average stem number, average height or average volume figures. Since uneven aged stands consist of trees of a high variation in tree dimensions and heights, average values do not provide a useful description in order to support decision-making in forest practice.

2.3.4
Changing Growth Conditions

Recent publications show that growth conditions for trees in Europe have changed significantly during the last decades (Kenk 1991, 1993; Spiecker et al. 1996; Karjalainen et al. 1999). Although the methods applied in several studies varied according to the data available, most studies showed the same general trend: site productivity has increased on many sites. An increasing growth trend has been observed in the southern regions of northern Europe, in most regions of central Europe and in some parts of southern Europe (Spiecker et al. 1996). It is not possible to identify any one factor as being solely responsible for increasing growth trends. There is a mixture of several aspects, such as forest management, land use history, natural disturbances and climate, including atmospheric deposition. Even though changing growth conditions could also be integrated in stand growth models, the individual tree growth modelling approach seems to be more flexible with respect to these changes. In contrast to yield tables they are more convenient to handle.

Modern forest management usually intensifies tending, thinning and harvesting regimes and thus influences site productivity by altering nutrient cycling as well as competition for light and water. Species composition may have effects on the root system, litter quality and nutrient storage. Also fertilising, soil preparation and the choice of tree species and/or genetic selection can have positive effects and increase growth on many sites (Bonneau and Nys 1999). It is very important to recognise that practical forestry over the last 200 years has helped to overcome the negative effects of previous land use. Many sites were devastated due to extensive litter raking, grazing, foraging and pasturing as well as uncontrolled overuse of timber extraction (Glatzel 1999). Forest management has helped in restoring soils and overcoming the damages of early excessive land use. Natural disturbances, such as storm, insects, pests, fires or droughts, may have effects on site productivity and/or competition at least for a certain period of time. Atmospheric deposition of sulphur, nitrogen and ozone alter site productivity in many respects. Additionally the increased content of CO_2 in the air is one of several factors responsible for changing growth conditions not being represented in many yield tables (Cannell 1999). As modern silviculture tends more and more toward individual tree management systems, tree models are preferred that integrate more than just growth and yield aspects, e.g. information on nutrient cycling, carbon balance or diversity.

As shown in the four sections above, modern management of contemporary forest ecosystems requires a wider spectrum of variables due to the changing demands of users, and the forests' increased diversity. This can only be handled when using more complex computerised processes. Apart from tree and stand attributes such as growth, assortment, yield and financial characteristics, other ecological, economic and socio-economic variables are becoming more important, which, in the future, should be taken into account in forest growth description and prediction (Pretzsch 2002).

2.4
Purposes of Modern Tree Models

For many years, traditional stand models (in the form of yield tables) have served forestry in describing and predicting forest growth. Their limitations have been listed above. Over recent decades there has been a substantial development in the field of forest growth science and modelling. One of the most important steps was the idea to not model average values of pure, even aged stands, but to study the growth of individual trees and the prediction of their development with respect to competition of the surrounding trees. Such models are called single tree models. Average values of stands are obtained only by adding up the values of the single trees. In this way it is possible to predict the growth of combinations of different tree species and ages. The change from average values as used in yield tables towards a single tree assessment marks a paradigm change in forest growth prognosis (Hasenauer and Kindermann 2002). As stated above, this refers better to a treatment of mixed and uneven aged stands. Moreover, alternative treatment strategies can be depicted and compared.

Even so, it is recognised that there has been a remarkable development in stand-related modelling too. It has to be remembered that the modelling of representative trees with similar characteristics (age, height, etc.) is an alternative in order to avoid some of the shortcomings of classical stand models (von Gadow 2004). Up till now such models have not found widespread application in Europe. It is for this reason that they are not considered any further in this chapter.

From the point of view of practical forestry, modern tree models have three basic functions:

1. A short- and medium-term function in order to enhance sustainability control and/or the choice of alternative forest operations. They enable the quantification of current state and planned target values of stand characteristics, groups of stands or values of enterprise level by simulation of inventory data.
2. A long-term strategic function, as they support the development, test and comparison of new silvicultural treatment alternatives and their economic and ecological consequences.
3. A training function with the purpose of visualising the consequences of various operations and treatment alternatives for decision makers, other stakeholders and the public.

In the following examples, some applications of tree models in practical forestry are described.

2.4.1
Tree Models in Forest Management Planning

Traditional forest management planning is today still widely based on average values derived from yield tables. A rising number of forest owners and forest administrations though have shifted towards systematic sampling methods in order to obtain better information on growing stock and its structure. Repeated inventories additionally make data on growth and yield as well as harvested volume available. Some forest owners have a long tradition of gathering systematic sampling data (Böckmann 2004). Thus, even without the application of tree models, the basis for decision-making is improved simply by the fact that real inventory values are known, which may differ quite substantially from the average values of yield tables.

Further improvement can be achieved when using tree models. In the state forest administration of Lower Saxony, Germany, the distance-independent tree model BWIN-Pro is used (Böckmann 2004). The distance-dependent model SILVA 2.2 was first applied in the community owned forest of the city of Traunstein, Bavaria (Pretzsch 2001), and is now used as a standard tool in forest management planning in the state forest administration in Bavaria. Both model applications work in a similar way. In a first step the model is applied in order to reduce inventory costs. Inventory data are supplemented using form factor and volume functions measured on experimental plots, based on which the tree model is calibrated. In a next step, the model is used to predict diameter and height growth if no repeated inventory data are available.

It would be too time consuming and there would be no significant gain in prediction accuracy if the model simulation were to be applied to every single stand (smallest treatment unit). Consequently the model application can be applied to *(pars pro toto)* experimental stands that represent the typical situation of a group of stands. In other cases the strategies are based on data derived from temporary indicator stands of small size (0.1–0.3 ha).

Another alternative is to apply the simulation to systematic sampling plots of an enterprise or whatever other area the inventory data are raised for. Each sampling plot is allocated to strata of similar plot structure of actual state and future treatment. After having generated virtual stands from the inventory data, the model predicts the growth of each virtual stand. Various treatment strategies (return rate of thinnings, thinning intensity, etc.) can be applied using the model. The harvested volume of the plots is added up, thus providing information on the allowable cut per stratum. The resulting data can be linked to economic or ecological analysis. In this way, the consequences of alternative utilisation strategies, such as the output in terms of commercial timber assortments into volume per size and quality class, etc., can be assessed. After having defined appropriate treatments in each stratum, predictions of enterprise level can be carried out. It is now possible to assess the consequences of utilisation scenarios on a stand or strata level. The extension of a growth simulator from a single stand or single stratum simulator to an enterprise level in which a variety of stands or strata are analysed together is an important step in implementing tree models into forest practice. It is the key step in the use of tree modelling as a management tool on a strategic level.

Not only are the results important in terms of allowable cut, economic figures, etc., but also they provide a thorough analysis of the present structure of the growing stock based on inventory data. Applying model simulations demonstrates changes in development not only of several output values, but also with respect to the possible consequences to the amount of growing stock and its specific structure and consequences for a variety of other forest functions. This is important in considering various aspects of sustainability.

A specific strength and the main emphasis in applying individual tree models is the calculation of treatment scenarios in stands that diverge significantly from the conditions of classical yield tables. This especially holds for mixed or uneven aged stands, as well as such stands with a high deviation between yield table and observed values. They also provide a better assessment of the future development of heavily damaged stands due to insects, storm, drought, etc., as well as their reaction to further silvicultural treatments.

2.4.2
Long-Term Silvicultural Production Programmes

Modern tree models are also used to assess the consequences of different long-term silvicultural treatment programmes (Pretzsch 2003). Thus they serve as an instrument for strategic decisions on various spatial levels (stand, management strata, enterprise, landscape) (Dursky 2000; Hanewinkel 2001; Pretzsch 2002). It has to be admitted, however, that simulations over a long period of time (100 years or longer) have a problem with prediction accuracy. Nevertheless, there is currently no alternative. The simulator is calibrated with data from long-term experimental plots. The simulation runs can also be based on experimental plots or on inventory data. As a result of modern inventory methods the quality of the input variables usually is very good. In most cases it is based on systematic sampling results.

Examples of the application of growth simulators for long-term production programmes can be the simulation of a conversion scenario from even aged to uneven aged spruce stands and their impact on commercial timber supply (Hanewinkel and Pretzsch 2000). Ledermann and Sterba illustrate this in Chapter 10 with an example from a private enterprise (Prämonstratenser monastery Schlägl) in Austria. In Chapter 16, Brunner et al. provide details of a case study of the conversion of secondary plantations of Norway spruce into beech-dominated forests in Denmark.

For practical forestry it is not only of importance to evaluate certain management scenarios and then decide the most promising alternative. Since the process of transition from one management system to another takes a time period of at least several decades, it is crucial to assess the impact of management during the transition period itself on several forest functions. It may happen that the disadvantages during the phase of transition from one management system to another are so severe that the forest owner decides not to take the risk of this option and remains with the previous system. Forest growth simulators provide the means to study the long-term impacts of management alternatives and give them a numerical basis (Hanewinkel 2001).

Such scenario analysis significantly improves the quality of decisions related to long-term silvicultural programmes. The results after applying these programmes can, however, still prove to be wrong, due to changing growth conditions over time or the possibility that some of the applied algorithms in the model were not appropriate. The improvement for forest practitioners lies in the fact that the starting conditions (due to good inventory data) are well known. Additionally the envisaged silvicultural treatment is clearly defined by using “if…, then…” statements which are documented numerically. In order to ensure good quality it is crucial to explicitly describe management objectives such as tree species composition and stand structure (e.g. diameter distribution) for a certain point of time in stand development, for example, the end of a rotation period. Should the results prove to be wrong, it is possible to readjust the underlying algorithms and thus improve the model quality over time by comparing the model predictions with real values. It can be expected that the prediction of forest growth for practical use in long-term silvicultural programmes will improve in the near future.

2.4.3
Decision Support Systems

In the past, forest management focused mainly on timber production. Today foresters have to keep in mind multiple forest functions when forest management decisions are made. Multiple ecological functions such as biological diversity, protective functions (endangered species, water protection, etc.) and socio-economic questions (income, jobs, ergonomics, recreation, etc.) become increasingly important. Increasing public interest in forests and forest management impact demands participative planning methods. As long as simulators had to deal with various silvicultural treatment scenarios at stand level with optimisation under forest growth conditions, forest growth models were sufficient. Connecting economic questions required additional modules to the simulator. Complex multifunctional demands with a wide variety of sometimes conflicting objectives show the necessity of a more comprehensive system to support decision-making. The combination of forest inventory databases, forest growth simulators, economic modules, geographical information systems and visualisation tools lead to complex decision support systems (DSS, e.g. Pukkala 2002; Albert 2003; Hanewinkel 2003). The idea behind this is not to create a black box where data are fed in at the one end and ready results emerge at the other, but to show in a transparent way the consequences of different treatment alternatives on a variety of different forest functions. This is why the use of such systems is always an interactive computer-based process.

Increasingly often, the public or specific interest groups demand the right of participation. Since decision-making becomes more and more complex due to the task of optimising various forest functions, it is inevitable that non-expert groups will be involved, having to visualise different management alternatives. Thus it is possible to select different management objectives as well as respective weights of fulfillment for various parts of the systems objectives, and optimise the maximum output in the form of a best management alternative in a simulation run. As a result, decision-making in forest management will not be a mechanistic process, but will enable causal arguments with different stakeholders and an objective-oriented forest management. The decision support systems presently available do not yet integrate all possible relevant variables. While applying decision support systems, the user always has to be aware of the limitations of the models available. This shows that the use of complex decision support systems requires a sound knowledge of the possibilities and restrictions of the modules in order to avoid false interpretations of the results.

2.4.4
Natural Regeneration

Tree modelling has made tremendous progress in recent years. Many modules have been developed in order to cover various questions, e.g. economic evaluation. The comprehensive application of tree models in practical forestry requires the possibility of assessing natural regeneration as an important phase of stand development and its impact on other forest functions.

Over the past 30 years there has been a significant change in regeneration practices in forestry. Around the middle of the 20th century, forest stands were widely regenerated by planting. With the exception of beech forests it was state of the art to plant the new forest generation in a regular pattern using different numbers of plants per hectare. In the state of Baden-Württemberg, Germany, natural regeneration at the beginning of the 1980s was only applied to approximately 25% of the annual regeneration area in the public forests of this state (MLR 1993b). With the shift to a more nature oriented forestry, natural regeneration became increasingly important. Today its share has increased to between two thirds and three quarters (von Gilsa and Moosmayer 2002).

Consequently, modelling tree growth today requires modelling natural regeneration. The process of natural regeneration can be divided into two basic processes. One deals with the question of seedling establishment and juvenile tree growth. The second is the process of "in-growth". The model predicts the probability of existing small plants exceeding a predefined threshold level. This makes sense, because, for economic reasons, regular inventory of forests defines a threshold level where inventory of trees starts.

If for a certain area there is no regeneration, information on the expected establishment of seedlings and their expected growth rate is needed. The driving factors for this process are light, site conditions (soil, exposition, water supply, etc.), competing vegetation and browsing impact by deer populations. A model approach has to take these factors into account. Once the conditions of seedling establishment are known, the next step is to estimate density.

For existing regeneration the annual growth in height has to be assessed. Here the determining factors are competition and, again, the availability of light (Hasenauer and Kindermann 2002). For light, there is a direct correlation with the density of the growing stock in the overstorey of the stand.

Browsing of deer populations can have a crucial effect on the establishment of natural regeneration as well as its growth. Therefore it is vital to include this factor in the modelling approach. The question of browsing depends on a multitude of influencing factors, such as the relative densities of the regeneration and of the deer population. Again site conditions play an important role.

In order to integrate the modelled information into forest management processes easily, it would be advantageous to base it on standard inventory data. Chapter 9 (by Hasenauer and Kindermann) describes an innovative approach to this.

2.4.5
Coppice Management and Cork Production

Simulation of forest growth can be applied not only to classical forest management, such as the management of productive high forests, but also as an interesting instrument for other forest activities.

One example of this is growth simulation of coppice forests, which have a long management tradition since the Roman era throughout the whole of Europe. Today this forest system is still widely applied in southern European countries. During the past 100 years in these countries, there have been important steps in conversion of coppice forests. In Greece, for example, since 1938 at least two thirds of the state owned coppice forests and one fourth of the privately owned coppice forests were converted into high forests, as Chatzphilippidis and Spyroglou describe in Chapter 17. Today, the remaining coppice management is undergoing a clear shift away from classical pure, even aged coppice forests towards more uneven aged and in certain cases mixed species stands. The knowledge of growth and yield in these forests as well as the assessment of different silvicultural treatment alternatives are lacking. There are yield tables especially designed for coppice forests, but they deem to be unreliable for forest growth predictions under today's management conditions. Consequently there is an urgent need for a new instrument to predict growth and yield in Mediterranean coppice forests. This is especially important for the construction of management plans. Chatzphilippidis and Spyroglou have developed an approach to be applied in practical forest management.

A little known application of tree modelling is described in Chapter 14 by Ribeiro et al., who developed a tree model for cork production in Portugal. In this case, cork production enlarges the wood-production focus of tree models to non-wood forest products (Borges et al. 1997). The forest owners and cork producers needed a management tool not only in order to predict the amount of expected cork growth, but also as an instrument to balance silvicultural management activities and grazing or undercover cultivation in this filigree agro-silvo-pasture system. If the balance in these ecosystems is disturbed, there is increased likelihood of either erosion or, conversely, forest fires. Tree models are expected to enhance management for both economical as well as ecological purposes.

2.5
Required Attributes, Limits and Unsolved Problems of Tree Models

At the end of this chapter dealing with practical user needs related to tree modelling, it feels appropriate to mention the limitations of these tools from an applied management point of view. Additionally some of the unsolved problems with regard to the practical application of tree models should be addressed.

From a user's point of view, tree models should fulfil the following five general requests (Lemm 1991, 2004) in order of priority:

1. Clear purpose specification.
2. Reasonable accuracy of prediction value and trustworthiness.
3. Integration into information flow in forestry.
4. Communicability of model results.
5. User friendliness and documentation of simulation process.

2.5.1
Clear Purpose Specification

In this context it has to be stated that there is no one model for all purposes. Basically a model should be designed as precisely as possible for the specific purpose it is used for. Transparency of a model is a factor of quality. The more complex an application, the more complex the model has to be. However, this statement is also true the other way around. If the question asked is rather simple, it does not make sense to use a complicated model, because for the user the driving factors of the model reaction should be comprehensible. The best models are the simplest, given the question that must be answered. Much can be gained by defining precisely the managerial problem to be solved and by limiting the model strictly to that problem (Buongiorno and Gilless 1987). Of course, this statement can only hold as a general rule. In practice one has to accept compromises.

2.5.2
Reasonable Accuracy of Prediction Value and Trustworthiness

The user should be able to rely on the accuracy of the model results. They should give a true picture of reality with respect to the specific model purpose. For this it is important to know the range of validity of the applied model. This holds for the geographical range as well as the range of variables of different treatments the model was calibrated for.

Models are more trustworthy if they are "tried and tested". This means that a model should have some references or certification. An important step in this direction was made with the *Recommendations for Standardized Documentations and Further Development of Forest Growth Simulators* originating from the section Yield Science of the German Association of Forestry Research Organizations (Pretzsch et al. 2002). If users consider the model to be a "black box" and they do not understand the underlying algorithms, the acceptance of the model may suffer. Finally, the model structure should be adequately documented.

2.5.3
Integration Into Information Flow in Forestry

An important request from a user's point of view is that there should be interface solutions to input data, such as inventory, close-to-practice definitions of silvicultural strategies and output variables such as economic modules for further processing of the resulting growth and yield data.

2.5.4
Communicability of Model Results

The output results of the model should be easy to understand. There should be standard methods for the interpretation of data, such as comparison values. Visualisation of the results can be an instrument to explain complex correlations. On the other hand, visualisation can be seductive. Good animation and visualisation does not guarantee either the quality of the input data or the accuracy of the model. Practitioners should be well aware of this and always apply criticism towards the model they use. They should be aware of the limitations of the model in use and ensure they do not expect too much of it. This holds especially true for situations in which the model is applied beyond the range of variables it was calibrated for.

2.5.5
User Friendliness and Documentation of Simulation Process

The user interface should be adapted to the conventional design of standard software. It should be interactive, self explanatory and require little training. Available components should be clearly separated and have appropriate basic settings in order to reduce the chance of misuse. User friendliness comes down to good software engineering. This requires close cooperation between modellers, software engineers and end users.

Finally, the simulation process has to be traceable for the end user. This makes the documentation of the simulation process an important step within the use of tree models. Documentation starts with the saving of the settings and assumptions for the simulation session and a comprehensive log-file creation alongside the session. This allows for a later revision of the settings if the simulation result does not fit reality. A complete model software handbook and a glossary with an explanation of the main technical terms are also needed. Finally, scientific references for background information will also raise the trustworthiness of the model. Even though some aspects of the required user friendliness are not of much scientific interest, they demand large financial funds, especially for continuous maintenance and updating of the model software.

For several models one important question still remains unanswered. Tree models are widely developed by scientific institutions such as universities and forest research institutes. The development of the model is a scientific challenge the scientist is interested in surmounting. Once the model is ready, the problems of maintenance, support (hot line, etc.) and further development emerge. Practical application depends very strongly on the availability of these services. In the long run, they are of similar importance to the model quality itself. Usually the application of a tree growth model requires some investment, not only in software and hardware but also (and often more expensively) in the education and continuous training of the personnel dealing with the model. This training should even start at the early stage of university-level education. An exception to the rule is the situation where a forest service or a forest administration develops a tree model and provides the service to keep the model with its own resources (Böckmann 2004). Since the input of money and personnel is very high, this will generally only be possible for large administrations or for forest owners.

Some questions still remain unresolved regarding the satisfaction of forest practice. One of those aspects is risk evaluation. Catastrophic events such as storms have become increasingly important in every-day forest management. Tree models are hoped to provide an instrument to better assess expected storm damage as well as the consequences for management.

Another important area of research related to tree modelling is the field of quality assessment of standing trees. There is an increasing need for better evaluation of the quality of the growing stock in order to maintain economic sustainability.

2.6
Conclusion

In recent years, progress made in tree modelling has been tremendous. Tree models have proven to be adequate instruments to enhance forest management planning as well as strategic long-term planning in forestry. Some solutions for visualisation and training purposes related to tree models are already available. Modern tree models excel to a high degree of flexibility in silvicultural scenarios and integration into business operating processes. Decision support systems have not yet been developed, but it can be expected that within a couple of years they will be well integrated into the decision-making processes of many forest owners.

As for other technical progress, universities and research stations have played the leading role up to now. To ensure an integration of tree models into practice in the future, a closer cooperation between end users and model developers is needed. This requires a deeper understanding of the growth models by forest practitioners and constant backup by and availability of the model experts. An integration of forest practice could lead to results to the benefit of both parts: a comprehensive description of model limits, identification of data gaps, refinement of the algorithms, definition of practice-relevant silvicultural scenarios, including their transfer to quantitative settings for the simulation process, and furthermore, an enlargement of the growth and yield core of tree models towards sustainability criteria and indicators (compare MCPFE 2003; see progress of SILVA: Pretzsch 2004).

Finally, a continuing development of tree models does not mean to transform all existing simulators into all-purpose tools. Rather such development aims to invest more in those components and the main purposes of each simulator that offer best-practice solutions. This would also correspond to an economic use of limited financial resources.

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Standardizing and Categorizing Tree Growth Models

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Abstract. This chapter 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.

3.1
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 ground. Several European states decided upon regulations that force at least the state forests, and in some cases all forest owners as well, to follow uneven-aged forest management methods such as "structural thinning", "target diameter harvesting" and the establishment and care of mixed stands. During the past two decades this has been aided by the development of forest growth simulators in central

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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 are being put forward. In contrast to yield tables they lack, as yet, any form of standardization that could serve as a guide for users and developers. Efforts to develop such guidelines have been made by the Section Forest Yield Science of the German Association of Forestry Research Organizations, by issuing a document recommending the introduction and further development of growth simulators (Pretzsch et al. 2002b). Within the project "Implementing Tree Growth Models as Forest Management Tools" funded by the European Community (no. QLK5-CT-2000-01349) these guidelines have been revised and generalized to support the transition from yield tables to simulators more suitable for forest management.

3.2
Background and Objectives of the Recommendations

The recommendations presented here document the practical applicability of growth simulators, 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 guidelines for model description, model evaluation and software processing the recommendations contribute towards efficient cooperation.

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 ecophysiological processes.

For a better understanding the following strict differentiation is made between the concepts of the 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 need not necessarily result in a simulator.

3.3
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, needs and 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 in so far 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. This may be used as initial values and controlling parameters for the new generation of growth simulators to achieve better and 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 and stands.

As long as the need for information 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 ecosystem management a wider range of options is required which can be provided only by more complex computer 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, in the future, should be taken into account in forest growth simulation. 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.

3.4
Forest Growth Simulators and Their Application Potential

3.4.1
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 200 years. The development of the series of yield tables established, for example, by Schwappach (1889, 1890), von Guttenberg (1915) and Wiedemann (1949), based on graphically smoothed experimental results, into stand growth simulators reveals an increasing tendency towards greater flexibility. This refers to the use of biologically plausible growth functions, better 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.

3.4.2
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 single tree dimensions (Clutter and Bennett 1965). They aim at a more distinctive assessment of grade and value development in pure, even-aged stands. Stand growth models providing information on stem number frequencies include 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). Diameter and height distributions are smoothed out using 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 individual tree dimensions by updating a given initial diameter or height distribution.

3.4.3
Simulators Based on Tree-Level Models

Growth simulators based on individual trees construct a stand from a mosaic of its individual trees by simulating their interactions in a spatio-temporal system. In most cases the main component of individual-tree simulators is a system of difference equations controlling the growth behaviour 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 modelling unit in both of these model structures is the individual tree, through aggregation, the output from low resolution models (i.e. the development of stand characteristics such as mean diameter, or mean height and diameter frequency distributions) can be derived easily.

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 Lee (1967), Mitchell (1969, 1975), Lin (1970), Bella (1971), Arney (1972) and Daniels and Burkhart (1975). In the mid-1970s 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 recent individual-tree models developed since the 1980s, inter alia by Wensel and Daugherty (1984), van Deusen and Biging (1985), Wensel and Koehler (1985), Burkhart et al. (1987), Pukkala (1987), Eckmüllner and Fleck (1989), Kolström (1993), Hasenauer (1994), Sterba et al. (1995), Biber (1996), Nagel (1996, 1999), Kahn and Pretzsch (1997), Pretzsch (1997, 2001) and Pretzsch et al. (2002a,b), largely rely on the methodical principles of their precursors but are much easier to use thanks to the novel developments of graphical user interfaces.

The following six different forest growth simulators are now 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 expansion, 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.

SILVA 2.2 consists of different sub-models (stand structure generator, thinning, competition, allocation, regeneration). Several stand measures [such as diameter at breast height (dbh), tree height and crown diameter] are calculated at 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 in addition.

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 using inventory data on a larger scale. PROGNAUS also consists of different submodels (basal area increment, height growth, mortality, dynamic crown ratio, harvesting). Growth and yield of trees 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.

BWIN calculates tree measures (diameter and height growth, change in crown base) from stand input variables (crown surface area, crown competition) with several functions at tree level. Height increment depends on the potential height growth, competition situation, age and thinning. The diameter increment depends on crown surface area and competition situation.

The Stand Management Support System STAND (Pukkala and Miina 1997) considers individual tree growth as one part in a multi-functional system within the landscape. STAND consists of a stand simulator linked to 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.

3.4.4
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 method if only stand-level characteristics are measured in forest inventory (Pukkala and Miina 1997).

3.5
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 3.1, the most important characteristics of models and simulators are compiled for each of the ten criteria described below.

3.5.1
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.

3.5.2
Range of Application

A precise definition has to 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).

3.5.3
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.

3.5.4
Input

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

3.5.5
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.

Table 3.1. 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 references from literature

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 Parameterization and calibration specifications	3.1 Specifications with regard to region
	3.2 Site specifications
	3.3 Types of mixtures and stand structure
	3.4 Integrated treatment variants
	3.5 Integrated tree species
	3.5 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

Table 3.1. Continued

Criterion	Model properties
	4.5 Database interface
	4.6 Maximum number of trees per calculated area
5 Program 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
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

Table 3.1. Continued

Criterion	Model properties
	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 analysis
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)

3.5.6
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 is all important for making the simulator an integral part of the information flow in forestry practice.

3.5.7
Sub-Models of the Growth Simulator

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.

3.5.8
Additional Algorithms

Further model components which enable, for example, 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 become available.

3.5.9
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. Reynolds et al. 1981; Mayer and Butler 1993; Sterba and Monserud 1996; Vanclay and Skovsgaard 1997; Pretzsch and Dursky 2001) as well as a statement characterizing 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 provided.

3.5.10
Software and Hardware

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

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

3.6
Criteria for Model Evaluation

The evaluation of models should be related to the suitability of the selected model approach for given objectives and purposes, 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).

3.6.1
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 at the enterprise level, based on statistical sampling.
2. *Does the model approach fulfil the user's information requirements?*
   The model approach should take into account changes in silvicultural practices, changing social demands on forests and forestry and disturbance factors affecting forests.

3. *Does the model approach make the best possible use of existing data and the state of biological knowledge to solve user problems?*
   The model should be grounded on a solid empirical basis. In past decades a vast amount of information has been gained on the dimensions, structure and growth characteristics of individual stand components. A number of growth laws (e.g. the law of optimum basal area from Assmann 1953, 1956; the self-thinning rule from Reineke 1933 and Yoda et al. 1963) have been derived, with which individual-tree models may be verified. At the same time information on site and disturbance factors, based on more detailed inventories of test and inventory sites, has improved much.
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 predicting 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).

3.6.2
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 behaviour. Here, forest inventory information from permanent investigation sites is an important and independent data source. Its 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 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 as given by Yoda et al. (1963) or the concept of optimum and critical basal area management established by Assmann (1953, 1956).
7. *Do prediction results correspond with 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.

3.6.3
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. *Is 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 programmes. By contrast, simulators for growth forecasts at forest enterprise level which 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 frame. For this purpose program control is maintained 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 3.5, 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 of 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 that describe the database for the model parameterization, the model parameters and model functions, model evaluation and technical conditions for model installation.

3.7
Research and Development Needs

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

3.7.1
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, parameterization and validation; (2) inventory data that will impart less detailed information, but will give rather more general information on growth in larger areas. Continuous forest inventories based on permanent sample-plot design are well suited to the parameterization and evaluation of models. The two data sources complement each other.

While the tree species Norway spruce, Scots pine, common 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, maple, common 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 to 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 towards the information requirements of new model approaches.

3.7.2
Further Development of Growth Models

One of the priorities is the improvement of the simulation of survival probabilities and tree mortality processes, where some models have large deficiencies. The consequences are imprecise 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 damage, 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 that can be used 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 optimization of management regimes, especially in the present transition to wide spacing and early, severe treatment measures as currently favoured in forestry.

3.7.3
Software Development

A standardized development of modularized programs may lead to a division of labour 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 breakdown into modules ensures the use of these algorithms as components for either evaluation or prediction software. New program modules, e.g. for stand structure analysis or value calculations, may also be used for actual state evaluations and prediction calculations.

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Description of Tree Growth Models Used

European experts in the field of tree growth modeling have developed their own tree growth models. Thus the intention of the work presented in this book is to allow each modeler to maintain independence and the ability to continue the application of the model as he/she chooses. With this step we avoid the development of one "super model", which in the long run may destroy the regional aspects within tree modeling, flexibility, model diversity, innovation and the competition among model developers, which is important for enhancing the technology and addressing specific end-user needs. Although each tree growth model deals with individual trees, there are substantial differences within the model depending on the regional application, the data availability the end user needs and the philosophy the model developer has chosen for solving problems related to tree growth modeling. In the following, we give an overview of the five different tree growth models in Europe selected for the work presented in the book. Note that software demos to each of the presented models can be obtained from the responsible model developer.

4.1
The Silvicultural Decision Support System *BWINPro*

Jürgen Nagel[1], Matthias Schmidt[2]

Abstract. In the past decade German forest policy has undergone a major shift from pure stands to mixed-species stands. Consequently the Forest Research Station of Lower Saxony (NFV) has focused its research on the construction of a tree growth model. This growth model was incorporated into a computer software program (*BWINPro*) which allows for forest growth simulation and strategy development. In addition, this program can be used for permanent plot inventory to calculate future growth, thinning and timber harvest at the enterprise level. The program is used by the Forest Service of Lower Saxony.

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Hubert Hasenauer (Ed.)
Sustainable Forest Management
Growth Models for Europe

Throughout most of Germany silvicultural policies have changed during recent decades. The long-term ecological forest development policy of Lower Saxony aims at uneven-aged mixed forests for the state-owned forest area (*LÖWE*; Otto 1989, 1991). In forest management, yield tables have been used so far, which are designed for even-aged single species stands. If these yield tables are applied to mixed stands, foresters separate the different species virtually and apply the tables to the resulting pure stands. Special mixed forest yield tables have been developed (Bonnemann 1939; Christmann 1939; Wiedemann 1942), but were not found usable in practical forestry, because it was not possible to apply them to the great variety of possible species and types of mixture.

New treatments (i.e. wider spacing, crop tree selection) and changing environment (i.e. higher nitrogen input) induce growth patterns not represented in yield tables (Spellmann 1991). Forest management therefore needs a new instrument, to help in planning, management and analysis of pure and mixed stands. These were the reasons for developing a single tree growth model at the Forest Research Station of Lower Saxony. The model should provide information about a stand situation and a stand's development in practical forestry. In addition it should provide information for other groups such as landscape architects and environmentalists. The program *BWIN* was a first step to create such a planning instrument (Nagel 1996). By integrating the growth model into an easy to use computer model, foresters could access information about the status and the development of pure and mixed stands on a PC.

The Forest Research Station of Lower Saxony has a huge growth and yield experiment data pool of about 3500 plots which are scattered all over northern Germany. The data consist of long-term series of diameter and height measurements taken from single trees. There are numerous values for crown base and a few for crown width. On the newer research plots tree coordinates were also measured. There is little information on untreated plots. This information deficit will hopefully be filled by data from forest preserves. The permanent plot inventories that have been started in several forest districts will be important for model validation. In order to obtain information about regeneration several experiments have been set up. The database was the main prerequisite for the parameterisation of single tree growth and mortality functions, height curves, crown base and crown width functions, a diameter at breast height (dbh) distribution generator based on the Weibull function (Nagel and Biging 1995) and the development of a spatial stand structure generator (Pretzsch 1993). Additional data such as segmented stem diameter and branch diameter were used to parameterise taper functions and wood quality models (Schmidt 2001). Rule-based systems for applying thinning regimes in growth simulations have been built without using empirical data (e.g. Spellmann et al. 1999; Döbbeler and Spellmann 2001; Albert 2002).

The first model version and the simulator have been improved by reparameterisation based on an extended database and the development and implementation of further functions (Nagel et al. 2002), e.g. a wood quality module (Schmidt 2001). The resulting silvicultural decision support system (DSS) *BWINPro* consists of three major blocks (Fig. 4.1): database, program routines and preparation/presentation of results. The database module covers the raw input data, the completed data set after data generation and the storing of calculated results but also model

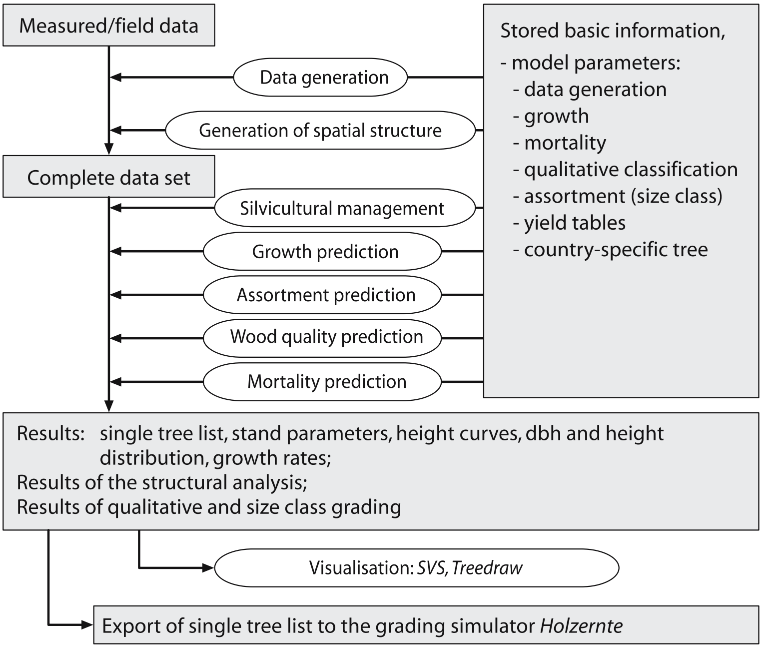

Fig. 4.1. Main structure of the silvicultural decision support system *BWINPro*

parameters, defaults for decision variables and threshold values, etc. The program routines are necessary to handle the input data, generate missing tree parameters for model initialisation, growth and thinning/harvesting prediction, calculation of results and visualisation. The presentation of results includes visualisation of dbh, height distributions and height curves, stand visualisation and formatted tables containing various single tree, stand and structural information.

The program versions *BWIN* and *BWINPro* were used in the beginning mainly for research and to assist the development of silvicultural recommendations for stand treatment according to the LÖWE program, but they have been also available to foresters in the field. By distributing the program over the internet to the public from the beginning, both the growth model and the computer program could be improved through input and critical analysis by external users. Recently, the program has been integrated into the forest planning process of the Forest Planning Agency of Lower Saxony in two different ways.

The State Forest Service of Lower Saxony has installed up to 10 training plots in each forest district to discuss silvicultural guidelines in the field. The program *BWINPro* provides visualisation, analysis of the current status and analysis of scenario simulations for this negotiation process using data from the training plots. Markings of crop trees and thinnings can be evaluated directly, as well as their effects on the future development of the plot. The effects of different management alternatives can be illustrated, e.g. the improvement of diameter growth of crop trees caused by thinnings from above compared to thinnings from below. Since assortment and wood quality routines have been implemented the simulator enables the prediction of the effect of different crop tree selections and thinning regimes on assortment structure and wood quality composition.

For mid-term strategic planning a specific version of the program *BWINPro* has been developed in order to conduct a forecast on the enterprise level using permanent sample plot inventory data. The two-phase permanent sample plot inventory which was installed in the mid-1990s in the first forest districts of Lower Saxony (Böckmann et al. 1998; Dahm and Saborowski 1998) provides an excellent database for the initialisation of a single tree growth simulator. Single tree growth models are the most appropriate tools for updating high resolution single tree inventory data because they allow for growth prediction without aggregating tree level into stand level information (Pretzsch 2001). A disintegration of updated stand level variables into tree variables as they are needed for most planning decisions is dispensable.

The Forest Planning Agency of Lower Saxony needed a planning tool that forecasts the future mid-term amount of thinning and target diameter harvest as well as the future status of the forest enterprise, also controlling the convergence with respect to the *LÖWE* program. Therefore a version of the growth simulator was conceived which is especially adapted to these demands. This program version called *KSP* automatically predicts the growth of hundreds or thousands of sample plots within one simulation run. Thinning and target diameter harvest are applied automatically using a rule-based system, whereas the strength and type of thinning/harvest can be controlled using decision variables. Within the ITM project the functions of the program *KSP* have been enhanced and the decision support system *KSP_DSS* for a support of strategic forest planning has been developed. Some of the main modules that have been implemented into a DSS in order to improve the program *KSP* are as follows:

- A database for storing huge amounts of input data and simulation results.
- A data interface for an easy exchange of data with the Forest Planning Agency.
- A tool for an automatic assignment of management objective to stand types with respect to the *LÖWE* program.
- Tools for calculating frequency and volume distributions by dbh and assortment classes.
- A tool for analysing the regeneration status.
- A tool for calculating forest district areas covered by similar stand types, whereas the similarity can be assessed for a variety of stand variables as standing volume, etc.

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4.2
The Tree Growth Model MOSES 3.0

Hubert Hasenauer[3], Georg Kindermann[4], Petra Steinmetz[5]

Abstract. MOSES is a distance-dependent tree growth model. The model has been developed using permanent research plot data from Austria and Switzerland including more than 78,000 5-year growth periods recorded in uneven-aged mixed species forests. The model covers nine tree species. One additional application has been developed for Quercus frainetto in Greece. In combination with the stand generation tool STANDGEN the model is explicitly designed for forest stand simulations.

4.2.1
Introduction

MOSES – MOdeling Stand rESponse (Hasenauer 1994, 2000) – is a distance-dependent tree growth simulator consisting of diameter increment, height increment, dynamic crown model, and mortality components. The simulator is calibrated for all major tree species in Austria and Switzerland. The tree species currently incorporated are: Norway spruce, fir, larch, Scots pine, stone pine, "other needle trees", common beech, oak, willow, "other broadleaves" as well as *Quercus frainietto* in Greece (Spyroglou 2004). The data source for calibrating the model came from permanent research and sampling plots across the Alpine Arch and included x and y coordinates, repeated breast height diameter, tree height, and height to the base of the live crown measurements. The prediction interval is 5 years, except for willow (Wohlgemut 2004) which uses a 1-year prediction interval.

4.2.2
Model Approach

Increment predictions within MOSES follow the potential growth concept (Newnham 1964), which predicts the current annual height (ih_{obs}) and diameter increment (id_{obs}) according to a predefined potential height (ih_{pot}) and potential diameter increment (id_{pot}) for each tree. Species and site-specific potentials are reduced by crown ratio (CR) which represents past growing conditions. Overstocking impacts are expressed by competition index (CI) according to Monserud (1975) and change in competition (ΔCI) represents changes in growing conditions resulting from crown release. Different crown releases or thinnings (meas-

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ured by ΔCI) can result in either an acceleration or a decline in diameter or height growth for trees that experienced similar past growing conditions. To avoid trivial relationships between observed and potential tree growth, the relative 5-year increment is predicted as follows:

$$\frac{id_{obs}}{id_{pot}}, \frac{ih_{obs}}{id_{pot}} = CR^{b_1}\left[1 - e^{\frac{b_2}{CI\,(1+b_3 \cdot \Delta CI)}}\right] + \varepsilon$$

where id_{pot} is determined from empirical open grown tree dimensions in Austria (Hasenauer 1997) and ih_{pot} follows a suggestion by Newnham (1964) as well as Monserud (1975) and uses the height increment development of dominant trees for a given site. The potential periodical (e.g. 5 years) height increment for a given tree is derived from regional site index functions according to the following procedure: After determining the site index the corresponding index function is rearranged to derive the calculatory age a given tree would have had if it had grown as a dominant tree. Adding the length of the prediction interval (e.g. 5 years) and calculating the future dominant tree height, the difference between the two heights gives the potential periodical height increment. These tree heights are needed and used for deriving the breast height diameter (Hasenauer 1997). The corresponding differences give the potential periodical diameter increment for a given tree.

To update crown ratio a dynamic crown ratio model is used which predicts the change in the height to the live crown base (ΔHLC) as a function of tree height h, crown ratio CR, competition index CI, and the diameter at breast height (DBH) using the following form:

$$\Delta HLC = b_0 \cdot h^{b_1} \cdot e^{\left(b_2 \cdot CR^{05} + b_3 / CI + b_4 \cdot DBH\right)} + \varepsilon$$

Finally, the probability of individual tree mortality (P) is predicted using LOGIT:

$$P = \frac{1}{1 + e^{(d_1 + d_2 \cdot CI + d_3 \cdot CR + d_4 \cdot DBH)}} + \varepsilon$$

where CI is the competition index (Monserud 1975), CR the crown ratio, and DBH the breast height diameter. All models (see software demo) include the remaining error component to address the variance not explained by the model.

Equations within a tree growth model can be considered as a system of equations and may not be independent. For example, the remaining error components of one equation may affect the calibration results of the other equations within the system (see Hasenauer et al. 1998). To address the simultaneous nature of tree growth models and to ensure unbiased coefficient estimates within MOSES, the system of equations was calibrated using full information maximum likelihood (FIML) methods (Hasenauer 2000).

The model includes form factor functions (Pollenschütz 1974; Schieler 1997) and assortment tables (Sterba 1983; Eckmüllner 1985; Kleine 1986) to assess merchantable timber volume. It also allows for a simple assessment of storm and/or snow damage (Schön 1982) using probability functions based on the height to diameter ratio as an indicator for stability.

MOSES includes an explicit regeneration tool for all trees smaller than 1.4 m (Golser and Hasenauer 1997; Hasenauer and Kindermann 2002; Kindermann et al. 2002; Kindermann 2004). The algorithm predicts the probability of regeneration within a 5-year growth period, the species proportion, and the regeneration density of all juveniles. Once the juveniles are established their growth and mortality are developed from overstory competition, the intra- and interpecific competition, and compensatory adjustments due to edge effect (Golser and Hasenauer 1997) incidence of light. If the juvenile trees have passed the threshold height of 1.4 m they belong to the overstory and can be modeled with the standard growth functions as previously defined.

4.2.3
Model Application and Validity

The model has been calibrated for all major tree species in Austria and Switzerland using more than 78,000 5-year growth periods ranging from even-aged pure forests with no treatment to uneven-aged mixed and thinned forest stands. The data set used for calibration included x and y coordinates, DBH, tree height, and height to the live crown measurements for each tree. Note that in our regression runs we used only observed tree data, in order to avoid a potential bias due to a heuristic transformation of missing tree data, for deriving increment data (Hasenauer and Monserud 1997) because generated input data do not have random variation. Thus they lead to artificially high coefficient of determination and even more importantly this procedure may lead to biased or inconsistent coefficient estimates (Hasenauer and Monserud 1997).

MOSES has been used in a variety of applications such as using tree growth models to assess timber values resulting from differing treatment scenarios (Hasenauer et al. 1995), treatment scenarios in beech forests (Hasenauer et al 1996), assessing the success of thinning (Hallenbarter and Hasenauer 2003), developing treatment strategies for protecting forests along rivers (Wohlgemut 2004), regeneration establishment and juvenile tree growth scenarios according to different silvicultural treatments (Kindermann 2004), etc.

The model has also been extensively validated using independent data sets from Switzerland and Austria including more than 52,500 growth periods. For example, MOSES has been recently validated for Swiss conditions (Hallenbarter et al. 2005).

4.2.4
Software and Data Input Requirements

The current version of MOSES for Windows is available in two variants. The first variant is a stand level simulation program, which allows interactive individual tree treatments during a simulation run (Steinmetz 2004). This version is useful for education and training purposes as well as hypothetical tests of silvicultural management strategies. It includes a stand level visualization tool and features all functions that were previously described.

The second variant is a batch version, which allows runs for a large number of forest stands (Kindermann 2004). The idea here is that the simulation of forest stands follows a sequential order and each stand can be assigned to predefined treatments. This batch version can also be used for historic plot data and has the option to deactivate each equation. This has been proven to be very important for model testing and validation using data from long-term field experiments and permanent inventories (Hallenbarter et al. 2005; Fig. 4.2).

Both versions require tree locations which may come from measurements or by using stand generation procedures (Pretzsch 1993; Degenhardt 1998; Pommerening 2002; Kittenberger 2003). They also require the DBH, tree height, and height to the live crown base for each tree. Furthermore, a regional site index function must be specified for each tree species. All equations as well as the corresponding coefficients are available to the public and can be changed or adjusted by the user without recompiling the program.

4.2.5
STANDGEN 2.1

An important feature within the MOSES simulation system is STANDGEN, a stand generation program (Kittenberger 2003) developed at the Institute of Forest Growth Research, BOKU University of Natural Resources and Applied Life Sciences, Vienna. This tool was developed for creating stand situations that are necessary for scenario testing and/or for generating missing coordinates. The motivation for STANDGEN is that for most of our future applications it will be difficult or even impossible to obtain x and y coordinates for trees, although the spatial distribution of the trees may be very important. Note that if no fixed position is assigned at the beginning of a simulation run a mean distance among trees at the beginning of each prediction interval is assumed (see the distance-dependent approach). Conceptually trees move during the simulation run because at each stage an average competition situation at a given plot would be assumed, because the actual stand situation is not known. STANDGEN includes a graphical user interface to develop the stand (Fig. 4.3) and allows any form of forest stand that the user desires (polygon model).

It includes three stand generation algorithms: (1) random, (2) raster, and (3) structured tree distribution patterns according to Kindermann (2004). The typical working steps within STANGEN are: (1) define a forest stand; (2) generate and/or import available tree data; (3) assign the tree distribution according to certain rules (cluster, aggregation, etc.); and (4) exporting the data so that they can be used within MOSES 3.0.

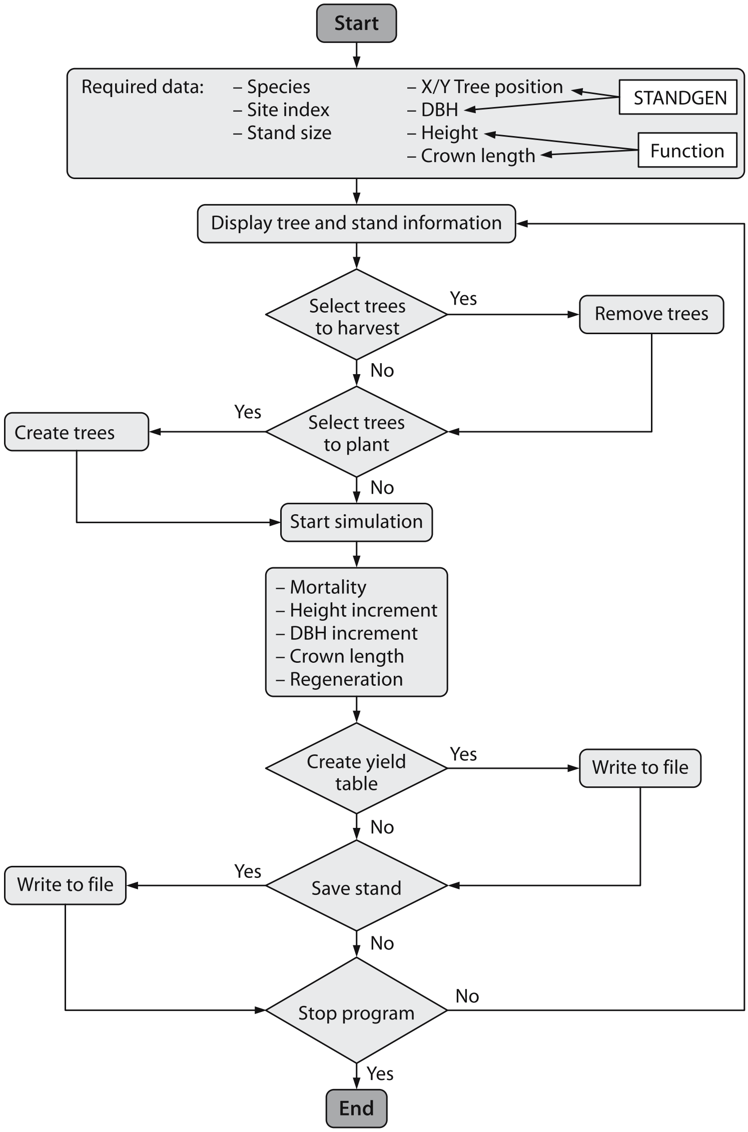
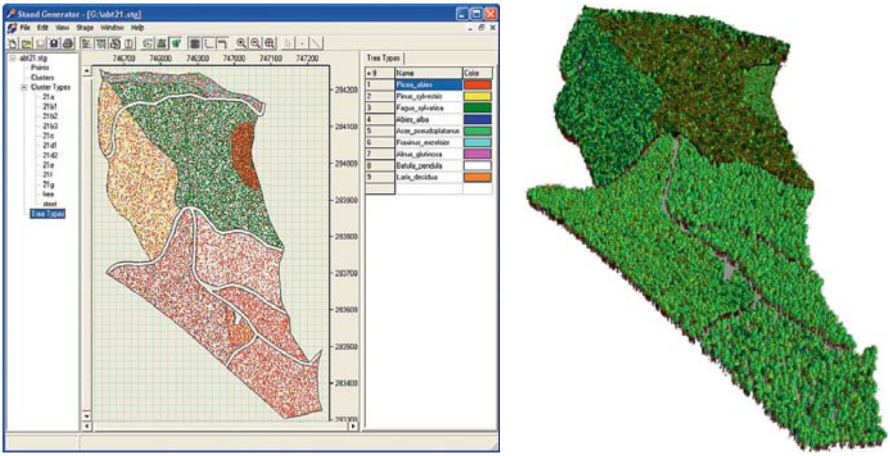


Fig. 4.2. Flowchart of the tree growth simulator MOSES



= 9	Name	Color
1	Picea_abies	🟥
2	Pinus_sylvestris	🟨
3	Fagus_sylvatica	🟩
4	Abies_alba	🟦
5	Acer_pseudoplatanus	🟩
6	Fraxinus_excelsior	🟦
7	Alnus_glutinosa	🟪
8	Betula_pendula	⬜
9	Larix_decidua	🟧

Fig. 4.3. *Left* 38,000 trees generated with STANDGEN for a forest area of about 30 ha. Different *colours* are the differences in the dominating trees species. *Right Visualization of this stand situation using the electronic distribution version of the Stand Visualization Program (McGoughey 1997)*

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4.3
Description of PrognAus for Windows 2.2

Thomas Ledermann[6]

Abstract. Users of forest growth simulators are often faced with specific problems requiring a growth simulator with specific capabilities. Because of the great variety among the existing growth simulators, it is not always an easy endeavour to find an appropriate one. In this situation a standardised description is very helpful. The description of the growth simulator PrognAus for Windows 2.2 follows the recommendations of the German Association of Forest Research Institutions for the standardised documentation and further development of forest growth simulators. It should facilitate the comparison of various growth simulators and help potential users to find the appropriate simulator for their specific needs.

4.3.1
Model Approach

The growth simulator PrognAus for Windows 2.2 is based upon the implementation of the individual-tree growth model PrognAus (*Prognosis for Austria*) which is comprised of a distance-independent individual-tree basal area increment model (Monserud and Sterba 1996; Hasenauer 2000), an individual-tree height increment model (Schieler 1997), an individual-tree mortality model (Monserud and Sterba 1999), and an ingrowth model for trees exceeding the 5-cm diameter at breast height (DBH) threshold (Ledermann 2002a). Treatments, i.e. thinning and harvesting, are based on tree species, DBH classes, and tree attributes. The growth models are independent of age and predict the increment directly, i.e. they do not follow the potential growth concept. Site factors such as elevation, slope and aspect, depth of soil and humus horizons, relief, soil moisture class, soil and vegetation type are included in the growth equations as continuous and dummy variables. Figure 4.4 represents a flow chart which graphically shows the conceptual framework of the simulator and its components. *Configurations* depend on the data set and should only be changed if the data set changes. *Options* can be changed before/after each simulation run.

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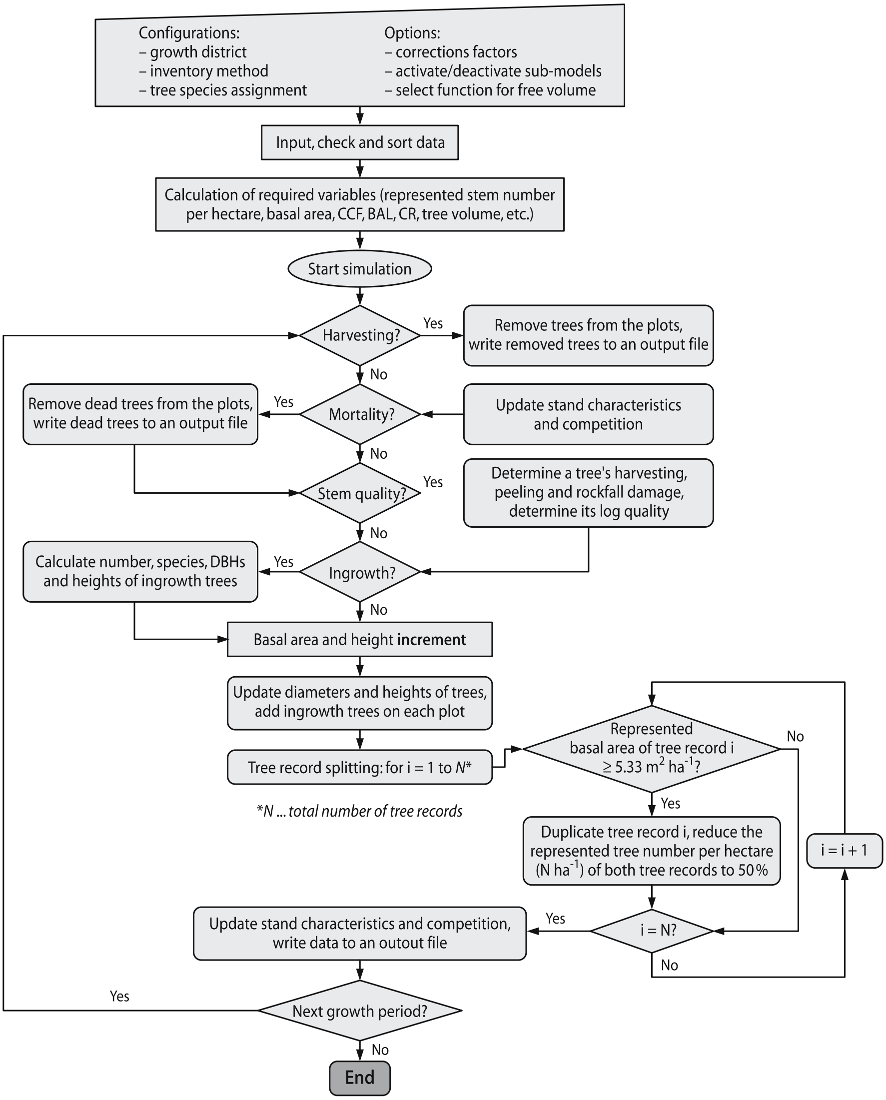

Fig. 4.4. Flow chart of the individual-tree growth simulator PrognAus for Windows 2.2

4.3.2
Range of Application

The individual-tree growth simulator PrognAus for Windows 2.2 can be used to evaluate silvicultural treatment scenarios, and for making forecasts of forest stands and forest inventories, respectively. It is used for research and to determine the annual allowable cut for forest enterprises.

4.3.3
Validity

All sub-models of the simulator were developed from data of the Austrian National Forest Inventory (ANFI). Thus, the validity of the simulator refers to the whole forested territory of Austria. The simulator can be applied to even- and uneven-aged mixed stands of common Austrian tree species, and to all types of commercial and pre-commercial thinnings and harvesting strategies as represented in the data of the ANFI. The input data are limited to trees larger than or equal to 5 cm in DBH (1.3 m); a maximum DBH was not defined.

4.3.4
Input

The input data are independent of area shape and size, and must be provided in an ASCII file or in an MS ACCESS database. Missing information must be generated outside the growth simulator. The number of tree records is not limited, but is rather determined by the computer's available RAM. The requirements for the input data are according to the instructions of the ANFI (Forstliche Bundesversuchsanstalt 1981).

4.3.5
Program Control

The individual-tree growth simulator PrognAus for Windows 2.2 provides an interactive program mode and a semi-batch mode. Furthermore, it is designed for interactive and algorithmic stand treatment referring to DBH classes, tree species, and tree attributes. Both the basal area increment model and the height increment model can be modified by a multiplier; an external change of the actual model coefficients can be done in an ASCII file. Changing the equations is not possible. The simulator provides the opportunity to save interim results; the continuation based on these interim results is possible.

4.3.6
Output

The output of the simulator comprises tree lists of remaining, harvested, and dead trees for each 5-year period. All tree lists can be exported to an MS ACCESS database. For a given stratum, the simulator also provides the development of several stand characteristics such as volume per hectare, stem number per hectare, basal area per hectare, annual increment, harvesting and mortality, quadratic mean diameter, mean height (Lorey), mean tree volume and mean height/diameter ratio, and, finally, the development of the quadratic mean diameter and mean tree volume of the harvested trees. All these characteristics can be obtained at the forest enterprise level or any other substratum (e.g. age class, management district). Structural characteristics at stand or forest enterprise level are limited to distributions of DBHs, species, and tree attributes. Economic parameters in terms of commercial assortments with regard to log size and log quality classes, costs of harvesting (felling + skidding), and the contribution margin (CM, revenue minus costs) are also provided by the simulator. The visualisation features are limited to charts of DBH, species, and tree attributedistributions, and to charts presenting the development of stand characteristics.

4.3.7
Growth Model

Data for estimating model coefficients were available from the ANFI comprising more than 30,000 sample trees. The log-linear basal area increment model was developed by Monserud and Sterba (1996) and Hasenauer (2000):

$ln(BAI_5)=f\ (DBH, CR, BAL, CCF,$ elevation, slope, aspect, thickness of *F*-humus and *H*-humus horizon, soil depth, relief, soil moisture, vegetation type, soil type, growth district)

where

BAI_5	basal area increment of a 5-year period;
DBH	diameter at breast height;
H	total height;
CR	crown ratio;
BAL	basal area in larger trees (Wykoff 1990);
CCF	crown competition factor (Krajicek et al. 1961);
F-humus	semidecomposed, fragmented organic matter and humus;
H-humus	amorphous organic matter without mineral material.

The height increment model by Schieler (1997) is a simple linear model:

$$ih_{11}=f\ (DBH, H, id_{11})$$

where ih_{11} is the height increment of an 11-year period and id_{11} is the DBH increment of an 11-year period.

The simulator contains a static crown ratio model (Hasenauer and Monserud 1996):

$CR=f\ (DBH, H, BAL, CCF,$ elevation, slope, aspect)

and a mortality model (Monserud and Sterba 1999):

$$P_5=f\ (DBH, CR, BAL)$$

where *P5* is the mortality rate of a 5-year period.

In order to estimate the number, dimensions, and species of those trees that exceed the DBH threshold of 5 cm during a 5-year growth period, the simulator contains an ingrowth model (Ledermann 2002a) which on its own part comprises the following five sub-models:

$P_{Ing} = f\,(QMD, BA, CCF, J1, J2, MAS,$ elevation, slope, vegetation type, soil type, growth district)
$ln(N) = f\,(QMD, BA, CCF, J2, MAS,$ elevation, slope, aspect, growth district)
$P_{Spec} = f\,(Spec, BA, CCF, MAS,$ elevation, slope, aspect, soil moisture, soil type, growth district)
$DBH = f\,(N, BA)$
$H = f\,(Spec, QMD, BA, CCF,$ elevation, relief)

where

$PIng$	probability of ingrowth on a plot;
N	number of ingrowth trees on a plot (radius = 2.6 m);
P_{Spec}	probability of a specific tree species;
DBH, H	DBH and height of an ingrowth tree;
QMD	quadratic mean diameter;
BA	basal area per hectare
$J1$, $J2$	dummy variables for a specific development stage being present or absent on the plot;
MAS	management system (coppice forest, high forest, or protection forest);
Spec	dummy variable for a given tree species being present or absent on the plot.

Effects of thinning or harvesting are represented by parameters describing density and competition (CCF and BAL). Depending on the user's choice, the basal area increment model, the height increment model, the mortality model, and the ingrowth model can operate either deterministically or stochastically. All models are statistically fitted models. For estimating model coefficients simultaneous regression techniques and ordinary least square methods were used. Coefficients of probabilistic models were estimated by logistic regression using maximum likelihood methods. Both regression techniques and maximum likelihood methods were provided by SAS (SAS Institute 1989).

4.3.8
Additional Algorithms

Timber grading is based on the assortment tables according to Sterba et al. (1986) and Eckmüllner and Sterba (2002). Furthermore, the individual-tree growth simulator PrognAus for Windows 2.2 contains new models (Vospernik 2004) that allow timber grading in terms of log quality classes A, B, and C according to the Austrian national assortment guidelines (A stands for good quality, B medium quality, and C bad quality). Other algorithms refer to interactive or algorithmic stand treatments. The interactive stand treatment mode is based on species, tree attributes, and DBH classes, the width and the number (maximum 20) of which can be determined by the user. The algorithmic stand treatment mode comprises the following algorithms (Söderbergh and Ledermann 2003):

- removal percentages in defined DBH classes;
- target DBH;
- equilibrium curve;
- LOGIT models for tree removal;
- tree numbers.

In addition to these thinning/harvesting algorithms a snow breakage model is implemented in order to simulate salvage cutting. PrognAus can process both inventory data and data from entire stands. However, data from small plots lead to a differing resolution of the competition variable basal-area-in-larger trees (BAL) during a simulation run. Therefore, a special algorithm (Ledermann and Eckmüllner 2004) is implemented to avoid biased predictions of stand development.

4.3.9
Model Precision

Specifications regarding precision, bias and accuracy can be found in the following references: Monserud and Sterba (1996, 1999), Sterba and Monserud (1996, 1997), Schieler (1997), Sterba (1999), Hasenauer (2000), Sterba et al. (2001), and Ledermann (2002a).

4.3.10
Software and Hardware

The current version of the individual-tree growth simulator PrognAus for Windows 2.2 was released in January 2004. It was programmed in Visual Basic 6.0. An IBM-compatible PC with MS Windows 95/98-XP is required in order to run the simulator; a 300 MHz CPU and 64 MB RAM are recommended.

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4.4
The Individual-Tree-Based Stand Simulator SILVA

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Abstract. The forest growth simulator SILVA is single-tree based, tree-position-dependent and age-independent. The model's core algorithm evaluates the three-dimensional structure of forest stands in order to determine inter-tree competition. SILVA is parameterised with a large amount of data from long-term research plots in pure and mixed species forests, mainly from southern Germany. SILVA covers the tree species Norway spruce, Scots pine, silver fir, Douglas fir, common beech and oak. It includes a regeneration submodel and modules for conducting and visualising large regional scenario analyses based on inventory data.

4.4.1
Introduction

Since 1989, the Forest Growth Simulator SILVA has been developed at the Chair of Forest Yield Science, Munich, Germany, as an applicable tool for management, research and educational purposes (e.g. Pretzsch 1992, 2001). In this distance-dependent individual-tree approach a stand is regarded as a three-dimensional system of single trees influencing each other mutually. This approach permits the simulation of the development even of complex structured even- and uneven-aged pure and mixed stands, which is not possible by conventional means. As defined by its parameterisation data, SILVA is reliable for most German site conditions, par-

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ticularly those found in southern Germany. The current version covers the tree species Norway spruce, silver fir, Scots pine, common beech and sessile oak.

An inventory interface serves for inputting information from practical forest management. Further model features exist to substitute incomplete input information (e.g. deriving environmental variables from rough site information, generating tree data from trial plot information). Additional output routines for timber grading and calculating harvesting costs and sales returns are available. For this, SILVA has been applied for various forest management purposes by several German forest services and private forest owners as well as in research and as an instrument for educating forest students and forest managers. A detailed description of SILVA including tree representation, input and output routines, core module equations of growth and mortality, as well as referring parameters can be found in Pretzsch et al. (2002).

4.4.2
Database

The main data source for parameterisation of model functions is the Bavarian trial plot network, maintained by the Chair of Forest Yield Science. The data were gathered on 288 plots on 570 occasions, which means that many plots were observed repeatedly within the period between 1952 and 1998. Over all plots and inventories, 155,000 tree observations were available for model development. Around 30% of these data points were used for parameterisation. All these observations covered trees from a broad range of diameters at breast height and stand structures, respectively (cf. Pretzsch et al. 2002). Additionally, data from the Forestry Research Station of Lower Saxony and the Swiss Research Station for Forest, Snow and Landscape in Switzerland were used for the development of the site-related potential height growth model (see Kahn 1994).

4.4.3
Tree Representation and Model Initialisation

In SILVA, a tree is described by the following set of key variables: tree species, diameter at breast height (*dbh*), total height (*h*), height of crown base (*hcb*), crown diameter (*cd*) and tree coordinates (*x*, *y*). Every tree is assumed to stand straight upright. Species-specific crown models are used to represent three-dimensional crown shapes (Pretzsch 1992). These models assume the crown to be rotation-symmetrical in the horizontal direction and to be divided vertically in an upper and a lower section. Crown shape is species-specific, but the crown is always assumed to be of maximum width (*cd*) at the height where both sections meet each other.

A simulation run is initialised with information about management, site conditions and tree key variables. Incomplete data can be completed using the stand structure generator module of SILVA (Pretzsch 1997). Recently, the structure generator was enhanced in order to derive representative tree data also from stratified sample plot measurements (Ïurský 1999).

Thinning type, grade and frequency define management conditions. SILVA allows, for example, the representation of different types of selective thinning, final crop-tree concepts, target diameter harvesting, thinning from below or above, no thinning and combinations of these concepts.

SILVA processes information from a set of environmental conditions such as mean temperature and precipitation sum within the growing season or atmospheric CO2 concentration, given as long-term mean values (cf. Pretzsch et al. 2002). Since the whole set of variables is seldom available for a single plot, it is possible to initialise most environmental conditions from the ecoregion code number (as defined by the German site classification), height above sea level, slope and exposition.

Species-specific unimodal dose-response functions are used to aggregate environmental information into ecologically significant site variables (Kahn 1994), determining the properties of a potential height growth curve formulated according to the Chapman-Richards equation:

$$h_{pot} = A \cdot \left(1 - e^{-k \cdot t}\right)^p$$

where h^{pot} is potential tree height at age t and A, k and p are species-specific parameters, which are derived from a vector of site variables.

4.4.4
Core Model Description

4.4.4.1
General Considerations

The smallest simulation time step with SILVA is a forest growth period of 5 years. This period corresponds with the time intervals provided by yield tables. It is also the standard time interval between two measurements on the trial plots used for model evaluation. The first step of each cycle is the three-dimensional competition analysis determining the degree of competition for each tree according to a number of indices described below. Then, preliminary tree growth is determined to be used in the mortality module to decide whether the individual is considered alive for the current simulation period. After the removal of dead or harvested trees, competition indices and dimensional changes of each tree are recalculated.

4.4.4.2
Inter-Tree Competition

In SILVA, inter-tree competition of each tree is calculated by the competition index *KKL*. This index is a geometrical competition measure calculated for the three-dimensional space surrounding a particular tree. Competitors are defined by the virtual-reverse-cone method (Pretzsch 1992; Pretzsch et al. 2002). Besides this index SILVA uses two additional measures for quantifying competition aspects affected by type and spatial distribution of the competitor trees.

4.4.4.3
Mortality

After determining the degree of competition, natural mortality within the next simulation cycle is estimated. The mortality module calculates the survival probability from the dimension of a tree and its expected basal area increase by means of a LOGIT function parameterised by empirical data (cf. Durský 1997; Pretzsch et al. 2002).

4.4.4.4
Thinning

Thinning will be performed according to the settings defined by the user at the start of the simulation. The available thinning types represent a great number of concepts relevant to practice. Some of them are based on a fuzzy logic controller (Kahn 1995), whereas others use other algorithms, e.g. the A-value concept defining the degree of selection tree removal.

4.4.4.5
Height and Diameter Growth

Site-dependent height growth potential zh_{pot} is calculated for each tree using Eq. (4.1) (cf. Pretzsch et al. 2002). zh_{pot} is reduced to the expected height growth zh according to the individual tree's conditions defined by its competition indices and crown dimensions. Tree diameter increment is also derived from potential growth similar to height growth. The potential diameter increment serves for determining the potential basal area increment and the expected basal area growth (cf. Pretzsch et al. 2002).

4.4.4.6
Crown Development

New crown dimensions are calculated by directly estimating the height of the crown base and the crown diameter from tree height and diameter. Data used for fitting indicate that the integrated species-specific parameters allow for a good representation of uneven-aged mixed forests (cf. Pretzsch et al. 2002).

4.4.4.7
Output

From the simulated tree dimensions various aspects of stand development can be visualised within SILVA. For illustration of the three-dimensional stand development, perspective stand views and crown charts are provided, which are supplemented by a realistic stand visualisation system (Pretzsch and Seifert 1999), allowing virtual walkthroughs and interactive thinning. In addition, a large set of numerical information is available which can be viewed as diagrams or as text files that are similar to standard yield tables.

Three kinds of output can be distinguished: first, classical growth and yield data are provided on stand and tree level, e.g. stem number, basal area, timber volume, current and mean annual increment and mean height; second, monetary values can be obtained from the calculation of stand assortment distributions with the timber grading routine BDAT (Kublin and Scharnagl 1988). This includes also detailed information about the monetary development of the stand, which is based on timber prices and harvesting costs specified by the user. If different prices and costs should be investigated, various economic scenarios can be evaluated with the same simulation run. The third group of output information describes ecologically important structural values. Several indices are calculated from tree dimensions and stand structure (cf. Pretzsch 1997; Biber et al. 1998), which can be used to judge non-monetary values such as habitat suitability or social forest functions.

4.4.5
Model Evaluation

The basic question is whether the simulator is suitable to be integrated into the information flow of forest practice, including that the available pool of knowledge is used for efficient planning, execution and control of forest management. This is ascertained in SILVA particularly by its input and output structure. The initialisation procedures provide the possibility for simulations even with incomplete data and allow the use of site information at very different resolution levels. The output methods and tools are developed in close contact with forest managers and thus are designed to meet their information demands. In comparison to classical yield tables, SILVA provides additional information that allows the estimation of monetary yield as well as the characterisation of stand structure and – to a certain degree – biodiversity.

Quantitative model validation was carried out in comparing simulated and observed growth using the example of 615 research plot inventories (Pretzsch et al. 2002). Regarding volume increment, validation resulted in a very low bias, which was less than 4.8% over- or underestimation, respectively. Relative precision resulted in deviations ranging from 18.5–38.6% for the respective tree species. Accuracy results did not differ considerably from precision.

With respect to its qualitative behaviour the model is shown to react in accordance with biological knowledge and practical silvicultural experience, such as Assmann's concept of optimum basal area, Reineke's widely accepted maximum density rule and the structure-related growth dynamics of mixed stands (cf. Pretzsch et al. 2002).

4.4.6
Model Application

The SILVA simulator is implemented as a software program for use with the operating systems MacOS, Windows 95/98/2000/NT/XP. In order to gain independence from the current operating system the core modules are transferred from Object Pascal programming language to C++. Input and output interfaces are designed to be appropriate for practical use from interactive operating at stand level to batch operation at enterprise level. The user manual is edited according to recently defined German and International standards (cf. Chap. 3, this Vol.).

SILVA can be used in forest management for operational and strategic planning. For operational purposes management plans or timber production prognosis can be derived for single stands, forest enterprises and landscape units (Pretzsch et al. 1998). In general, this is executed on a short- or medium-term perspective. In strategic planning, which normally covers longer time periods, SILVA helps to develop management guidelines for certain tree species or stand types under particular site conditions (Pretzsch 2003).

Considering forest research, SILVA is intended to investigate tree and stand responses to changing environmental conditions, including those induced by silvicultural management or climate change impacts (e.g. Biber et al. 1998). This is possible because traditionally gained knowledge from long-term experimental plots has been aggregated into the simulator and can thus be used to assess any combination of conditions that are within the range of the implemented information. Since this allows also for new combinations, the implementation of experimental plots can concentrate on the investigation of actually new conditions. In this respect, SILVA can also serve to define the requirements for new experiments.

SILVA can be used for training of non-professional private forest owners, forest managers and students, as well as to support public relations. For example, thinning can be executed and its effect can be impressively demonstrated with the simulator's stand visualisation system (Pretzsch and Seifert 1999). Trees can be marked by the user to be selected for thinning or as final crop-trees, respectively. So the development of the stand may be shown as a consequence of management activities. Additionally, SILVA is useful for the demonstration of biological and ecological principles of forest dynamics. For example, growth of light-demanding and shade-tolerant tree species as well as the dynamics of differently structured stands may be observed and compared over time.

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4.5
STAND: A Decision Support System for the Management of Even-Aged Stands in Finland

TIMO PUKKALA[11], JARI MIINA[12]

Abstract. A stand-level decision support system STAND can be used to study how forest management should change alongside changing goals. Such guidelines are laid down by a combined use of a simulation model and numerical optimization. The tree-level simulation model accommodates the relationships between management actions and outputs that the forest produces, while optimization searches for the best combination of management actions, through which the forest yields the best combination of multiple products and services. STAND's specific feature is the possibility to deal with multiple objectives, risks, and risk preferences.

4.5.1
Introduction

Private forest landowners do not usually produce timber for their own consumption but sell it to obtain income. Accordingly, from a landowner's point of view, it is not rational to maximize timber production. Neither is it rational to always maximize net income, because this goal does not consider the opportunity cost of the growing stock and the land.

Forest owners can best maximize their economic benefit from the forest by maximizing the present value of net incomes (i.e. the soil expectation value, or SEV). However, very few Finnish forest owners seem to manage their forests according to this objective. If a high SEV is pursued, with discounting rates of 3% or more, optimum management calls for later initiation of logging, heavier thinnings, and shorter rotation than in the present stand management (e.g. Valsta 1992; Pukkala et al. 1997).

One reason why forests are not managed for high SEV is the fact that forest owners have goals other than SEV. The forest may be seen as a source of economic security, liquidity, recreational possibilities, and other amenities. Non-timber forest products and nature conservation may also be of importance to some forest owners.

Because the goals certainly vary among stands, forests, and forest owners, single pragmatic instructions on "proper" forest management are insufficient. The instructions should rather indicate how forest management should change alongside changing goals. Such guidelines could be formulated by a combined use of a simulation model and numerical optimization. The simulation model accommo-

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dates the relationships between management actions and outputs that the forest produces, while optimization searches for the best combination of management actions, through which the forest yields the best combination of multiple products and services. The parameters that specify the treatment schedule are called decision variables. The "goodness" of the outputs obtainable from the forest with a given set of decision variables is described via objective function.

A system with these properties may be called a stand-level decision support system. STAND is a software product that belongs to this category. Its specific features are the possibility to deal with multiple objectives, risks, and risk preferences. Multiple objectives are made comparable by using a multi-attribute utility function as the objective function. The original goal variables measured in their own units are scaled in the range of 0–1, after which their weighted sum is calculated to obtain a utility value for the inspected treatment schedule. STAND can also consider various risk factors when ranking management alternatives. Furthermore, the decision-maker's attitude towards risk may be integrated in the comparison process.

This section first describes how the objective function used in the STAND software is formulated so that it simultaneously measures the quality of a stand's treatment schedule from the viewpoints of multiple objectives, risks, and risk preferences. Then, the simulation sub-system is briefly described.

4.5.2
Optimization

4.5.2.1
Integrating Risk

Risk is quantified uncertainty. The risk associated with future timber prices and growth of trees is taken into account by producing many alternative scenarios for future timber prices and growth level of trees. The value of the objective function is calculated with all scenarios, producing a distribution of the utility index. The wider this distribution, the more there is uncertainty concerning the value of the management schedule.

Another source of risk, which does not arise from the non-deterministic nature of outcomes, are the preferences of the decision-maker. The decision-maker is seldom sure about his or her preferences. The risk due to this fact is accommodated in the valuing process by making the importances of objectives and the discounting rates stochastic. When repeating the calculation of the objective function value with varying timber price and growth level, the weights of goals and the discounting rates are also varied according to user-specified parameters.

4.5.2.2
Integrating Multiple Objectives

The way to deal with several simultaneous management goals is to scalarize the optimization task into a single-objective problem through an additive utility function, as follows:

$$U_j = \sum_{i=1}^{m} a_{ij}u_{ij}$$

in which U_j is the utility index of outcome *j* of a given management schedule, u_{ij} is the sub-utility produced through objective *i*; a_{ij} is a stochastic relative importance of objective *i*, and *m* is the number of objectives. In deterministic optimization, only one outcome is calculated for the management schedule, while stochastic optimization produces many (e.g. 100) outcomes for every inspected combination of decision variables.

The formulae to derive the sub-utilities (u_{ij}), known as sub-utility functions, are used to remove the effect of dissimilarity of the units of different objectives, by scaling all objectives between 0 and 1. This is done by dividing the original measure by the maximum possible value of the variable in question (single-objective maximum), which means that linear sub-utility functions are assumed:

$$u_{ij} = q_{ij} / q_i^{max}$$

in which *qij* is the value of outcome *j* of objective variable *i*, and qi^{max} is the maximum possible value of objective *i*.

4.5.2.3
Time Preferences

The objective variables that forest landowners may have are either products collected from the forest (or income from these products) or services that can be described through the state of the forest, such as value of the growing stock, biodiversity index, or suitability of the stand for recreation. The time preferences connected to the products are taken into account through discounting, and by computing the sum of the present (net) values of the product obtained at different time points:

$$q_{ij} = \sum_{t=t_1}^{t_2} x_{ijk} / (1+0.01r_{ij})^t$$

where *t* is time (number of years), x_{ijt} is quantity of product *i* obtained from outcome *j* in year *t*, and r_{ij} is the stochastic discounting rate (in percent) for objective *i*.

The same idea is applied to state variables. The objective variable is the integral of the discounted value of the state variable between two time points:

$$q_{ij} = \int_{t_1}^{t_2} x_{ijk} / (1+0.01r_{ij})^t \, dt$$

4.5.2.4
Risk Preferences

The decision-maker's attitude toward risk is taken into account by giving different weights to different parts of the utility distribution. A utility index corrected by risk preferences (U) is computed as a weighted sum of a limited number of accumulation points of the distribution function of the utility index (Pukkala and Miina 1997):

$$U = \sum_{k=1}^{n} w_k U_k$$

in which n is the number of accumulation points, and w_k and U_k are the weight and utility index of the kth accumulation point of the distribution function of U, respectively.

4.5.2.4
Optimization Method

STAND uses the non-linear programming algorithm of Hooke and Jeeves to find the combination decision variables that maximize the objective function. The computer program developed by Osyczka (1984) was modified and adapted to work with the present problem formulation.

Due to a non-convex objective variable one can never be sure that the global optimum has been found. Therefore, to find the global optimum, each problem has to be solved several times using different initial values of decision variables. The optimization algothm, which is based on direct search, uses the best of a specified number of randomly selected feasible points as the initial point of a direct search run.

4.5.3
Simulation Model

4.5.3.1
Models for Uncontrollable Variables

The simulation sub-system of STAND includes stochastic models for timber price and growth rate of trees. If stochastic preferences (a_{ij}, r_{ij}) are used, the user must give the standard deviation of the preference parameter, in addition to the mean value. The stochastic models of Pasanen (1995) are used to produce scenarios for the annual growth rate (growth indices) of trees (pine, spruce, and birch). The models take into account the correlation between years (temporal autocorrelation), as well as the correlation between tree species (cross correlation). The stochastic models of Leskinen (1995) are used to simulate price scenarios for different timber assortments (pine log, pine pulp, spruce log, spruce pulp, birch log, birch pulp). Also these models generate the temporal autocorrelation and the cross correlation structure in the time series that they produce.

4.5.3.2
Stand Simulator

Simulation of stand development is based on individual trees. The simulation begins with bare land. The stand establishment is predicted with the models of Miina and Saksa (2004). The models predict the number of planted trees per hectare, as well as the amount of naturally regenerated pine, spruce, birch, and hardwood coppice. Stand development is simulated in 5-year time steps. Various models are used to predict the juvenile height growths and diameters of seedlings from the seedling stage to the sapling stage (dbh 5 cm), after which the individual-tree growth models of Nyyssönen and Mielikäinen (1978) are used. A tending treatment is simulated at a stand age of 5–20 years (depending on site and planted tree species). It removes all coppices and regulates the frequencies of other trees. The stand establishment and tending costs, used in the simulator, are based on cost statistics.

The self-thinning models of Pukkala and Miina (1997) are used to calculate the maximum stand density for a given mean tree diameter. Mortality occurs when this limit is passed, creating one or several cohorts of standing deadwood (snags). If the actual stand basal area exceeds this limit, the frequencies of trees are decreased until the stand basal area is equal to the limit. The removals from different diameter classes and tree species are proportional to the dying probability of the particular species and tree size, as computed by the model of Ojansuu et al. (1991).

During a time step, a part of a snag cohort forms a down-wood cohort, its relative frequency equalling the probability of falling down. Both snag and down-wood cohorts decompose with time, the decomposition rate being clearly higher for down-wood than for snags.

Stand development is simulated until a thinning age or the rotation age is reached, after which a cutting is simulated. In the final cut, retention trees may be left to continue growing, depending on the current input value of the retention tree parameter. The roadside value of the removed volume (gross income) is calculated using the stochastic unit prices of different timber assortments. The assortment volumes are calculated using the taper functions of Laasasenaho (1982). The harvesting cost is calculated with the models of Valsta (1992).

Simulation is continued for one or several additional rotations, keeping the deadwood cohorts and retention trees of the previous rotation(s). The simulation is otherwise similar to that during the first rotation except that there are initial retention tree cohorts and initial deadwood. The growth of retention trees is simulated using the growth models of Nyyssönen and Mielikäinen (1978). A part of a retention tree cohort is wind-thrown and another part may die of senescence during a time step, the relative frequencies of these new cohorts depending on the probabilities of these events. Dead retention tree cohorts decompose at the same rate as the other deadwood cohorts. A standing deadwood cohort originating from a retention tree cohort falls down with the same probability as other snags.

Retention trees are assumed to reduce the growing space that is available to the other trees: their effect on the other growing stock is simulated through an area multiplier. The share of growing space taken by retention trees is equal to the ratio of the basal area of retention trees to the maximum stand basal area that the site can sustain. If the basal area of retention trees decreases due to mortality, the growing space available to other trees increases, creating accelerated growth. It is assumed that the other trees can fully utilise the growing space left by dead retention trees. This kind of simulation is reasonable when retention trees occur in dense and small groups (which is the current practice).

In addition to costs and incomes, the simulator calculates a recreation score (Pukkala et al. 1988) and biodiversity index for the stand at every time point. The biodiversity index is a weighted sum of scaled values of various structural elements present in the stand. The structural elements are: volumes of different tree species, volumes of 10-cm-diameter classes, and volumes of deadwood components (standing deadwood and down-wood). Each element increases the index fast up to 30 m^3/ha, after which its additional contribution becomes very small.

In a steady-state optimization the objective function value is calculated from the last simulated rotation, which is assumed to be repeated to infinity. The other rotations are used to initialize the steady-state amounts of deadwood and retention tree cohorts present at the beginning of the last rotation.

In optimizations for bare land the whole simulation period (several rotations) is used to calculate the objective function value. Also in this case it is assumed that the last rotation will be repeated to infinity.

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Modeling Forest Regeneration

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Abstract. The aim of this chapter is to review different approaches for simulating forest development in regeneration modeling. The features, shortcomings, further needs and trends of regeneration modeling are presented and discussed in the context of mechanistic, gap, statistical and nonparametric forest models. The data requirements are also described. Special emphasis is put on supplying information for modelers applying individual-tree models in uneven-aged stands.

5.1
Introduction

Within sustainable forest management planning, mathematical models are used to predict forest development over time. One of the most difficult tasks of forest modeling is to predict regeneration dynamics. While our understanding of the development of overstory trees is well developed, many processes of forest regeneration are still poorly understood because it may be difficult or even impossible to measure all the factors that affect regeneration. In addition, there are strongly random temporal and spatial processes that affect the birth, growth, damage and mortality of seedlings. For example, seed production and dispersal are closely linked to species, age, size, vigor and distance of overstory trees, as well as to the prevailing climatic factors (e.g. Chazdon 1988; Kozlowski 2002), whereas germination of seeds and seedling establishment are more stochastic. These processes of germination and establishment can be derived from soil and weather conditions, competition by overstory trees and ground vegetation, etc. Silvicultural treatments such as cuttings, site preparation, planting and direct seeding are used to alter regeneration conditions and thus to promote establishment and development of regeneration (Fig. 5.1).

The term 'regeneration' can refer both to the process and to the resulting generation of new trees. In the literature, it is common that all trees which are not

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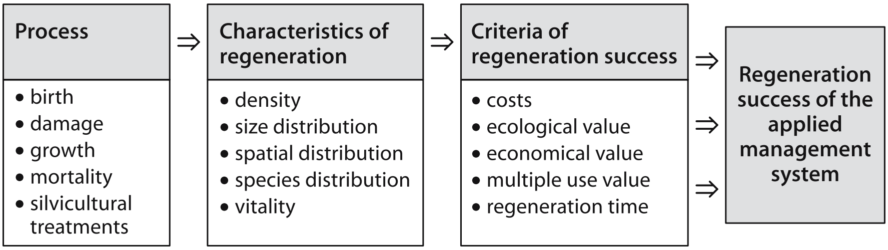

Fig. 5.1. Conceptual analysis of the processes affecting forest regeneration and regeneration development. (Adapted and modified from Valkonen 2000)

considered to be overstory trees belong to the understory and are thus considered regeneration. This distinction is mainly a result of the data collection system, which defines the minimum tree dimensions of trees belonging to the overstory population. In large-scale forest inventories, such as the Austrian National Forest Inventory, all trees with a diameter at breast height (dbh) greater than 5.5 cm are recorded (FBVA 1994) and thus considered to be the overstory. Other data sources, such as permanent research plot data, may consider all trees taller than a certain tree height (e.g. 1.3 m) to be included in the overstory population. These differences in the threshold level are a result of the data-recording design and may affect the theoretical model formulations as well as the applicability of regeneration modeling tools within the framework of a stand management system.

The distinction between regeneration models and so-called recruitment or ingrowth models is important. Vanclay (1994) defines the difference between these types of models as follows: regeneration models predict the development of trees from seeds or seedlings, whereas recruitment models predict the number and species of trees reaching some specified size limit (e.g. breast height). Thus, recruitment (or ingrowth) models predict the number and dimensions of new trees entering the smallest size class of the overstory population within a given period of time (e.g. Ledermann 2002). Once trees belong to the overstory, growth equations are used to assess the further development of the trees.

Regeneration models simulate the germination, early establishment and growth of new trees starting from seed formation or seeds (Ribbens et al. 1994). Some models do not start from seed germination but rather when seedlings reach later life stages with a higher probability of survival. These models may be called regeneration establishment models, and they can be applied to both natural and artificial regeneration. The development of regeneration is commonly predicted using juvenile growth models until the seedlings grow into the smallest size class of overstory trees.

The purpose of this chapter is to review existing knowledge of regeneration modeling so that modelers are able to evaluate different types of regeneration modeling approaches from their own point of view, i.e. considering the structure of their stand simulator, the regeneration data available, etc. Special emphasis is put on modeling forest regeneration in the context of individual-tree modeling and uneven-aged stand management because several silvicultural management practices are intended to promote the regeneration dynamics of our forests.

5.2
Modeling Approaches for Forest Regeneration

5.2.1
Mechanistic and Gap Models

Mechanistic (or process-oriented) models predict forest development as a system of biological processes within a forest stand (e.g. photosynthesis, respiration, transpiration, allocation of photosynthesis products, uptake of nutrients and water) and in the soil (e.g. decomposition of litter and humus). These biological processes are controlled by the physical environment (e.g. shading, weather and soil conditions). In general, large-scale biogeochemical-mechanistic models simulate regeneration by assuming a certain minimum carbon content in the stem and leaf fraction (e.g. 25 and 10 g/m^2, respectively), which gives the starting leaf area by species for a simulation run (see Thornton 1998; Pietsch and Hasenauer 2002).

Regeneration models have been derived from relations that describe forest regeneration, including amount and quality of the seed crop, seed dispersal, germination and predation of seeds, and survival and growth of seedlings (Kellomäki et al. 1987; Pukkala 1987; Pukkala and Kolström 1992). Usually these relations are modeled stochastically, which allows us to evaluate the risk of failure in a particular regeneration situation. Such models (e.g. seeding models) have led to theoretical analyses that test the role of factors such as site fertility, stand density, site preparation, weather conditions, etc. in natural regeneration (e.g. Rogers and Johnson 1998).

In gap and patch models, establishment of regeneration is simulated as a stochastic process constrained by species-specific environmental ranges (e.g. temperature sum, soil moisture, frosts) and regeneration attributes (e.g. pioneer or shade-tolerant) (e.g. Price et al. 2001). In the first gap or succession models, regeneration was not driven by the trees in the overstory (see Botkin et al. 1972; Shugart 1984; Botkin 1993): new trees were added from a fixed list of species but could not exceed a maximum number of stems per unit area and time period. Each tree was initialized by a given tree height (e.g. 4.5 ft or 1.37 m) and a certain minimum dbh.

Detailed regeneration models mimicking flowering, fructification, seed production and dispersal, and establishment and growth of seedlings require extensive data, analysis and programming. Furthermore, such approaches have seldom been used because they may lack accuracy due to too many parameters that are difficult to localize for a given situation. However, recent advantages in modeling regeneration have improved this procedure. A good example is the spatial individual-tree gap model SORTIE (Pacala et al. 1996). The regeneration sub-model of SORTIE predicts the number and locations of seedlings produced by each overstory tree stochastically as a function of tree size and location using an extensive set of data collected from north-eastern USA (Ribbens et al. 1994).

5.2.2
Statistical Models

5.2.2.1
Whole Stand and Size Class Models

Statistical models are usually classified according to the basic growth unit for which the predictions are made (Munro 1974). Whole stand models (e.g. growth and yield tables and equations) use stand characteristics such as dominant height, stand basal area and age to simulate the stand growth and yield. Models work well in managed even-aged stands where ingrowth and mortality are ignored or assumed to be constant over a wide variety of stand management practices.

Size class models (e.g. stand table projection, transition matrix models) predict the ingrowth, growth and mortality in each size class. In most cases, diameter classes have been used. Stand table projection uses a current diameter distribution (stand table) and ingrowth, growth and mortality predictions by diameter classes to project the future diameter distribution (in uneven-aged stands, see, for example, Ek 1974). With a transition matrix, the ingrowth and upgrowth transition, as well as mortality probabilities estimated for each size class are used to determine the future diameter distribution. Ingrowth has been assumed to be constant (e.g. Kolström 1993) or a function of stand density: increasing stand basal area will decrease ingrowth, and increasing the number of trees will increase it (e.g. Buongiorno et al. 1995). Size class models are used for uneven-aged and uneven-sized forests, especially in the tropics (Vanclay 1994; Peng 2000).

Diameter distribution models are commonly used to smooth diameter classes: the distribution of diameters in a stand is described by a probability density function (e.g. Weibull, Johnson's SB). The parameters of the function are predicted from easily measured stand variables using, for example, a parameter recovery method or other parameter prediction approaches. Diameter distribution models predict stand development but may give unreliable predictions for the number of smallest trees in the stand, i.e. ingrowth (e.g. Maltamo and Kangas 1998). The diameter distribution of uneven-aged stands is typically reverse J-shaped, the frequency decreasing with increase in diameter. If the ratio between the number of trees in successive diameter classes is almost constant, the diameter distribution can be described by a descending geometric series or an exponential curve of the form: $y=k\times\exp(-a\times x)$, where y is the number of trees in diameter class x, k reflects the occurrence of regeneration, and a determines the relative frequencies of successive diameter classes (Meyer 1952).

5.2.2.2
Individual-Tree Models

Individual-tree growth models are of interest in forest modeling because conceptually they allow incorporation of any kind of silvicultural treatment. Such models simulate the growth and mortality of each individual tree. Aggregating the tree information of each tree within a stand provides stand-level growth and yield. Individual-tree models may be divided into distance-dependent and distance-independent models according to whether or not information on the spatial locations of trees is utilized in modeling. It has been proven that spatial distribution plays an important role in regeneration processes. For example, spatial patterns resulting from the small-scale randomness of individual births can have significant impacts on larger-scale aspects of the forest dynamics (Ribbens et al. 1994). In addition to individual-tree simulation models, analytical approaches have been used to model the effect of spatial interaction on birth, growth and death in ecological systems (e.g. Bolker and Pacala 1997). These, mainly theoretical approaches, enable us to explore both the analytic and ecological consequences of the spatial structure within a stand simultaneously.

In tree-level modeling, regeneration may be considered at different development stages. Due to highly variable survival and growth of germinated seedlings, the logical starting point of modeling would be the phase when seedlings are established (establishment models), seedlings have reached a certain threshold size, e.g. breast height (ingrowth models) or young trees enter a certain diameter or height class in the stand (recruitment models). For example, a seedling height of 10 cm has been used as a threshold by Schweiger and Sterba (1997) to assess establishment of regeneration within natural and planted forests.

Regeneration modeling based on individual-tree models involves two main parts: (1) establishment of regeneration and (2) juvenile tree mortality and growth. Due to the differences in the regeneration data available and the constraints as given by the model to be used, different concepts have been developed (e.g. Golser and Hasenauer 1997; Schweiger and Sterba 1997; Biber and Herling 2002; Hasenauer and Kindermann 2002; Hynynen et al. 2002). A regeneration model consists of several equations which predict the number, species, height distribution, survival and height growth of new established trees until growth can be predicted using equations for overstory tree growth. Note that although damage to seedling establishment and regeneration growth due to browsing, timber harvesting, etc. should be taken into account, relatively little information is available for regeneration modeling.

Forest regeneration tends to be sporadic, i.e. little or no regeneration for some years and large amounts in those years when it does occur. To overcome this feature, a two-stage approach of regeneration modeling has been applied (e.g. Ferguson et al. 1986; Ferguson and Carlson 1993; Solomon et al. 1995; Ferguson 1997; Schweiger and Sterba 1997). First, the probability of regeneration on a given plot is predicted using a logistic regression model. When the logistic equation is applied in a deterministic way, the average regeneration probability in the data set can be used as the 'threshold' regeneration probability above which regeneration is present (Schweiger and Sterba 1997). In stochastic predictions, to decide whether regeneration occurs or not, a uniformly distributed random number [0,1] is compared to the calculated probability. Second, if regeneration occurs, the number, species and dimensions of new trees are predicted using a set of equations.

The data used in regeneration modeling usually have a hierarchical or nested structure, e.g. there are sample plots within regeneration areas which are grouped within geographical locations. This can be taken into account by fitting random parameter models where the intercept, and possibly also the coefficients, vary randomly across hierarchical levels. If the data for fitting the set of equations are measured from the same sample plots, the equations should be fitted simultaneously due to the fact that the residuals of the equations are correlated. Due to the hierarchical data structure and simultaneous estimation of several equations, multivariate multilevel modeling is recommended (e.g. Goldstein 1995; Snijders and Bosker 1999). The multivariate estimation of several response variables (e.g. the number and size of different tree species) measured from the same sample plots would enable, for example, estimation of the correlations between the responses at different hierarchical levels and comparison of the effects of predictors on different responses.

A model for predicting the number of trees of a given tree species on a sample plot is a typical example where the response is a count, i.e. nonnegative and integer-valued (e.g. Wilson and Maguire 1996). Fitting a normal linear regression model is no longer an appropriate approach unless the mean of the counts is high, in which case the normal approximation and other related regression methods may be satisfactory (e.g. McCullagh and Nelder 1989). In count data analyses, the starting point is to fit a Poisson model using a log link function, which ensures a nonnegative mean. In some cases, the data-generating process is not Poisson, i.e. the counts of regenerated trees in sample plots are not Poisson distributed. A common deviation from the basic Poisson model is that the conditional mean and conditional variance differ. An explanation for the feature that the variance exceeds the mean (so-called over-dispersion) is that naturally regenerated trees are clustered in the stand (e.g. Ripley 1981), while planted seedlings are systematically distributed, which indicates an under-dispersion of the Poisson model.

An example of using multilevel multivariate Poisson models in predicting the rate of regeneration establishment in uneven-aged stands is given by Eerikäinen et al. (unpubl.). The modeling was conducted within the project 'Implementing Tree Models as Forest Management Tools'. Since uneven-aged forests are spatially and structurally heterogeneous, distance-dependent variables were used to account for the competition between trees. Statistical, tree-level models including the establishment, survival and growth of seedlings were capable of predicting highly variable and seemingly unpredictable regeneration in uneven-aged mixed-species stands. The models were used to construct a simulation system applicable, for instance, to optimization of the management of uneven-aged forest stands in Finnish conditions.

The modeling of regeneration and juvenile tree growth may be simplified by using ingrowth or recruitment models. Such models require data representative for the area of interest (e.g. large-scale forest inventories) to predict the number and species of new trees entering the overstory during a given growing period (see Ledermann 2002). Once the number and proportion of species is known, the recruited trees have to be initialized by defining, e.g. dbh, tree height and height to the live crown base, so that they can enter the overstory simulation system. For example, Trasobares et al. (2004) prepared models for predicting the number of new *Pinus sylvestris* and *P. nigra* trees entering the first diameter class (7.5–12.4 cm) and the mean diameter of ingrowth at the end of a 10-year growth period.

An important constraint of ingrowth models is that conceptually they ignore the fact that it may take years for seedlings to reach a given threshold size, and that at the time of establishment conditions may have been different from those of the ingrowth period. In addition, the species composition and stand treatments that may have initiated regeneration are not explicitly addressed. The main goal of ingrowth models is to ensure that during simulation runs the ingrowth of trees is predictable according to management, site and stand conditions.

The applicability of traditional regression techniques for predicting forest regeneration was found to be limited, for example, in Prognosis^{BC}, which is an adaptation of the US Forest Vegetation Simulator (Robinson and Kurtz 1998). Only a small part of the total variation in regeneration establishment can be explained. To imitate the observed variation, the unexplained variation would be added stochastically to the predictions if the variance–covariance matrix of the stochastic components is known. In addition, large data sets are needed to estimate reliable and representative regeneration models. Thus, the high cost of collecting detailed regeneration data may limit the availability of regeneration models fitted by regression techniques.

5.2.3
Nonparametric Models

Recently, new modeling techniques have been applied in forest modeling, and also in regeneration modeling. Imputation methods, e.g. tabular imputation, k-nearest neighbor (k-NN) and k-most similar neighbor (k-MSN) approaches, have shown several potential advantages over traditional regression techniques in forestry situations (e.g. Moeur and Stage 1995; Haara et al. 1997; Maltamo and Kangas 1998; Sironen et al. 2003). For example, imputation approaches do not require distributional assumptions and they are multivariate, i.e. provide estimates of many variables (species, height class, etc.) at one time. Imputation models are more efficient in using limited data, which is often the case in predicting forest regeneration (Ek et al. 1997; Froese et al. 2002; Hassani et al. 2002, 2004).

All imputation methods make use of the regeneration data of previously measured observations (reference plots), which must be available at the prediction phase. In the tabular imputation approach, the reference plots are tabulated or classified, e.g. according to treatment, site and stand characteristics; and the average regeneration establishment of an appropriate class is used as the estimated establishment of regeneration on the target plot (Hassani et al. 2002, 2004). The tabular imputation provides only average post-harvest regeneration for different conditions; therefore, to mimic the variability in regeneration establishment, the MSN or NN imputation approaches must be applied (Froese et al. 2002; Hassani et al. 2002).

The k-NN approach provides establishment of regeneration for a given target plot by selecting k-nearest-neighbor sample plots from the reference plots and imputing their regeneration establishments for the target plot. Selection of the nearest plots is based on a similarity measure that considers the relationships between the two different sets of data, i.e. easy-to-measure treatment, site and stand characteristics. Similarity measures have been based on absolute differences, Euclidean or Mahalanobis distance functions. In the MSN method, the similarity measure is solved analytically using canonical correlations and Mahalanobis distance. Finally, the weighted average of the regeneration establishments of a chosen number (k) of reference plots is used as the estimated regeneration establishment of the target plot. Estimates for regeneration establishment improve when more similar neighbors are used (Froese et al. 2002; Hassani et al. 2002).

Artificial neural networks represent a computational methodology which is used to uncover the structure of a large variety of data (e.g. Anderson 1995). Neural networks, in particular, are applied to the modeling of processes characterized by noise, poorly understood intrinsic structure and random factors. These characteristics are usually present when regeneration establishment is predicted. In general, neural networks act as nonlinear, nonparametric function estimators. Their behavior is the result of a training process where typical situations in the application area are presented to the neural network, which adapts its structure accordingly. During training, the neural network seeks to adjust its structure in such a way that the correct, or sufficiently close to target, data (e.g. regeneration establishment) are produced for each input (independent variables). A problem in training is that a too complex network may fit the noise and not just the signal, which leads to overfitting. On the other hand, a network that is not sufficiently complex can fail to detect the signal in a complicated data set, which leads to underfitting.

Hasenauer and Merkl (2001) predicted the number of juvenile trees (≤ 1.3 m in height) and the relative percentage of individuals by tree species (target data) in uneven-aged mixed-species stands using maximum diameter, number of stems, basal area, a dummy variable for a stand edge, and humus type as input variables. They trained a neural net using multi layer perceptron (MLP) techniques and, as a learning algorithm, resilient back propagation (Rprop). Rprop is a local adaptive learning scheme, which performs supervised learning in MLP using the adaptive learning version of the Manhatten-learning rule (Riedmiller and Braun 1993). The results suggested that the estimation procedure is more accurate than the conventional statistical approach based on regression analyses.

Decision trees for regeneration modeling (see Kindermann et al. 2002) are a multivariate classification scheme based on a binary recursive distinction. Binary refers to the fact that there are always only two possible options at a given node, and recursive means that this distinction can be applied repeatedly. At each node, certain distinction rules are defined (e.g. dbh more than or less than 40 cm, etc.). To define a useful rule, all possible variables are tested. The variable that results in the best separation will be selected. This procedure will be repeated for each branch until no separation is possible or until less than a certain threshold number of observations for a given branch is evident.

The practical implementation of a decision tree can be done with the software package rpat (recursive portioning and regression trees) within the statistic program R (Ihaka and Gentleman 1996). The resulting decision tree needs to be simplified using a cross-validation procedure. This step is usually repeated 10 times to test whether the separation along a branch of a decision tree results in improvement of the decision or not. If no improvement is detectable, the branch can be reduced (Venables and Ripley 2002). Kindermann et al. (2002) used decision trees to test the probability of regeneration establishment during the last 5 years and found that high overstory competition was the key criterion for failure in regeneration.

5.3
Data Collection

Basically three alternative sources of data have been used for modeling regeneration: (1) controlled regeneration experiments, (2) collection of regeneration data as part of a routine forest inventory, and (3) specific regeneration surveys.

5.3.1
Controlled Regeneration Experiments

Such experiments allow for controlled empirical assessment of factors influencing the growth and survival of tree regeneration (e.g. regeneration method, site preparation, tree species, planting density, etc.). These studies help us to detect and describe the relationships between regeneration success and the factors affecting it. Controlled regeneration experiments are usually not geographically representative. In addition, their temporal representativeness is often weak, because the weather conditions that affect the regeneration result may vary greatly in different years. However, they are usually designed to cover a wide range of expected conditions and thus help us (1) to detect the variables that drive the system and (2) to formulate models to be fitted using representative sets of data.

5.3.2
Routine Inventory Data

Regeneration information from routine forest inventories provides representative regional data for regeneration modeling. The data collection system is based on a systematic sampling design which assumes that all growing conditions in the regions are covered. Routinely conducted National Forest Inventories (NFI) also allow periodical updating of regeneration models. For example, the regeneration model of the Finnish forest planning system MELA is based on the NFI data (Hynynen et al. 2002). In this system, establishment of regeneration is predicted at the tree level so that the density and species composition of a seedling stand (i.e. dominant height >1.3 m and mean diameter <8 cm) will resemble those observed in the NFI sub-strata. The sub-strata are defined by soil texture (mineral or peat), fertility class, regeneration method (natural or artificial) and target tree species (cf. tabular imputation approach).

When inventory data are collected, many factors such as earlier stand treatment, time since regeneration, method of site preparation, seedling material, origin of seedlings, etc. are difficult or even impossible to determine. Therefore several variables that play an important role in forest regeneration cannot be used in modeling, which decreases the usefulness of the inventory data in regeneration modeling. For example, it may be difficult to identify planted trees if the planted tree species also regenerates naturally and several years have passed since planting. In that case, a dummy variable can be used to determine plantation effects in modeling. If details of the pre-harvest structure of the stand and the timing of harvest are needed in the regeneration model, they could be reconstructed and determined from stumps.

Another important issue in using regeneration data from a routine inventory is that in some inventories certain minimum threshold numbers determined according to the height of the regeneration are used to determine whether or not regeneration information will be collected (e.g. the Austrian National Forest Inventory – FBVA 1994). Plots where no or very little regeneration occurs may be excluded from the data, which makes assessment of how certain silvicultural management techniques affect regeneration establishment and development difficult or even impossible. Note that from a practical point of view it may be important to understand why under certain growing conditions we have no or very little regeneration.

5.3.3
Regeneration Surveys

Regeneration surveys monitor the success of forest regeneration. In addition, data from regeneration surveys can be used to develop regeneration models. These surveys have been conducted to determine establishment success and the quality of regeneration methods applied in practice (e.g. Räsänen et al. 1985; Saksa 1992; Kinnunen 1993; Hyppönen 2002). Regeneration surveys are sometimes designed to assess the impacts of deer damage or browsing on regeneration (Reimoser and Gossow 1996; Posch 2003). Due to incompatibilities such as different geographic survey areas, different times since regeneration, regeneration material and practice, and measurement guidelines, it has been difficult to combine and use data sets from different surveys.

In Finland, regeneration is surveyed in private forests from 3 to 5 years after a regenerative cut (Saksa et al. 2002). A similar regeneration survey is also used in the forests of a large Finnish forest company. Data on the regeneration area, method and result are stored in a database, which is used to provide quantitative and qualitative information on regeneration establishment and its variation at different levels (e.g. regeneration year, forestry center, municipality, regeneration area, sample plot). This information helps us to find the best regeneration methods for a given set of conditions. A database has also been used for predicting establishment of regeneration using a multivariate multilevel model (Miina and Saksa, unpubl.).

Froese et al. (2002) and Hassani et al. (2002, 2004) have utilized data from regeneration surveys to develop imputation models. Regeneration establishment was surveyed from stands that were selected to cover a wide range of overstory densities, time since cutting, site preparation methods, slopes, aspects and elevations. Within the surveyed stands, nested plots were measured using systematic sampling. For each plot, silvicultural events and site and stand variables were identified and recorded. Despite its simple structure, tabular imputation makes good use of the limited data available. The usefulness of imputation techniques depends to a great extent on the data used for the analysis. However, the models can easily be updated as more data become available.

In regeneration surveys, it is recommended that the sample unit should be a plot instead of a stand; and several plots are measured from a stand. This allows regeneration predictions to be sensitive to within-stand variations. Especially in uneven-aged stands, changes in overstory density within the stand could be considered by predicting regeneration on several plots. The stand edge also affects the incidence of light and may reduce or even compensate for overstory light competition for juveniles. According to Flemming (1962), Canham et al. (1990) and Golser and Hasenauer (1997), the edge effect decreases proportionally with increasing distance from the stand edge and is negligible when the distance reaches twice the dominant height (about 60 to 70 m).

When a regeneration survey is designed and the hierarchical structure of the regeneration data is modeled, the allocation of plots among stands, the allocation of stands among geographical or management areas, etc. will affect the precision of the regression estimates of models (e.g. Goldstein 1995; Snijders and Bosker 1999). In addition, there are generally differential costs associated with sampling more plots within an existing stand as opposed to selecting further plots in a new stand (see, e.g., Snijders and Bosker 1999). Finding the optimal study design becomes more difficult when regeneration is measured over several years or there are repeated measurements (i.e. random cross-classified effects).

Unbiased sampling of regeneration is important. Surveys will produce biased results if failed regeneration attempts are discarded from the sample because there is no regeneration to measure or, alternatively, if sampling is concentrated to borderline cases in which the differentiation between success categories is the main objective of the survey. Another example would be if only a certain range of regeneration density is considered, which may lead to misinterpretations concerning the regeneration situation within stands. Such a data collection procedure may be adequate for even-aged stands but does not represent the heterogeneous regeneration situation in uneven-aged mixed-species stands.

Regeneration survey data may also be biased due to missing observations for a given variable of interest. For example, site preparation is usually omitted if enough advanced regeneration is available. Consequently, regeneration models tend to overpredict the regeneration success on untreated sites if advanced regeneration is not separated from regeneration established after harvesting. One assumption is often that the effects of seed crops, herbivores and weather conditions are covered randomly in the data. Between-year variation in regeneration success is difficult or even impossible to predict, but it could be included in modeling and simulations using random components. For example, unexplained between-year variation in regeneration establishment, which is caused partly by between-year variation in weather conditions, can be taken into account by adding random between-year components to the model.

Regeneration establishment is usually described by the number of trees and size distribution of different tree species. If planted trees can be identified in the data collection, separate models could be fitted for planted and naturally regenerated trees. In some cases, so-called crop-trees or best trees are assessed (e.g. Ferguson et al. 1986; Hassani et al. 2004). Crop-trees are selected subjectively according to the tree species, size distribution, location and vigor of seedlings. Subjective selection of crop-trees may be a problem if proper instructions for selection are not given. In Finnish regeneration surveys, the main emphasis is put on having a sufficient number of crop-trees. In planted stands, crop-trees are healthy planted seedlings or naturally regenerated seedlings that supplement irregularly spaced regenerations of varying density. To determine the need for and timing of precommercial thinning, deciduous tree species of low economic value are measured by the number of stems and the dominant height.

Due to changes in technology and silvicultural practices, regeneration models need to be updated using the latest available data set. Current models may fail to predict the regeneration establishment if new harvesting methods or improved planting materials are used. In addition, long-term changes in weather conditions or forest-damaging agents (e.g. increase in the mammal population) will require improvements in regeneration models. Sometimes there is no need or even possibility to collect new data and refit the regeneration models again, but it can be calibrated for new environmental conditions or a new geographical area using a limited data set.

5.4
Discussion and Conclusions

Regeneration models are needed in both stand- and forest-level planning. In silvicultural planning, regeneration inventories and modeling are needed for evaluating alternative stand management practices or possibilities to promote regeneration and regeneration development. Computer-based systems are useful tools: a forest owner who wants to minimize the risk of failure in forest regeneration selects a management method that gives the highest probability of sufficient regeneration (e.g. Saarenmaa 1990; Pukkala and Kolström 1992; Rogers and Johnson 1998; Saksa et al. 2002). In systems for forest management planning, simulated removals from both uneven- and even-aged stands are often based on reliable predictions of regeneration.

In even-aged forest management, establishment of regeneration and juvenile growth models linked with the growth models of overstory trees are widely used to predict or simulate stand development (e.g. Ferguson et al. 1986; Ferguson and Carlson 1993; Ferguson 1997; Monserud et al. 1997; Hynynen et al. 2002). Regeneration models initiate the stand development after regeneration cuttings. Models are needed for both artificial seedlings and natural regeneration, which should have mixed stands of sufficient density. Later on, ingrowth models are used to predict the additional regeneration of mainly shade-tolerant tree species. In simulations, regeneration establishment will form the future forests and therefore greatly affects long-term predictions of forest growth and yield.

With uneven-aged forest management, sufficient natural regeneration is essential to sustain the uneven-aged structure of forest stands. Optimal selection harvests maintain and enhance the reproduction potential of stands, the vitality of seedlings and all sizes of trees, the desired composition of tree species and stand structure in terms of size and spatial variation. So far, individual-tree simulators, such as the Prognosis model (Haight and Monserud 1990), that include a regeneration model and enable optimization of uneven-aged forest management are scarce.

There are several approaches to regeneration modeling. Neither a single source of data nor one single modeling approach will cover all purposes. In general, statistical and nonparametric models are heavily dependent on data and thus lack generality. Process-based models describe the behavior of the forest ecosystem in a more realistic and general way, but they may lack accuracy if they are derived from generalized data. Unfortunately, the process-based approach has not been widely used to develop regeneration models.

The appropriate modeling approach should be selected according to the use of the regeneration model. Briefly, it must be possible to update the input parameters over time to ensure a continuous simulation run within a stand growth mode. Note that data collection for forest regeneration is seldom designed for preparing regeneration models. If no representative data for statistical regeneration modeling are available, nonparametric methods such as imputation models provide a promising alternative. However, there are some unsolved problems related to imputation methods. Because "extreme" regeneration situations are often not included in reference plots, imputed regeneration predictions may be biased towards the average regeneration situation if extreme events occur. In addition, for improved modeling results, the choice of neighbors and the selection of the best imputation method for a given situation could be considered.

Neither statistical nor nonparametric models can give correct predictions if forest management or climate conditions represented by the data differ from expected future scenarios. This suggests that to obtain regeneration predictions based on changing growing conditions we need a more process-oriented approach in regeneration modeling. Currently, many predictors (e.g. weather conditions, soil properties, spatial distribution of trees) that would provide valuable information for assessing regeneration are difficult to obtain, and thus the applicability of mechanistic, process-oriented regeneration models is limited.

In future, we can expect measurement of tree positions, heights, crown dimensions and density using airborne remote sensing. This will give more information on forest characteristics and, consequently, enable more accurate and detailed modeling of regeneration. However, the large variation in soil and site properties as well as the temporal variation in the weather conditions are still an unsolved problem in regeneration modeling. Incorporation of elements that allow linking of mechanistic and process-oriented ideas with statistical models suggests a possibility to enhance our understanding of regeneration processes, as these processes may be affected beyond the calibration conditions, such as changing future forest management and climatic growing conditions (e.g. Mäkelä et al. 2000; Peng 2000).

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Harvesting Rules and Modules for Predicting Commercial Timber Assortments

Hubert Sterba[1], Sonja Vospernik[2], Ingrid Söderbergh[3], Thomas Ledermann[4]

Abstract. Individual tree-growth simulators that are to be used to support decisions in forest management must be able to provide forest growth forecasts for different stand treatments and forest management scenarios as well as giving results in terms of not only cubic metres or biomass, but also commercial assortments, including measures of wood quality. In the context of the ITM EU project, several known growth simulators were supplemented by incorporating additional modules to express a variety of thinning and harvesting algorithms. This allows studying the results pertaining to different management regimes. Their applicability has been considered in their dependence on the concepts of the specific growth simulation models within which they were to be implemented. Commercial assortments, as long as they only relate to log dimensions and log properties (which can be estimated using individual tree breast-height diameter, tree height and crown ratio), are easily implemented through the application of taper curves or the commonly used assortment tables. If other qualitative stem measures are needed to predict log quality, the relationships between the log quality distribution and the stem quality assessment are strong enough to encourage the use of modules to incorporate stem quality distributions into the growth simulation models. However, these relationships and classifications are very different in the different countries, regions and forest enterprises. Therefore a number of different logistic models have been presented to predict stem quality. Furthermore, it is deemed necessary and it is recommended that concrete relationships between stem qualities and log qualities are developed individually at a forest enterprise level.

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6.1
Introduction

If forest growth models are to support decisions in forest management, they must (1) make possible forest growth forecasts under different stand treatments and forest management scenarios; and (2) provide results in terms of not only cubic metres or biomass, but also commercial assortments, including predictions of wood quality.

Owing to the need to select from among various modelling strategies (e.g. making predictions for stands, larger forest management units or whole forest enterprises, using distance-dependent or distance-independent models with or without input data on stem quality assessment), different ways of developing modules to implement different stand treatments and for making predictions about commercial assortments must be chosen.

The objective of this chapter is to describe the means and algorithms to implement:

- different stand treatments and different forest management scenarios;
- modules for commercial assortment prediction; and
- methods of forecasting stem and wood quality.

In addition it will suggest in which types of growth simulator each of the algorithms can be used.

Based on the many options given in the growth models presented in the ITM EU project (Implementing Tree Growth Models as Forest Management Tools, QL-RT 1999–31349) this chapter can also be seen as a review and summary of the authors' tasks within this programme.

6.2
Simulating Thinning and Harvesting

The modules used to simulate thinning and harvesting within individual tree growth simulators can be classified, first according to the method by which they have been derived, second according to the silvicultural "thinning type", and third by the way they are implemented in the simulators.

In general, there are two methods of deriving thinning and harvesting models, the empirical and the analytical.

Empirical harvesting models need data from thinnings already undertaken in order to derive and parameterize the probability functions which predict the probability that any particular tree in the database will be removed. These data may come from marking experiments, where foresters mark the trees for removal in different stands based on their experience, or from continuous forest inventories where from repeated observations one can determine which specific trees *have in fact been removed* from the inventory plots.

Analytical models describe by very different rules how, according to a generally accepted or an individual strategy, trees *should be removed* from a stand and this information is then included in the database for the model.

Many silvicultural thinning types can be described in either way, empirically or analytically. For example, selective thinning can be described by using thinning experiments involving a "selective thinning" treatment and use the data of these plots to derive an equation describing the probability that a given tree will be removed (e.g. including variables such as tree size and competition index). The same thinning type can be described analytically by stating the rules defining which trees are to be removed (e.g. trees that are within a specified distance to a future crop tree).

6.2.1
Freely Defined Harvesting and Thinning Methods

Since one reason for the development of individual tree growth simulators is to provide a tool for investigating and predicting the results of new thinning methods that have not yet been applied or even defined, the tool thus being open for any new idea of stand treatment, one "silvicultural" option must be to define freely which trees are to be removed.

If the underlying growth model of a simulator is distance-dependent, and is thus able to display each individual tree on a monitor, an easy way to study any free harvesting procedure is to individually mark on the screen the trees that are to be removed (cf. MOSES in Eckmüllner 1990; Fig. 6.1).

For distance-independent models, the trees cannot be addressed individually on the monitor. One option in this case is to thin the stand by reducing tree numbers. Hence a file is defined containing information about which tree is to be removed and when (e.g. by tree number), followed by the thinning algorithm (e.g. BWINPro and PrognAus; see Söderbergh and Ledermann 2003).

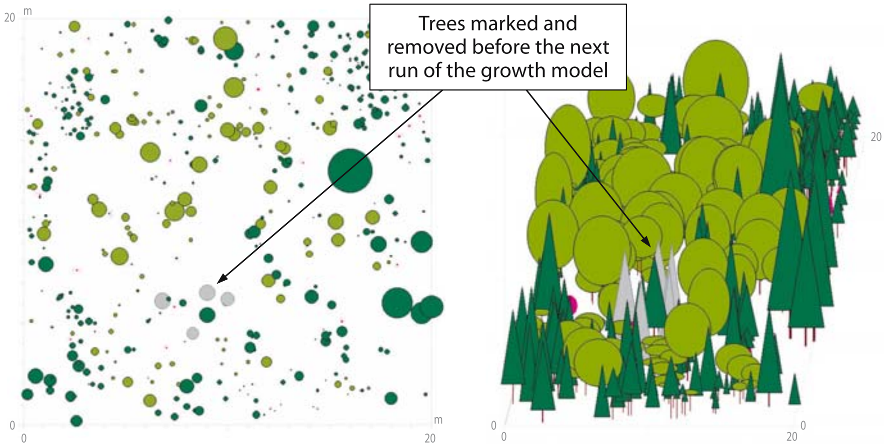

Fig. 6.1. The marking procedure on the monitor in the MOSES simulator. Trees indicated in *grey* have been marked for removal

Another option to freely select trees for thinning and harvesting in distance-independent simulators is to display the frequency of tree classes in terms of species, diameter at breast height (dbh) and stem quality, and then interactively to reduce the frequencies in each of these classes (e.g. Vanclay 1989; and PrognAus in Ledermann 2001; Fig. 6.2).

6.2.2
Mimicking Practically Performed Thinning and Harvesting Procedures (Empirical Approach)

While the procedures in the above section make possible very free simulations of any stand treatment, even without regard to their practicability, there are other possibilities to mimic thinnings and harvesting procedures on an individual tree basis as performed in practice.

ThiCon is a procedure implemented in BWINPro (Nagel 1996; Daume and Robertson 2000; Albert 2002; Albert and Guericke 2003) using tree positions, dbh, species, tree vitality, stem quality and the crown tension between neighbouring trees. These variables are combined by logical statements, i.e. heuristic rules,

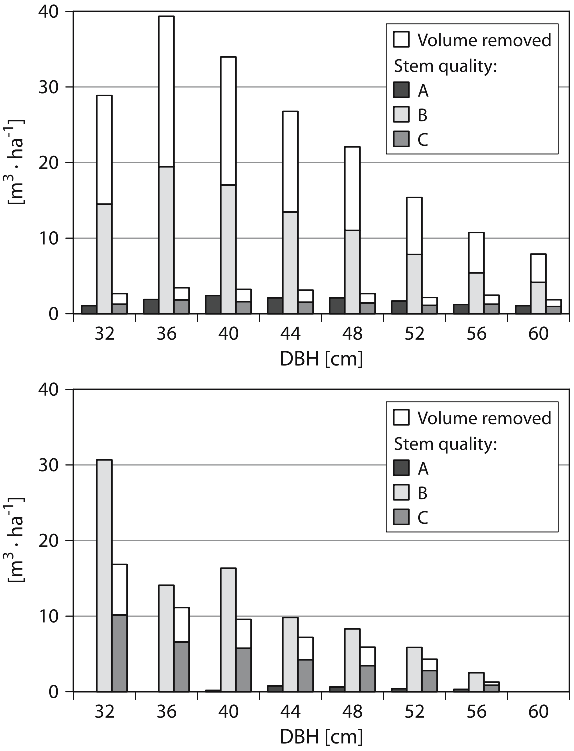

Fig. 6.2. Thinning (reduction of tree number) by species, stem quality class and dbh in PrognAus (*above* Norway spruce, *below* common beech)

which can be defined freely and which are used to search the database to select the trees matching the rules and are thus to be removed.

The empirical approach provides a probability function that can be tested for influential variables and parameterised by logistic regression methods (Ledermann 2002) as described earlier.

6.2.3
Developing Algorithms to Simulate Silviculturally Defined Thinning and Harvesting Rules (Analytical Approach)

Behind terms such as selective thinning, thinning from below, geometric thinning, thinning according to guidelines describing optimum basal area in even-aged forests or equilibrium curves in uneven-aged forests, there are very often implicit numerically defined rules which can be used to define a matching algorithm.

Stand-based guidelines such as Assmann's (1970) optimum basal area, Abetz' (1975) stem number guidelines or de Liocourt's (1898) equilibrium stem number curve for uneven-aged stands are easy to follow mathematically, although additional rules are needed for individual-tree models in order to decide which specific tree is to be removed.

If the guidelines are based on dbh distributions, a reasonable way to decide removal is to use a random number algorithm, relating the percentage of trees that have to be removed to the surplus number of trees in a given dbh class (Fig. 6.3). If the guidelines only give a target stem number or a basal area on a stand base (Fig. 6.4), additional "silvicultural" rules are needed to describe whether the percentage of stems or basal area to be removed should be removed by thinning from below, from above or by way of selective thinning.

For thinnings from below, a central module with an intrinsic fuzzy logic controller was developed by Kahn (1995a,b, 1996), which consists of a simple rule base with no more than seven rules. These rules are designed to evaluate the "urgency" for removing a tree, based only on the relative dbh ("larger or smaller

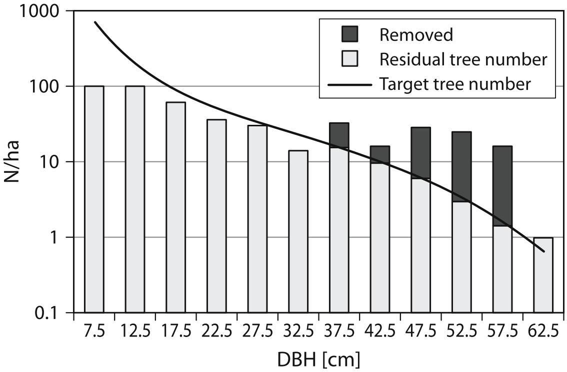

Fig. 6.3. Thinning by a stem number (N/ha) guideline

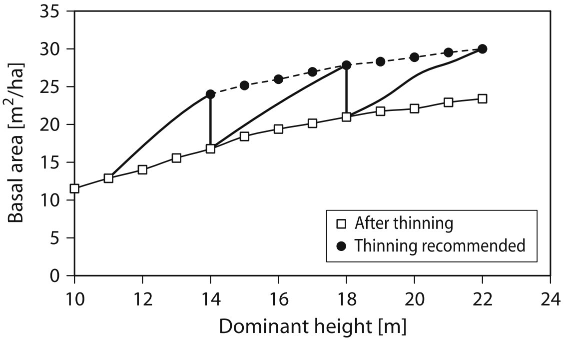

Fig. 6.4. A basal-area-dominant-height-based thinning guideline. If the line "thinning recommended" is reached by growth, the basal area between the two lines has to be removed

than the neighbour") and the competition index, KKL, used in SILVA (Pretzsch et al. 2002).

For selective thinnings, several modules are available and implemented in the different simulators. They generally consist of two sub-modules, one for the selection of future crop trees and the other for removing their competitors. These modules are described in more detail in Söderbergh and Ledermann (2003). Generally, the selection of the future crop trees starts with the number of crop trees per hectare given, and then uses the height-to-diameter ratio as a measure of vitality. Sometimes, in addition, the crown ratio, stem quality and stem damage, and the ratio between the individual tree dbh and the quadratic mean diameter of the stand may be used to calculate weightings according to which the trees of the database are sorted. Those trees with the highest weightings are then selected as future crop trees. In distance-dependent growth simulators, a minimum distance between the future crop trees can additionally be defined.

Several rules are implemented in the simulators to select the competitors to be removed. The simplest, used in distance-dependent models only, is to remove all trees within a chosen radius around the future crop trees. A more sophisticated one uses Johann's (1982) critical distance, calculated as:

$$Dist_{iz} = \frac{h_z}{A} \cdot \frac{dbh_i}{dbh_z}$$

where *Dist* is the distance between the future crop tree *z*, and the neighbour *i*, h_z and dbh_z, the height and dbh of the future crop tree respectively, dbh_i the breast-height diameter of the competitor *i*, and A is a value between 3 and 6, indicating the chosen severity of the thinning, with 3 for very heavy thinning and 6 for very light thinning.

More sophisticated rules for competitor selection are defined in the heuristic thinning algorithm *ThiCon* of BWINPro (Albert 2002), and as logistic regression models in PrognAus. Both these models again use relative tree dimensions, species, tree vitality, stem quality and damage classes, while BWNPro additionally uses inter-tree distance and crown tension to define the thinning algorithm.

Two more "harvesting models" have been developed and implemented in the simulators of the ITM project. One describes salvage cut made necessary by snow breakage in Norway spruce and Scots pine stands (Sterba 1990), and the other is a multi-objective optimization system implemented in STAND (Pukkala and Miina 1997).

The snow breakage model calculates the probability that a crown is broken by snow and the height at which it is broken depending only on the height-to-diameter ratio of the tree:

$$PSB_i = (1 - \exp[-4.02 \cdot h_i / dbh_i])^{28.5}$$

$$brh_i = h_i \cdot \exp(-5.532 \cdot h_i / dbh_i)$$

where PSB_i is the probability that the tree i is broken, brh_i the height at which the tree is broken and h_i the tree height in metres, and dbh_i the breast-height diameter in centimetres.

The multi-objective optimization routine does not describe given thinning and harvesting algorithms, but rather the number and timing of thinnings, the removal by tree species and dbh class optimized in the system according to an additive utility function, weighting different management objectives such as profitability, liquidity and scenic value.

6.2.4
Deterministic and Stochastic Implementation of Harvesting Algorithms

Many of the above rules result in probabilities of relative frequencies of trees to be removed. According to Söderbergh and Ledermann (2003) such rules can be applied in a deterministic way or in a stochastic way.

If – especially in distance-dependent simulators – specific trees in the database have to be removed, the calculated probabilities or relative frequencies are compared with uniformly distributed random numbers between 0 and 1 for each tree. If the random number is smaller than the calculated probability, then the tree is removed.

The deterministic approach to decide whether a specific tree is to be felled uses a threshold value which is compared with the calculated probability. In distance-independent simulators, however, each tree in the database can be regarded as representing a specific number of trees per hectare, depending on the stand size, plot size or basal area factor in angle counts (Bitterlich 1948). In this case, this number of trees per hectare is simply reduced by the probability calculated by the harvesting model.

A table describing which thinning and harvesting models are or could be implemented in any specific growth simulator has been produced by Söderbergh and Ledermann (2003).

6.3
Commercial Assortments and Stem Quality

Commercial assortments are usually classified according to dimensions (diameter) and wood quality. The rules for classification – especially for quality, and there especially in hardwood – differ tremendously between countries, within countries between regions and even between individual forest enterprises, depending on their regular clients.

Converting tree dimensions (dbh and height) to log dimensions can be performed:

- through modules that interactively "cut" the tree into logs using taper curves [e.g. BDAT in SILVA, based on the taper curves of Kublin and Scharnagel (1988); in BWINPro using the procedures of Riemer et al. (1995), Pain and Boyer (1996) and Schmidt (2001); or in STAND using the procedures of Kilkki and Varmola (1979), Laasasenaho (1982) and Lappi (1986)]; or
- through assortment tables [e.g. those of Kleine (1986), Sterba et al. (1986) and Eckmüllner and Sterba (2002) for MOSES and PrognAus, or those of Petráš (1992) and Mecko et al. (1993) in the version of SILVA used for Slovakia].

The timber quality of logs, however, is defined by two types of measure: (1) those that are the result of stem growth, such as branchiness, tree ring width and taper, and (2) those that are the result of damage caused by forest operations, peeling or root rot from fungi in the soil.

The first group of measures can be modelled depending on standing tree measures, dbh and height. Tree ring width as an important log-quality measure is directly obtained from the dbh increment, which is always modelled in all growth simulators.

With respect to the other group of stem quality measures, it must first be ascertained whether these measures correlate with the timber quality of the logs at harvest. For those that do, it is subsequently necessary to model the development of these measures over time. For individual southern pine trees (*Pinus taeda* L., *Pinus echinata* Mill), Clark and McAlister (1998) have shown that careful visual stem quality assessment made it possible to distinguish significantly well between three different stumpage value classes, based on timber grade yield. Nevertheless, it is necessary to determine whether any significant relationship between stem quality and stem damage, assessed in the stand, and timber quality classes as defined in terms of central European grading systems exists before developing models to predict stem quality classes and stem damage.

6.3.1
Modelling Individual Tree Stem Quality

Among the simulators included in the ITM project, several models predict the height to the live crown that can be used as a measure of individual tree branchiness. An Austrian study on the relationship between growth and crown transparency (Sterba and Eckmüllner 1988) investigated 158 spruce trees that had been

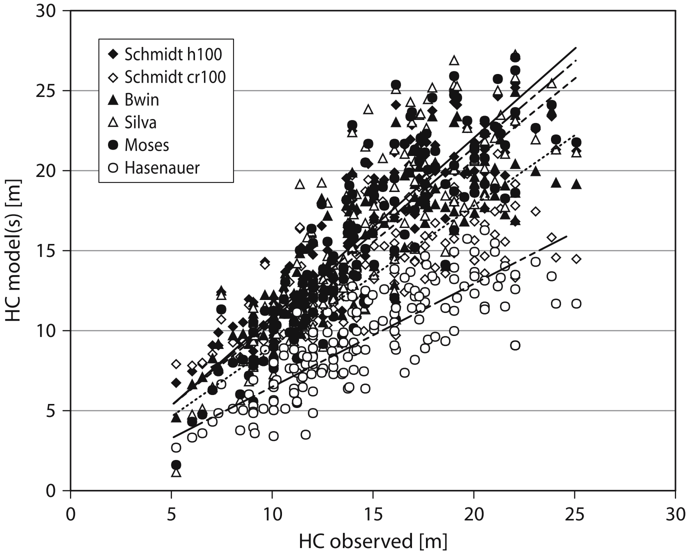

Fig. 6.5. The height to the crown base (*HC*) of 158 spruce trees compared in the respective models, discussed in the ITM projects (see also Table 6.1)

Table 6.1. Coefficients of determination (r^2) and model efficiency (*EF*) (Loague and Green 1991) of the crown models used in BWINPro, SILVA, MOSES and PrognAus, and those of Schmidt (2001), one including the dominant height (h_{100}) and the other including the crown ratio of the 100 largest trees ($CR\ h_{100}$)

Model	Schmidt (2001)		BWIN Pro	SILVA	MOSES	PrognAus
	h_{100}	CR h_{100}				
r^2	0.763	0.562	0.716	0.698	0.748	0.668
EF	0.554	0.478	0.667	0.379	0.486	–0.788

felled and measured for crown length and branch thickness (Eckmüllner 1987). These data were used to validate the crown models of Nagel (1999) as used in BWINPro, of Kahn and Pretzsch (1997) as used in SILVA, of Hasenauer (1994) as used in MOSES, of Hasenauer and Monserud (1996) as used in PrognAus, and of Schmidt (2001) which was intended to be used in any of these models (Fig. 6.5).

Obviously most of the models correlate quite well with the validation data, although some of them are markedly biased, which may be due to different definitions of the crown base in different countries, regions and the data set (Table 6.1).

A similar procedure compared Schmidt's (2001) model for the diameter of the thickest branch in each whorl with those of the Austrian validation data set, i.e. with a total of 1,302 branches in the 158 spruces. The r^2 of 0.620 and the not much smaller model efficiency of 0.514 indicate that the data correspond quite well with the model.

6.3.2
Correspondence Between Observed Log Quality and Stem Quality Assessment in Inventories

In order to answer the question whether stem quality and stem damage classes are reflected well in the harvesting results, i.e. the recorded log quality of harvests in forest enterprises, four forest enterprises – two Austrian forest management districts, *Weitra* and *Angerhäuser*, the *Stauffenburg* management district in Lower Saxony, and the Slovakian management district *Oravská Polhora* – provided data of their permanent inventories and their harvest records. These harvest records related to compartments of different sizes, thus containing different numbers of sample plots and trees harvested. The volume of the trees harvested between two inventory assessments was calculated and classified according to the stem quality classes of the inventory for all the plots in a compartment (Fig. 6.6).

From the harvest records, the distribution of log quality classes in the harvested volume could be calculated from the enterprises' book-keeping records and related to the stem quality data for the compartments. In the Stauffenburg district, broadleaves dominated, and thus only the quality of these was evaluated; in the other three districts, Norway spruce and some other conifers dominated. In Weitra and Oravská Polhora, peeling damage was considered to be a major stem quality problem, while in Angerhäuser the quality problem was considered to be harvesting and skidding damage.

The way timber quality was classified was very different in the four enterprises. While in Angerhäuser, best, medium and poor qualities (A, B and C respectively) are distinguished in the records, in Weitra there is only one good quality mix-

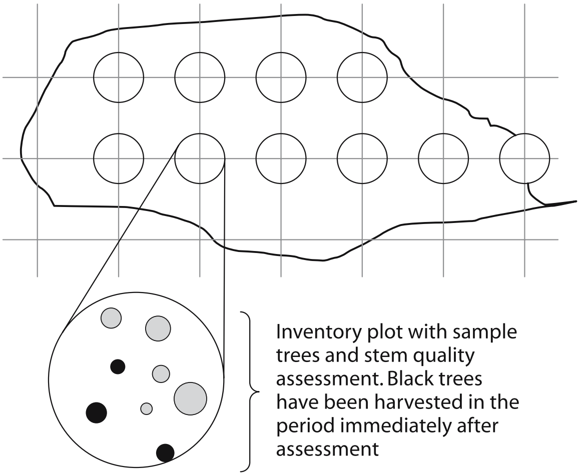

Fig. 6.6. Inventory plots in a compartment, for which harvested *log qualities* are available in the forest enterprise book-keeping. *Stem quality* of removed trees has been assessed in the first inventory, and should thus correlate with the reported log quality

ture AB/AC distinguished from C (poor quality). In Weitra the poor quality categories are different from those in Angerhäuser. The Slovakian classification – although for Norway spruce, too – differs very much from the other two spruce-dominated management areas, with classifications of I to III for good and IV and V for poor timber quality classes. From this it is concluded that it is not feasible to implement generally applicable functions to convert stem quality, as modelled in a simulator, directly into log quality classes. Rather this information has to be derived by each individual forest enterprise using its own data.

Furthermore we cannot calculate correlations between stem quality in the inventories and timber quality in the compartments as recorded in the book-keeping even for the four enterprises, i.e. by aggregating their data: these correlations have to be calculated separately for each enterprise.

It is clear that the possibility of detecting significant correlations between stem quality distribution and log quality distribution depends on sample size (Table 6.2). The accuracy of the stem quality distribution depends on the number of plots per compartment and the plot size, i.e. number of trees harvested within the plots. In this regard, the sample size in Oravská Polhora is rather poor, but somewhat compensated by the large plot size.

Since each compartment is one data point for the correlations between stem quality and log quality, the number of data points is quite low for all management areas. Especially in the two Austrian management districts, the correlations must be quite high in order to be detected (i.e. significant). Each of the correlations reported below relate to 7 degrees of freedom in Weitra, 11 degrees of freedom in Angerhäuser and 27 degrees of freedom in Oravská Polhora and Stauffenburg.

Nevertheless, significant correlations were found:

- In Weitra, the proportion of stem volume that was classified as good saw timber in the inventory was inversely correlated with the proportion of "C-logs", which are defined as poor saw timber ($r=-0.911$, $\alpha < 0.01$), and the proportion of stem wood recorded with peeling damage in the inventory was positively correlated with the proportion of poor pulp wood sold ($r=0.785$, $\alpha < 0.05$).

Table 6.2. Sample sizes for the correlations between stem quality assessment and log quality records

Location	Number of compartments (strata)	Plots per stratum Min.	Av.	Max.	Plot size
Weitra	8	5	9	17	Point samples, BAF=4 m^2/ha
Angerhäuser	12	26	44	77	Point samples, BAF=4 m^2/ha
Oravská Polhora	28	1	1	1	300–500 m^2
Stauffenburg	28	5	11	16	130–540 m^2

- In Angerhäuser, the proportion of stem volume classified as best stem quality in the inventory was significantly and positively correlated with the proportion of "B-logs" sold (r=0.874, α <0.01) and negatively with the proportion of pulp and paper logs (r=–0.905, α <0.01) and the proportion of fuel wood (r=–0.695, α <0.05).
- In the Slovakian enterprise, Oravská polhora, the correlations shown in Table 6.3 indicate that the percentage of stem volume found to be peeled at inventory was positively correlated with the proportion of timber rated as poor quality and negatively correlated with the proportion rated as good quality.
- In Stauffenburg, the correlations were very poor. Only the proportion of stems that were assessed to have "A quality" in the inventory showed a correlation negatively with the proportion of "B quality" timber in the book-keeping (r=–0.387, α <0.05). This poor correlation is probably a result of the well-known very complex and difficult quality assessment for broadleaves.

In summary, the correlations found indicate that, at least for conifers, stem quality assessment is significantly correlated with harvested log quality. Therefore, it seems justifiable to incorporate stem quality models into the different growth simulators.

6.3.3
Stem Quality Modelling as Part of the Individual Tree Growth Simulators

Definitions of stem quality in terms of branchiness are already implemented in several of the simulators (see Sect. 6.3.1 and Fig. 6.5, and the branch model by Schmidt 2001). In addition, stem quality is seriously affected by stem damage caused by peeling or by harvesting and skidding. Since these assessments are based on assigning categories, frequently using dichotomous variables, a proper

Table 6.3. Correlations (r) between the proportions of different stem qualities from the inventory assessment and log qualities from harvest records in the management district Oravská Polhora. Correlation coefficients in *italics* are significant at α=0.10; in **bold**, they are significant at α=0.05; *italic* and **bold** coefficients are significant at α=0.01. *dg* Quadratic mean diameter

		Assortments harvested			
		I+II	III	IV	V
Inventory assessment	Peeled	–0.248	–0.456	***0.476***	**0.399**
	dg of removed trees	***0.711***	***0.768***	***–0.774***	***–0.709***
	Peeled × dg	–0.143	–0.202	0.241	0.155
	Peeled/dg	–0.293	***–0.626***	***0.630***	**0.563**

way to model stem quality is the development of logistic regression models, predicting the presence or absence of a certain category. Given a data set of permanent inventories, these models can be developed as static or as dynamic models.

Static models model the probability that a given tree in the database exhibits a specific quality class or a specific type of damage. This kind of model is needed if the initial database from which the simulations start contains no information about stem quality or damage. It is also needed for "new" trees entering the database from models describing ingrowth or regeneration.

The dynamic models give the probability that a tree exhibiting a certain stem quality class or a certain stem damage at the beginning of a growth period changes its properties during the next growth period.

Both types of models have been developed from Austrian National Forest Inventory (ANFI) data (Forstliche Bundesversuchsanstalt 1981).

The static models predict the probability that a tree exhibits:

1. a certain stem quality class defined according to the ANFI manual (Forstliche Bundesversuchsanstalt 1981);
2. damage through harvesting and skidding operations;
3. damage through peeling by red deer; and
4. the probability that at least one tree on a sample plot exhibits rockfall damage.

The dynamic models predict the probability of a change in one of these measures during a 5-year growth period.

The variables proving to be significant in the one or other model (α=0.05) and the total proportion of trees exhibiting or being allocated to one of the above quality classes or damage classes are given in Tables 6.4 and 6.5. It should be noted that the damage percentages given in the tables are not the damage percentages for Austria as a whole because only 'relevant' plots were included in the models. For the dynamic model for harvesting damage, for example, only those plots were considered in which harvesting occurred in the previous growth period.

6.3.4

Sensitivity Analysis of the Damage and Harvest Models

The sample size and the proportion of cases in which a specific damage or stem quality is recorded are always higher in the static models than in the dynamic models. The statistical characteristics for goodness of fit were always better in the static models. However, using a static model, the initial distribution of stem attributes cannot be taken from the inventory itself, but has rather to be generated by models that estimate the probability of there being a certain stem attribute (i.e. quality or damage class).

In contrast, dynamic models, which predict the change in quality or damage, allow the setting up of the initial distribution of the stem attributes in the inventory, and these can then be developed for the subsequent growth period. It was therefore necessary to determine which of these models predicted reality better.

Table 6.4. Models to predict stem quality. *Ticks* indicate that the variable is significant in the respective model; *dbh* is breast-height diameter; *Presence of damage* is a dummy variable equal to unity if at the beginning of the period there is damage to one of the trees in the plot but is otherwise zero; *CCF* is the Krajicek et al. (1961) crown competition factor; *New damage* is a dummy variable indicating whether the tree has received new damage (in one of the damage models) or not

	Variable	Stem quality	
		Static	Dynamic
Individual tree	Species	√	√
	dbh	√	√
	Tree height	√	√
	Presence of damage	√	√
	New damage		√
Stand	Elevation	√	√
	CCF	√	
	Number of observations (trees)	108,452	64,062

To provide an example of the process, the sensitivity analysis is demonstrated for models representing harvesting and skidding damage.

Data of the permanent forest inventory of a forest management district (*Sonnenwald* in upper Austria) were used for these test runs. Older stands of this forest management district are managed according to the target diameter harvesting system (Reininger 1987), while in younger stands a structural thinnings approach is used. The two management strategies were quantified for use in this analysis by calculating the proportion of removed basal area in five relative dbh classes, each of them representing equal basal area. The removals were calculated separately for stands older than 100 years and for the younger ones. Through this approach, the harvesting strategies applied in the simulation runs represented the harvesting strategies applied in this management district during the last 10 years. Note that the only criteria for removing trees were the relative breast-height diameters of the trees in the plot and the ages of the stands.

Using these removal percentages, four different 50-year simulation runs were performed. In the first scenario, removals were conducted ignoring stem damage. In the second scenario, the removals were basically the same as in the first scenario, i.e. in each dbh class the same amount of basal area was removed; however, in this case damaged trees were the preferred target for harvesting. Undamaged trees were only removed when there were insufficient damaged trees in a given

Table 6.5. Models to predict stem damage. *Ticks* indicate that the variable is significant in the respective model; h/d ratio is the ratio between tree height and dbh; *CCF* is the Krajicek et al. (1961) crown competition factor; *dg* is the quadratic mean diameter; h_L is Lorey's mean height; h_{dom} is the dominant height. *Growth class*, *Harvesting type*, *Red deer dispersion*, *Alluvial forest*, *Soil type*, *Slope position*, *Protection forest*, *Soil depth* and *Previous damage* are dummy variables for plot characteristics; *Species proportion* is the proportion of conifers

	Variable	Skidding damage		Peeling		Rockfall	
		Static	Dynamic	Static	Dynamic	Static	Dynamic
Tree	Species	√	√	√	√	√	√
dbh		√		√	√		
	h/d ratio		√				
Stand	Basal area	√	√	√		√	
	CCF						√
	dg		√				
	h_L	√	√				
	h_{dom}					√	
	Growth class			√			
	Species proportion			√	√	√	
Damage risk	Logging distance	√					
	Harvesting type		√				
	Removed basal area			√			
	Red deer dispersion			√	√		
	Elevation	√		√	√		
	Alluvial forest			√			
	Slope		√			√	√
	Soil type		√			√	√
	Slope position					√	

Table 6.5. Continued

Variable	Skidding damage Static	 Dynamic	Peeling Static	 Dynamic	Rockfall Static	 Dynamic
Protection forest					√	
Soil depth					√	
Previous damage				√		√
Percent of damage	12.0	6.7	5.2	0.7	34.4	2.2
Number of observations	51,133	7,614	138,228	84,874	1,963	14,413

dbh class to make possible removal of the same number of trees as for the first scenario. For each of these two types of harvesting strategies, both the static and dynamic models were used to predict harvesting and skidding damage (Fig. 6.7).

It can be seen that, in general, the static model overestimates the percentage share of damaged trees (22% versus 8%); this is a result of its not having been set up using actually observed initial damage distributions. More importantly, since

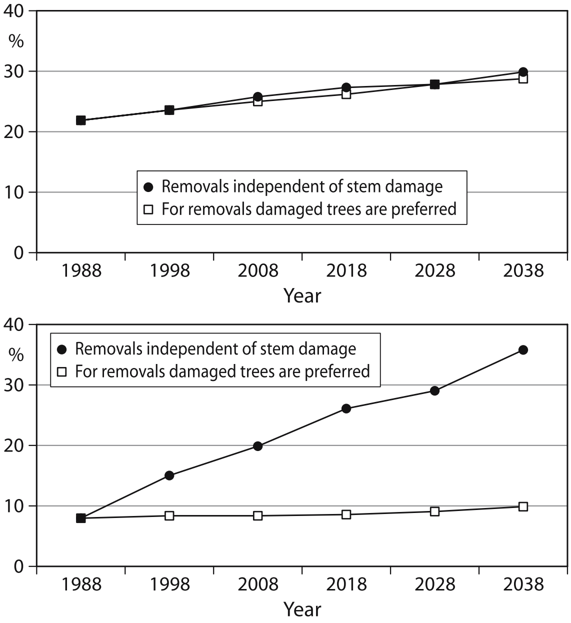

Fig. 6.7. Development of predicted proportion (%) of volume exhibiting harvesting and skidding damage in Sonnenwald. The scenarios were calculated using the static damage module (*left*) and dynamic damage module (*right) implemented in the individual-tree growth simulator PrognAus*

the proportion of trees with harvesting damage does not vary much between the two scenarios (i.e. the one in which damaged trees are selected for harvesting and that in which damage is ignored), it is much less sensitive to the harvesting strategy that preferentially selects damaged trees for removal.

Thus it is clear that – if it were ever possible to apply this type of approach – the dynamic models are the ones that should be used, because only they are sensitive to respective treatments.

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Applications of Tree Growth Modelling in Decision Support for Sustainable Forest Management

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Abstract. Multi-functional silviculture and sustainable forest management in Europe was recently defined by the Helsinki Resolution H1 (MCPFE 1993). Sustainable development (SD) is associated with abandoning the concept of even-aged forests. In view of this extended SD perception, the conventional forest planning procedure has to be revised. By relying on yield tables and the model of normative forests at the overall enterprise planning level, the conventional results become increasingly irrelevant in forest management. Such outdated planning tools do not provide the information needed for multi-criteria strategic planning. Modern strategic forest planning and decision-making require appropriate tools and technologies, such as forest growth simulators, evaluation and optimisation algorithms, geographical information systems, sample-plot data and visualisation routines, most of which are supplied by forest growth and yield science. The main aspect is to combine these tools and integrate them into decision support systems supporting the planning and decision processes at the enterprise level. In particular, the application of forest growth simulators will enable an improved SD evaluation and a more flexible adjustment between single stand and total estate planning. Simulation models can replace common indicators with aggregated dynamic long-term indicators. Management alternatives can be analysed with regard to their estate-referring and long-term consequences. In this chapter, we will point out: (1) how forest planning and decision-making can evolve from monitoring forest development to strategic planning, (2) how the Pan-European criteria can be used for monitoring and strategic planning of SD at estate level, (3) how available forest planning data can be best utilised for the planning process, and (4) what could be contributed by forest growth and yield science to developing decision support systems for multi-criteria forest enterprise planning.

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Sustainable Forest Management
Growth Models for Europe

7.1
Introduction

For almost 300 years, ordinary forestry has been arranged according to the demands of sustainability (e.g. von Carlowitz 1713; Hundeshagen 1826). The modern perception of multi-functional silviculture is reflected in the Helsinki Resolution H1 (MCPFE 1993, p. 1), in which sustainable forest management is defined as: "The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems". The six Pan-European criteria and indicators of sustainable forest management (Table 7.1) negotiated at the Lisbon Resolution L2 should support the coverage of sustainability and their operational implementation (MCPFE 1993). In view of this extended perception of sustainable development (SD), which is associated with abandoning the concept of even-aged forests, the conventional procedure of forest planning has to be revised (Hanewinkel 2001; Spellmann et al. 2001; von Gadow 2003). Increasingly, its usefulness is restricted by: (1) deficient flexibility in terms of strategic planning, (2) a limited applicability for uneven-aged forests and variable management procedures, and (3) insufficient integration of those silvicultural functions that exceed timber production. Using yield tables and the model of normative forests to measure forest growth at the overall enterprise planning level is becoming increasingly outdated. These planning tools do not provide the information needed for multi-criteria planning. On the other

Table 7.1. Pan-European criteria 1–6 and corresponding indicators for sustainable forest development. (Adapted from MCPFE 1993)

Criteria	Indicators (examples)
1 Forest resources	Forest area, carbon storage, age and volume structure, ...
2 Forest ecosystem health and vitality	Chemical soil state, defoliation, deposition of nutrients/pollutants, ...
3 Productive functions	Growth, felling budget, non-wood products, ...
4 Biological diversity	Tree species diversity, orientation by nature, share of dead wood, landscape diversity, ...
5 Protective functions	Share of forest area for protection of climate, soil, water, ...
6 Socio-economic functions	Net financial yield, number of employees, natural scenery, ...

hand, apart from sample plots, site classification, etc., information is available that is barely utilised by the conventional forest planning procedure.

Modern strategic forest planning and decision-making require appropriate tools and technologies partially supplied by forest growth and yield science. For us, the main aspect is to combine the forest growth simulators with evaluation and optimisation algorithms, geographical information systems, sample-plot data or visualisation routines and integrate them into decision support systems supporting the planning and decision processes at the enterprise level. Applications of these methods and technologies – and dealing with the problems in the planning process – give transparency to the decision pathways, enable participation and negotiation with politicians and therefore pave the way for a strategic goal-orientated forest enterprise management.

This chapter highlights how forest planning and decision-making may evolve from monitoring forest development to strategic planning, how the Pan-European criteria can be used for monitoring and strategic planning of SD at estate level, how available forest planning data might be best utilised for the planning process, and what can be contributed by forest growth and yield science to developing decision support systems for multi-criteria forest enterprise planning.

7.2

Setting the Stage – Decision Support Systems and Tree Growth Models for Strategic Forest Enterprise Planning

7.2.1

Decision Support Systems

Strategic forest enterprise planning due to multiple planning objectives is a typical field of application for decision support systems (DSS) with many complex and unstructured problems (Bonczek et al. 1981). A DSS to support such planning decisions can be structured according to the theory of a rational objective-orientated decision (Bamberg and Coenenberg 2002). Therefore, it will be designed to evaluate a set of different management alternatives as well as integrating multiple planning objectives, by the fulfilment of which the management alternatives will be assessed (Sodtke 2003). DSS are defined as systems utilising data and modularly integrating several models and methodical components for the different tasks of problem solution and decision-making (e.g. Turban 1990; Janssen 1992; Rauscher 1999). Many tools and technologies are available to support decision-making at estate level, most of which are supplied by forest yield and growth science. Examples include forest growth simulators, forest inventory databases, geographical information systems (GIS), visualisation systems and evaluation and optimisation algorithms (Sodtke et al. 2004). Forest growth simulators serve for running scenario simulations, for analysing the long-term consequences of management alternatives, and for scaling the results at different spatial and temporal levels. GIS and visualisation routines illustrate these consequences on stand and landscape dynamics and pave the way for participative planning. With the use of evaluation models, simulation results can be structured, evaluated and passed on to the decision process: different planners' objectives and priorities leading to differing valuations of the same states and management actions can be revealed, and multi-criteria functional and sensitivity analyses can be conducted. All these tools should be combined to form comprehensive DSS for the purposes of strategic forest enterprise planning.

7.2.2

Enterprise Simulation as the Backbone of Strategic Planning

Simulation models promise an improved evaluation of SD and a more flexible adjustment between single stand and total estate planning. In the case of a particular objective, they may support identifying the optimum management alternative. Provided that growth models are applicable for stands of diverse mixture and age structure as well as for simulating realistic growth dynamics for a wide range of management alternatives, they might replace the common area-specific or volume-specific indicators for measuring the annual felling volume. These indicators lose significance in abandoning the concept of even-aged forests; equation-based indicators do so when measured growth rates deviate from expected values of yield tables. In contrast, simulation runs with growth models may replace common indicators in aggregating long-term growth dynamics caused by defined management strategies at stand and stratum level and transfer them to estate level. Models directly return long-term dynamics of growing stock, increment, property value, financial return, structural indices, diversity of tree species, etc. SD indicators based on the model of normative forests or yield tables become redundant.

The advantage of enterprise simulation runs performed by growth models in fact lies in its improved planning flexibility: undesired dynamics at estate level can be identified and corrected by a changed planning procedure at stand or estate level. The recursive procedure Speidel (1972, p. 162) strives for – "corrections are repeated as long as a convenient adjustment between singular and total planning is attained" – has proven to be elaborate, laboured and barely feasible with planning of sustainable timber production in even-aged forests. In uneven-aged forests with a wider range of management models and SD criteria, a recursive procedure is only possible with support of simulation models.

7.3
From Monitoring Forest Development to Strategic Planning

7.3.1
Monitoring

The criteria verifying sustainable forest development – negotiated at the European level (MCPFE 1993) –are characterised quantitatively by associated indicators aiming at a practical application from forest enterprise to the national level (Spellmann 2003). Indicators such as diversity of tree species, orientation by nature, proportion of dead wood within the standing or lying stock, and vertical stand structure have to be deduced from forest inventories. They can, for example, be used to determine the criterion 'biodiversity'.

For deriving indicators and determining the catalogue of criteria, a large variety of sources of information are available. For this, inventories of forest enterprise planning, constant ecological monitoring plots, maps of soil and site characteristics, and immission load maps are very revealing sources. Having collected this information, a multi-criteria impression of forest enterprise development evolves. For example, previous development can be compared with the enterprise's planning objectives. With this procedure – among others – objective fulfilment, erroneous trends and necessary corrections can be readily identified. However, criteria and indicators derived with such an application are restricted to information, data and knowledge that already exists.

Let us assume that forest development within the period $[t_0, t_m]$ according to a referred site unit (e.g. stand, stratum, estate, growth region, state) is characterised by the indicators $[I_1, ..., I_n]$ (cf. Fig. 7.1). Let indicators $[I_1, ..., I_n]$ be growing stock, volume increment, net financial yield, diversity, protective functions, etc. If this forest evolves to the states $[W_1, ..., W_n]$ the development may be documented by repeated measures of the aforementioned indicators (by inventories, random sampling, visual valuation) at the points in time $[t_0, t_m]$. The dynamic states

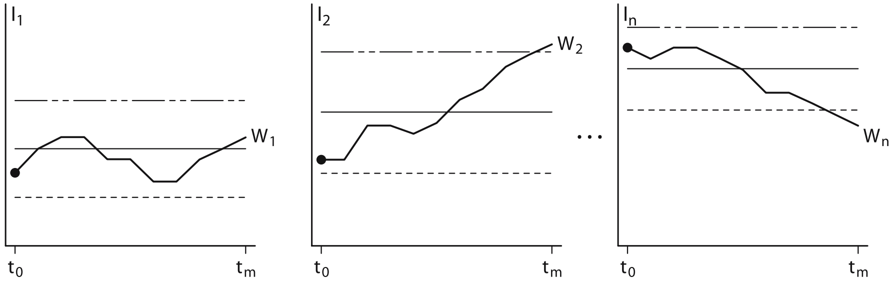

Fig. 7.1. Application of the indicators $[I_1, ..., I_n]$ for multi-criteria forest monitoring in the time span t_0 to t_m. *Solid lines* represent the target value of the indicator; *broken lines* show the critical levels

[W_1,...,W_n] can be compared with fixed target values, e.g. for tree species composition, growing stock, return on financial investment (cf. Fig. 7.1, solid lines). Furthermore, it will be evident whether observed dynamics evolve within a predefined target corridor, e.g. between specific limits for felling volume, financial yield, liquidity, critical levels for deposition or emission rates (cf. Fig. 7.1, dashed lines).

In our example (Fig. 7.1) at the initial point in time to (black circle), indicator I_1 deviates slightly from the target value but remains within the desired corridor the whole time. On the other hand, I_2 (e.g. growing stock) evolves in a totally undesired way. Indicator I_n (e.g. structural diversity) at first evolves in a target-orientated manner, but then converges to the lower limit and falls below it. The wider the topical range of the indicators [I_1, ..., I_2], the more comprehensively the dynamics can be reported, and the more criteria can be integrated for erroneous trends to be made obvious and demands for corrections to be made evident. The potential demand for corrections depends on the weighting of the particular criteria. The weighting results from the predefined objective hierarchy applied by the decision-maker.

7.3.2
Simulation and Scenario Analysis

However, using criteria and indicators only for monitoring, documentation and evaluation does not comply with our aims. In fact, effects of criteria and indicators will not become apparent until they are integrated into the planning and decision-making process. In such long-living systems as forests, long-term effects of the actual management have to be considered.

For this, growth models are the suitable tools; simulation is the target-orientated method. Enterprise simulation enables a planner to test and evaluate different management alternatives (e.g. tending strategies, final cutting rates, changing of tree species composition) and their long-term consequences for estate development. If possible, besides the classical variables of timber production (cf. Table 7.1, criteria 1 and 3), scenario simulations should also contain indicators of further criteria. In this case planning alternatives can be evaluated (simultaneously at stand, stratum or estate level) according to their multi-criteria objective fulfilment. By integrating them into enterprise simulation, SD criteria and indicators – which otherwise would be limited to their controlling and verifying functions – are realised in the planning process.

Figure 7.2 outlines the usage of indicators [I_1, ..., I_n] for strategic planning and decision-making: starting from the initial state of the referring site unit at time t0 (black circles), management alternatives (A, B, C) are simulated [e.g. continuation of the present even-aged forest (A), conversion of pure Norway spruce stands into mixed stands of Norway spruce and common beech (B), increasing cultivation of Douglas fir (C)]. Analysis of these scenarios reveals the consequences of management alternatives in a long-term run. Regarding all criteria in our example scenario, scenario C remains close to the target value, while scenarios A and B are sub-optimal. Scenario simulations are an important prerequisite for a mul-

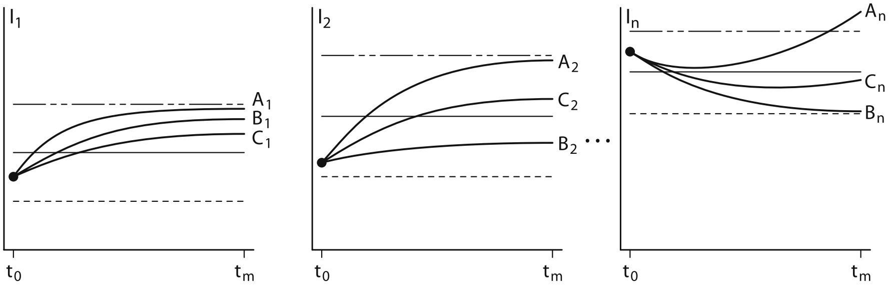

Fig. 7.2. Application of the indicators $[I_1, ..., I_n]$ for strategic forest management. Trajectories A_i, B_i and C_i show the simulated dynamics of $[I_1, ..., I_n]$ in time span $[t_0, t_m]$ as a result of alternative management regimes. *Solid lines* represent the target value of the indicators; *broken lines* show critical levels

ti-criteria evaluation of management alternatives. Analysis of indicator dynamics may replace area-specific, volume-specific or equation-based indicators. With the observed indicators covering a broad range of characteristics and their long-term dynamics, multi-functional SD can be made operational.

7.4
Simulation Models as a Tool for Strategic Planning and Decision-Making of Sustainable Development

The significance of silvicultural growth models and forest growth simulators results from the longevity of trees and stands. Because of the long growth periods covered, recently adopted silvicultural management strategies normally cannot be examined within field trials. The examined silvicultural management strategies would have become obsolete or forgotten before these long-term surveys are completed. Therefore, forest science derives functional relations from experiments and combines them into models of forest development. With those models, it is possible to simulate the system's behaviour in fast motion or "if–then" analyses. Through simulation, ecological, yield-referring and micro-economic consequences of management strategies or natural disturbances can be emulated with the model. Biogeochemical or ecophysiologically based process models outline limits (e.g. constraints in terms of critical inputs and outputs, actions and states) in which forestry can act without putting the stability criteria of the systems to be managed at risk (Fig. 7.3). To fix those constraints, permanent ecological observations, soil surveys and site mappings may contribute. Socio-economic constraints include estate management, protective regulations and forest laws. Once those constraints have been fixed, management models may help identify the optimal stand management for a given initial state and within the predefined corridor. In the example of the growth simulator SILVA which follows, it will be shown how management alternatives may be tested by enterprise simulation for their effects on the total estate, given an initial state and management objective. SILVA

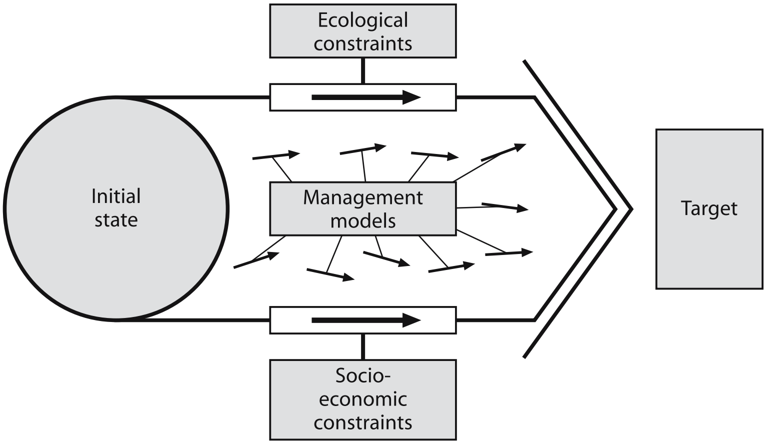

Fig. 7.3. Management models support the decision within a given decision corridor (*framed arrows*) by simulating long-term consequences of management alternatives (*mobile arrows*)

2.2 stands as a proxy of a new model generation which the models BWIN, PROGNAUS and MOSES also belong to (Hasenauer 1994; Sterba et al. 1995; Nagel 1999). Possible applications of SILVA 2.2 extending from tree to state level are exemplified at estate level (Pretzsch et al. 1998; Dursky 2000; Müller 2000). Application and evaluation of the SILVA simulator on other spatial scales are discussed by Knoke (1998), Hanewinkel and Pretzsch (2000) and Duschl (2001). The advantage of these model applications compared with abstract comparisons of alternatives is the consideration of numerous initial states at time to.

Figure 7.4 outlines four steps of strategic enterprise planning and decision-making in which growth models are applied:

1. All stands or sample plots registered by inventories are first assigned to specific strata by cross-classification. Strata may be typical classes of sites/stands or tree species/growth dynamics. With this procedure, a middle course between a rough and therefore less significant stratification and a too fine stratification with a number of strata similar to the number of stands is chosen. Indicator stands are then chosen representing defined strata. Indicator stands serve as the estate's yield classification (e.g. calibration with basic forest inspections) and define management alternatives. By applying a yield-referring growth model, economic and ecological consequences of the alternatives can be analysed. Discussing "if–then" relations of alternative management actions on indicator stands serve as a quantitative basis for objective definitions and objective agreements.
2. Management alternatives developed for indicator stands are assigned to associated strata. Using inventory data, simulation runs are carried out for all strata, highlighting the long-term consequences of the defined management strategies, e.g. for timber production, financial value increment and stability. Among others, global cutting rates are gained for each stratum and the set of chosen management alternatives.

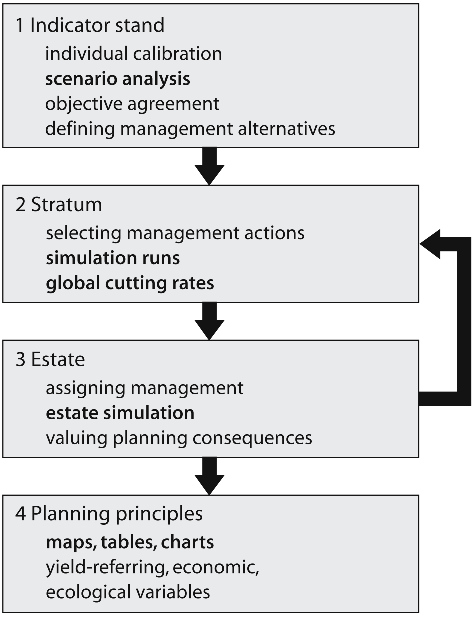

Fig. 7.4. Concept for the application of growth models for strategic planning at estate level. Simulation helps us understand what effect alternative management regimes have on the long-term development of a forest estate

3. After having assigned every inventory plot to a stratum and an appropriate stratum-specific management – or a set of managements – the total enterprise dynamics can be simulated. With this, it is possible to analyse the consequences of stand- or strata-referring management actions on long-term enterprise development. To avoid an undesired development at estate level, management strategies defined for the strata can be modified or combined in a different manner if necessary. With the model aggregating individual decisions from stand or stratum level to estate or higher levels, the advantages of different individual decisions become clearer. Simulation runs over several decades may reveal long-term consequences of chosen management alternatives at estate level, e.g. shortages in liquidity, deficits in specific assortments, etc. One may react to undesired dynamics at estate level by reconsidering or adjusting management strategies at stand or stratum level (feedback arrows in Fig. 7.4). It is exactly this that paves the way for strategic planning and decision-making at estate level.
4. Established management strategies for the defined strata, management-referring yield tables with global cutting rates, and thematic maps showing yield-referring, economic and ecological values of indicator stands – representing strata, stands, inventory plots and the total estate – are fundamental bases for silvicultural management.

Figure 7.5 shows the dynamics of annual volume increment, growing stock, cutting rate and net return from timber sale simulated by SILVA 2.2 within a 30-year period after the 2000 forest inventory in the Municipal Forest of Traunstein.

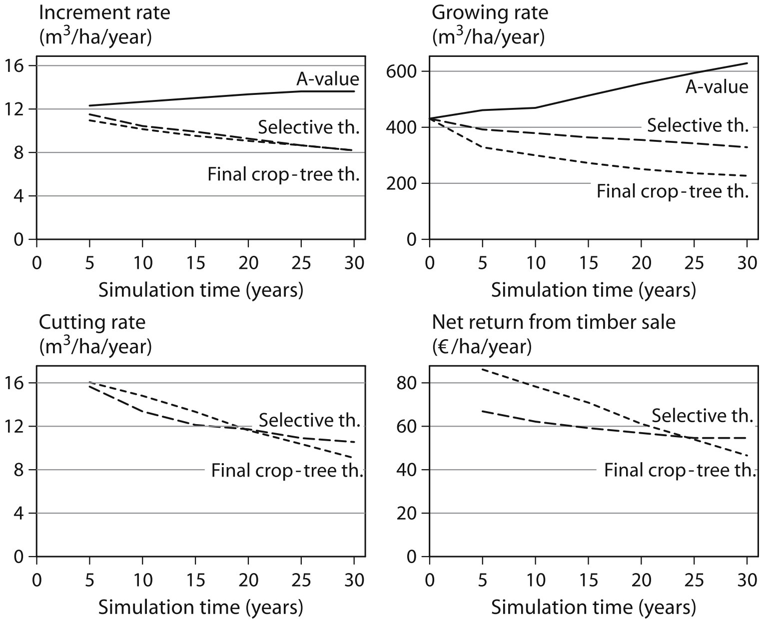

Fig. 7.5. Annual volume increment, growing stock, cutting rate and net return from timber sale for the forest estate Traunstein, southern Germany, simulated with different thinning alternatives applied: (1) A-value based thinning, (2) selective thinning, (3) final crop-tree thinning. Depending on the applied thinning regime, the growing stock stabilises, increases or decreases

With this example, the conceptual considerations discussed in Section 7.3.2 (see Fig. 7.2) are exemplified. The reference shows the dynamics of the A-value-based conditions. The strategy of final crop-tree thinning is superior to selective thinning in cuttings and net return and would lead to a significant growing-stock decrease accounting for 426 m^3/ha at present to about half the amount in 30 years. This management strategy would not be compensated by a higher increment, such that a sustainable net return would be put at risk. Selective thinning only would lead to a slight growing-stock decrease and therefore stabilise net return. Similar considerations could also be carried out for all other yield-referring, economic and ecological variables calculated in simulation runs. Only estate-level simulation of that kind reveals the long-term consequences of chosen management alternatives for the forest enterprise.

7.5
Spatially Explicit Modelling and Visualisation of Natural Scenery

Planning decisions, like tree species selection, thinning and regeneration, have impacts on the natural scenery and therefore on protective and recreational func-

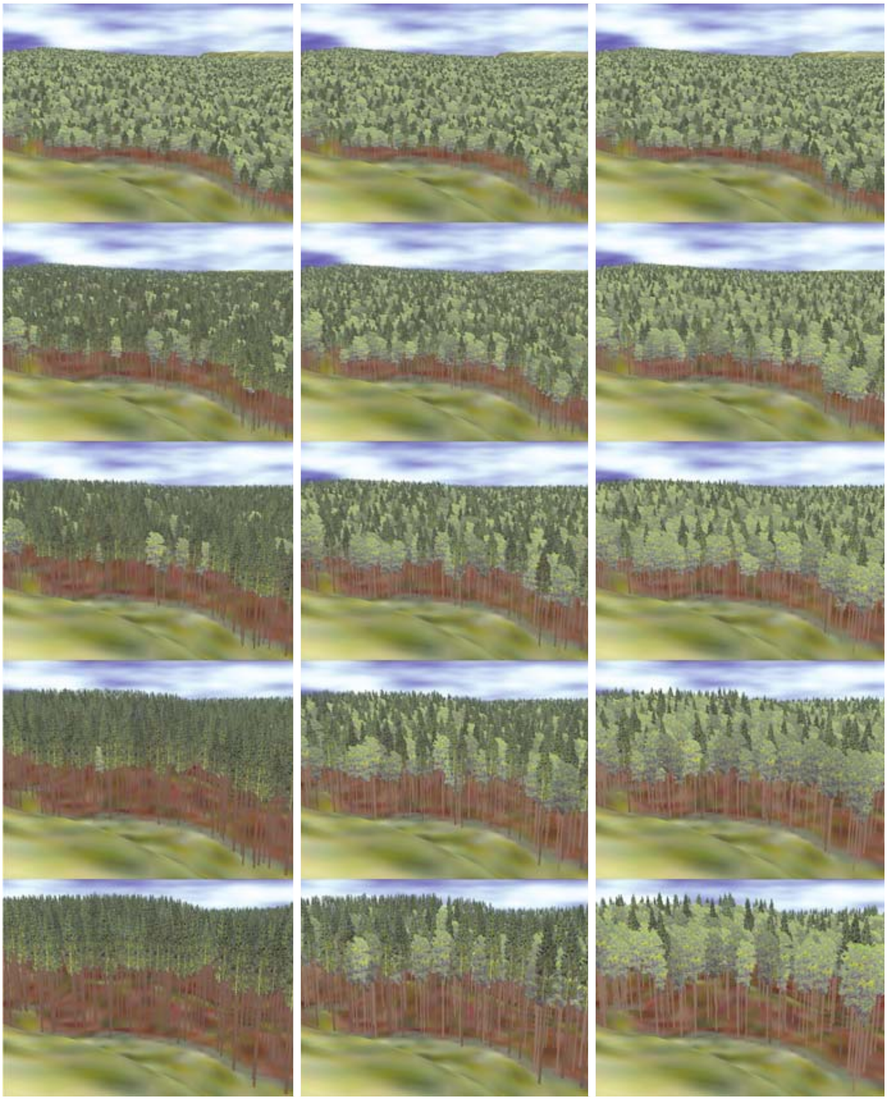

Fig. 7.6. Visualisation at landscape level. Development of Norway spruce/common beech mixed stands in the Traunstein forest estate, Germany, from age 25 to 125 (from *top* to *bottom*). *Left column* Without management; *middle column* thinned from above with moderate promotion of beech; *right column* heavy promotion of beech

tions (cf. Table 7.1, criteria 5 and 6). To support decision-making, appropriate computer programs can be used to visualise the long-term consequences of management alternatives. From available data of landscape relief, surface structure, stand boundaries and stocking type, three-dimensional landscape views are generated, enabling a user to look down from an arbitrary viewpoint. By coupling with an individual-tree-based growth model, static records can be assigned to a dynamic view (Pretzsch and Seifert 2000). This is shown in Fig. 7.6 by a section of the Municipal Forest of Traunstein. The initial situation forms a 25-year-old mixed stand of Norway spruce and common beech. This stand, with an area of about 5 ha, is at first displayed in its present condition by the visualisation program L-VIS (Fig. 7.6, upper row). In a second step, the stand development is simulated with an individual-tree growth simulator. In this simulation example, the growth simulator SILVA is used between the ages of 25 and 125. Three management alternatives are compared for simulation: (1) development without any silvicultural management, (2) moderate promotion of beech by thinning from above, and (3) strong promotion of beech by thinning from above. The results of these alternatives can be visualised (Fig. 7.6, left, middle and right columns, respectively). With no management, a homogeneous pure spruce stand evolves (left column). Without active promotion, beech underlies spruce and fails almost completely until the age of 125 due to self-thinning. With moderate promotion at the end of the simulation, beech's share accounts for 20%; with strong promotion it accounts for 50%.

Visualisation is based on scenario simulations with individual-tree models reproducing tree and stand dynamics spatially. In these types of models the single tree forms the basic informational unit. Its diameter, height, crown base and crown base position are modelled depending on site characteristics, competition, disturbances, silvicultural management, etc. The level of abstraction in the model is identical with the level of biological observation. For weighting up different planning alternatives and for deliberations with stakeholders in silvicultural planning, visualisation may evolve into an effective tool in participative planning and decision-making processes.

7.6
Structural Diversity and Biodiversity

Trees, forest stands and silvicultural landscapes are components between, within or by which physical, biological or ecological processes are running. Stand or landscape structure therefore affects habitat suitability and biodiversity (Fig. 7.7). For example, stand structure determines the abundance and population dynamics of owls, woodpeckers and bears to such an extent that it may serve as an indicator for evaluating habitat quality and managing population dynamics (Letcher et al. 1998; Wiegand 1998). The close relationship between structures of stands and trees and their colonisation by birds, beetles, spiders, lacewings and bugs is pointed out among others by Ellenberg et al. (1985) and Ammer and Schubert (1999). Knowledge concerning relations between structural characteristics and habitat or species diversity is still fragmentary. However, it is commonly agreed that with a rising structural diversity, the diversity of animal and plant species also increases (Haber 1982). Thus, structural characteristics account for easy-to-measure unspecific indicators for potential biodiversity of forest ecosystems (Ulrich 1999). Structural characteristics can be more easily surveyed and inventoried on a larger scale by forest inventories than number, density and diver-

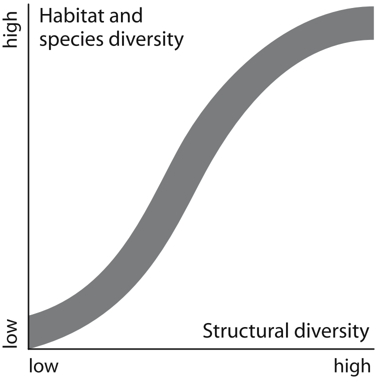

Fig. 7.7. Schematic relationship between structural diversity and species/habitat diversity. (Adapted from Begon et al. 1991)

sity of single animal or plant species themselves. Because of the high measuring costs, these can only be measured selectively, but they strongly correlate with the widely available structural variables. From this point of view, structural values – already known from forest inventories or otherwise easy to measure – serve as indicators monitoring detailed but difficult-to-access information. If structural characteristics are integrated into growth models, they might enter strategic planning (cf. Sect. 7.2.2).

7.6.1
Identifying Structures at Estate Level: the Species Profile Index

As an example, the index A_{rel} is introduced, describing the allocation of the stand space by tree species (Pretzsch 2002). The index may be calculated from inventory data and correlates with the habitat suitability of deer, hollow-nesting birds and deadwood-colonising organisms as well as with recreational functions and aesthetic values (Pott 2002). This index enables the description of a stand's structural state. From repeated measurements, structural changes can be quantified.

The index A_{rel} is based on the index of Shannon (1948). For its calculation a stand is divided into three height layers $j=1, 2, 3$, representing 0–50, 50–80 and 80–100% of stand maximum height, respectively. By enumeration, the number of individuals of species i in layer j is identified. Summing-up the products of species share and logarithmic species share for $i=1$ to S species and $j=1$ to Z height layers results in an index quantifying biodiversity and vertical allocation of species in a forest stand. The maximum index value with given species number S and layers Z is $A_{max}=\ln(S \cdot Z)$. Therefore the index A_{rel}

$$A_{rel} = \frac{-\sum_{i=1}^{S} \sum_{j=1}^{Z} p_{ij} \cdot 1n\, p_{ij}}{1n\,(S \cdot Z)} \cdot 100 \qquad \text{(Eq. 7.1)}$$

denotes how close a given stand structure is to the maximum structuring possible with the given species abundance. Equation (7.1) consists of: (1) S or number of occurring species, (2) number of height layers (Z, in this case three layers), (3) species share in layers (p_{ij})

$$p_{ij} = \frac{\mathrm{n}_{\mathrm{i,j}}}{\mathrm{N}},$$

(4) number of individuals of species i in layer j (n_{ij}), and (5) total number of individuals (N). Instead of height layers, diameter classes may also serve as an input to the index. Figure 7.8 shows the species profile index A_{rel} for pure and mixed stands of Norway spruce (*Picea abies* L.) and common beech (*Fagus sylvatica* L.). The index adds up to 100%, ranging from pure spruce stands (A_{rel}=26.5%) to even-aged spruce–beech mixed stands (A_{rel}=79.0%) and uneven-aged spruce–beech mixed stands (A_{rel}=92.1%).

7.6.2
Scale-Comprehensive Indicators

The ln(species number A)-ln(area F) diagram (Fig. 7.9) denotes the efficiency of using sample plot data for describing stand structures giving information regarding the α, β and γ diversity of tree species (Whittaker 1970). This analysis starts with identifying the number of tree species A_1 at an inventory plot with the area F_1. The identification shows the first tuple [A_1, F_1]. Now, around the centre of the inventory plot concentric circles with stepwise increasing radii are set. For each of these circles $k_{1,\ldots,n}$ the number of appearing tree species and the enclosed area may be identified. Species numbers $A_{1,\ldots,n}$ are recorded against the respective circle areas $F_{1,\ldots,n}$ in a double-logarithmic ln(A)-ln(F) diagram (Fig. 7.9). In order to obtain stable information for an observed region, many or all inventory

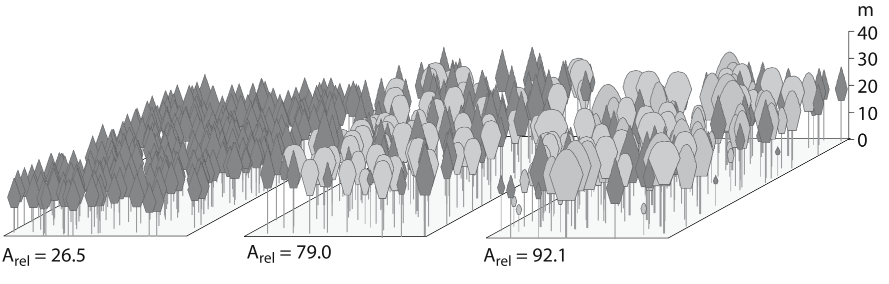

Fig. 7.8. Species profile index A_{rel} applied to a pure Norway spruce stand (*left*), an even-aged mixed stand of Norway spruce and common beech (*middle*) and an uneven-aged mixed stand of spruce and beech (*right*). Structural diversity increases from *left* to *right* with A_{rel}=26.5, 79.0 and 92.1%, respectively

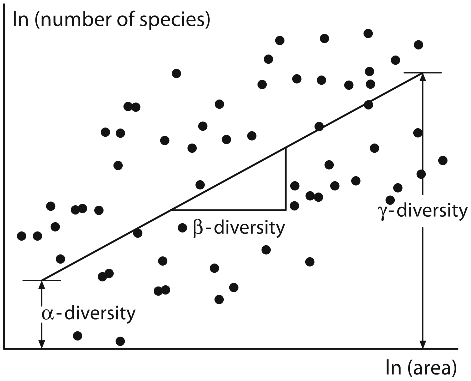

Fig. 7.9. Schematic determination of α, β and γ species diversity. The number of species A based on inventory data is plotted against area F in a double logarithmic grid. ln(A)/ln(F) regression enables diversity quantification from point to regional scale

plots must be analysed repeatedly. The resulting scatter-plot is smoothed by regression analysis with the model

$$1\text{n}\ A = a + b \cdot 1\text{n}\ F + \varepsilon \qquad \text{(Eq. 7.2)}$$

Parameters a and b denote the information on horizontal characteristics of species numbers within a region. If we are interested in the expected species number in an observed micro-area (α diversity), this can be identified directly from the regression line. Species numbers increasing with increasing areas (β diversity) is represented by the gradient b. To obtain the total number of tree species within a region (γ diversity), its area is applied to Equation (7.2).

The ln(A)-ln(F) line summarises information on horizontal characteristics of biodiversity and forms an indicator for habitat diversity (Rosenzweig 1995). It is appropriate for state description and diagnosis of changes in species composition as well as for characterising and evaluating planning alternatives (monitoring and strategic planning). Species A can be in the form of tree species, soil flora, dead wood, stand gaps, etc.

From simulation runs at estate level, temporal dynamics of ln(A)-ln(F) lines can be derived when comparing different management alternatives. Returning to the simulation run at the landscape level illustrated in Fig. 7.6 with each scenario, ln(A)-ln(F) lines showed the same course at simulation start (t=0). Figure 7.10 schematically illustrates ln(A)-ln(F) lines shifting until time t=100 a. With no action (left), α diversity largely remains unchanged. Because of failing beech and other admixed tree species, β diversity decreases. By keeping with the present management and moderately promoting beech (middle), the ln(A)-ln(F) line only changes slightly. If, however, the enterprise's forests are changed into multi-layered stands promoting beech β diversity and therefore habitat, diversity increases considerably.

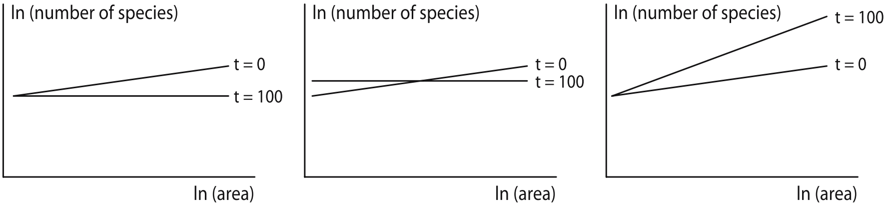

Fig. 7.10. Schematic shift of the ln(A)-ln(F) line affected by alternative thinning concepts. The line t=0 represents the α, β and γ species diversity at the beginning of a 100-year simulation period. Depending on the applied thinning (from *left* to *right*: unmanaged, promotion of deciduous trees, transition to uneven-aged forest) the ln(A)-ln(F) line will shift to the line t=100

7.7
Conclusion and Perspectives

Using SD criteria and indicators for monitoring is different from using them for strategic planning and decision-making. Monitoring claims to define unique and comparable indicators and criteria for a wide range of spatial scales (stand, estate, region, major region) and types of ownerships (state, municipal, private forests). State description and diagnosis of changes require a whole vector of indicators. For this, quantitative indicators and criteria are sought, with which available state data can be best used or which can be measured with an acceptable amount of effort. The temptation to limit data to a few easily measurable indicators is understandable. However, in view of the complexity of forest ecosystems, oversimplified monitoring approaches are not satisfactory when characterising complex forest systems. Key indicators presented by Spellmann (2003) highlight examples for quantitative, scale-comprehensive indicators, which can be generalised and inferred from available data. Suggested indicators have to be analysed regarding their applicability and integrity for monitoring.

As opposed to monitoring, strategic planning will use SD indicators and criteria for fulfilling individually fixed management objectives of an enterprise. Thus, only those criteria and indicators that are relevant for the management objective are selected. Furthermore, selected criteria and indicators are weighed according to the estate's objective hierarchy. In contrast to monitoring, a small number of indicators and criteria will generally be of concern. Weighing the criteria against each other is done by the estate's owner or manager (Sodtke et al. 2004).

The application of simulation models (dynamic growth models) will enable an improved SD evaluation and a more flexible adjustment between singular stand and total estate planning. Simulation models can replace common indicators by aggregated dynamic long-term indicators. Integrating simulation models into the planning process paves the way for strategic forest enterprise planning and SD decision-making – the concept of which is outlined in Fig. 7.11. Simulation models integrated into decision support systems – given initial site, state and management characteristics – may simulate stand by stand or stratum by stratum within batch-mode and can aggregate this partial information for the total

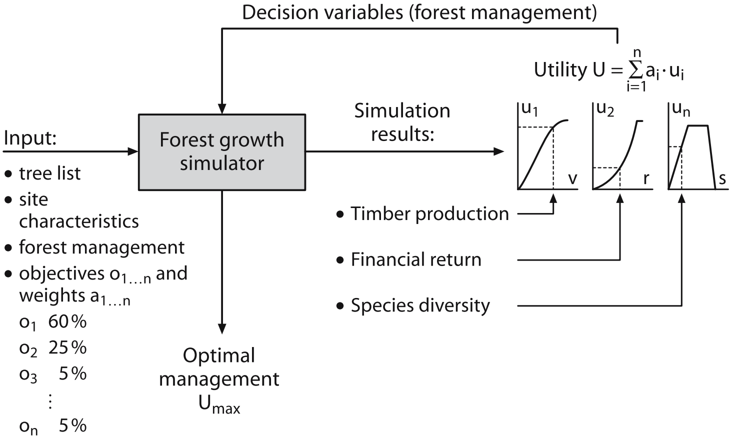

Fig. 7.11. Structure and essential elements of a decision support system for strategic forest management.

estate. Growth simulators can scale at different spatial and temporal levels: from stand or stratum to estate or inter-estate level, from short-term treatment reactions to long-term dynamics. Management alternatives can be analysed regarding their estate-referring and long-term consequences. Silvicultural re-orientation becomes transparent regarding its consequences for the total estate. Concepts and tools for shifting to a multi-functional strategic planning of SD are well developed (Pretzsch et al. 1998; Hanewinkel 2001; Spellmann 2003; von Gadow 2003; Sodtke et al. 2004). Technical equipment such as computers, simulation software, databases and inventory data are available. Their integration into forest planning and decision-making may speed up innovation.

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Evaluating Individual Tree Growth Models

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Abstract. Individual tree growth models have become important tools for forest management. Therefore proper model evaluation criteria are of increasing interest to achieve a consistent and reliable management output. Generally, a forest growth model consists of a set of model components or functions, estimated independently or simultaneously using a range of different techniques. While an evaluation should examine each individual model component, the overall system performance is usually considered much more important. In this chapter we discuss evaluation criteria within three growth models focusing on the general model approach, the parameterisation and estimation methods, variable selection and model simplicity, biological realism, as well as the compatibility and reliability.

8.1
Introduction

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). With the increasing use of growth models in operational forestry a proper model evaluation may be crucial to achieving sustainable management practices. As an example, there is a direct link from the precision and accuracy of model predictions to an optimisation of the economic revenue of management operations.

For practical application purposes an evaluation should comprise model-'internal' as well as model-'external' properties. Model-internal properties relate to biological, mathematical and statistical aspects of a model, whereas model-'external' properties relate mainly to the operator interface. More specifically, model-external properties include model transparency, model documentation, data input and output features, soft- and hardware requirements, flexibility in application, the potential for integration of the model into the flow of information in forestry practice and, more generally, user acceptance (Pretzsch et al. 2002; Robinson

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and Monserud 2003). Practical relevance could be added as an overarching issue in any model evaluation targeted towards forest management.

In a broader perspective, the qualities of a forest model may be best reflected by its utility for sustainability considerations. However, at this stage only few models for use in forest management are capable of addressing the multi-dimensional nature of the biological, social and economic factors that help define sustainability (Monserud 2003).

8.2
Evaluation Topics

Generally, a forest growth model consists of a set of model components or functions, estimated independently or simultaneously using a range of different techniques. While an evaluation should examine each individual model component, the overall system performance is usually considered relatively more important. This somehow contradicts the well-known problem that low-quality input leads to low-quality output, but reflects that overall model performance is generally considered good when predictions are sufficiently accurate, disregarding whether essential model components are all accurate or errors in different components cancel each other.

The evaluation of forest growth models is highly subjective, ranging from choice of variables, model functions and calibration data, to determination of threshold values in final tests. Furthermore, evaluation criteria cannot be divorced from evaluation objectives. This means that the consequences of choosing a specific approach should be carefully considered during model construction as well as during the evaluation process. Unfortunately, these elementary principles are often overlooked.

In contrast to stand level models individual tree models generally account better for spatial variation in the stand. However, more detailed information is needed to calibrate and use these models. In operational forestry, such information may originate from well-targeted traditional inventories (e.g. Böckmann et al. 1998) or inventories based on remote sensing (e.g. Dralle and Rudemo 1997; Nelson et al. 1997; Tarp-Johansen 2002a,b; Popescu et al. 2003). Based on modelling of between-tree interactions, individual tree models are especially useful for optimising management practices regarding forest types and silvicultural systems which are more complex than even-aged mono-specific plantation systems under the clear-cutting system.

In addition to criteria used for growth models that operate at a more aggregate level, the evaluation of individual tree models should specifically address the representation of the population of trees, the population dynamics (i.e. the interaction between individual trees), and the effects of management practice on population dynamics. Obviously, the identification of relevant model characteristics and relevant evaluation methods becomes more difficult with increasing model complexity.

Procedures, criteria and tests for use in the evaluation of forest growth models have been documented by numerous authors (e.g. Vanclay 1994; Soares et al. 1995;

Vanclay and Skovsgaard 1997; Pretzsch 2001; Pretzsch and Durský 2001; Pretzsch et al. 2002; Huang et al. 2003; Robinson and Monserud 2003). Here, we focus mainly on the evaluation of model-internal properties, with an emphasis on principles rather than specific techniques.

For evaluation of individual tree growth models, the following main topics should be considered (Vanclay and Skovsgaard 1997, modified):

1. Model form, parameterisation and estimation methods.
2. Variable selection and model simplicity.
3. Biological realism.
4. Compatibility.
5. Reliability.

8.2.1
Model Form, Parameterisation and Estimation Methods

A forest growth model should adequately reflect the temporal development of relevant mensurational characteristics at tree and stand level as well as allometric relationships between these variables. Growth behaviour is often modelled using non-linear mathematical functions, while allometric relationships are modelled using linear and power functions.

An appropriate representation of the multi-dimensional nature of the forest and its growth dynamics has long been, and still is, a major challenge. Often, growth modellers resort to relatively simple regression models with a number of more or less uncorrelated parameters. Such models may not reflect the temporal and spatial correlation in the data, or they rely on some kind of a priori principle in model construction, for example, Reineke's rule for stand density or Eichhorn's rule for the relation between height and stand volume growth (e.g. Pretzsch 2001). In contrast, such rules and principles are often appropriate for evaluation purposes when they were not included a priori in model construction.

The biological nature of the model may be examined by comparing derivatives, limits, maxima, minima, inflection points and other mathematical properties. Although some general principles apply, a professional forester's judgement may be needed. In terms of statistical properties, the compromise is generally speaking between model flexibility and over-parameterisation. No universal criteria exist for this compromise, but several statistical tests are available, each one suitable for different purposes.

On the practical/biological side, the implementation of statistical concepts should not be constrained by resources or technology. For example, the 'if...then... else...end if' structure of the computer language should not lead to the use of on–off behaviour rather than a gradual phasing in and out, when the latter may be more appropriate.

More thorough evaluations may also consider basic statistical properties of the model. One of the most important characteristics of non-linear growth models is the degree of so-called intrinsic non-linearity (Ratkowsky 1983, 1990), reflecting to which degree parameter estimates are based on unbiased, normally distributed, minimum variance estimators. Undesired statistical behaviour may invalidate predictions, but is often overlooked in model evaluations.

The evaluation of model form and parameterisation often depends on a trade-off between model performance and model complexity. With individual tree models, the correlation structure in calibration data and between individual model components should be given special attention. In most cases calibration data have a hierarchical structure, i.e. several observations originate from the same tree, several trees are measured in the same stand, etc. Moreover, trees and stands are often remeasured at intervals.

Spatial and temporal correlation in data may be handled using mixed-effect or multi-level models, accounting for fixed as well as random effects. The mixed model extends the general linear and non-linear models by allowing for both correlation and heterogeneous variance, while still assuming normality.

Due to correlation between observations generalised least squares (GLS) estimation or likelihood-based methods should be used instead of ordinary least squares (OLS) estimation. In addition to estimates of fixed and random parameters these methods provide information on the variance–covariance structure. In a forestry context this immediately leads to plot- or stand-specific estimates that account for effects of, for example, site and silviculture on tree form and stand growth (e.g. Lappi and Bailey 1988; Lappi 1997; Tarp-Johansen et al. 1997; Schadauer 1999).

One of the most efficient ways to detect autocorrelation and other remaining dependencies is through inspection of residuals or standardised residuals. This is often part of the final model evaluation, but the nature of the error term(s) should be considered and specified even at the stage of model construction. The classical choice is between additive and multiplicative errors, depending on the nature of variables and measurement methods. In the case of stochastic models or model components the location of error in model equations may strongly influence the ease of parameter estimation.

Another consideration is the pattern of error propagation through the model at large (e.g. Gertner and Dzialowy 1984; Gertner 1987, 2003). This issue is of particular importance when evaluating individual tree models. However, it may require a huge number of simulation runs to reveal possible inadequacies, and often this is omitted from the evaluation of a forest growth model.

Ideally, all of the equations in a growth model should be combined into a unified model as an integral part of the parameterisation and estimation process. Traditionally, the combination of equations has been carried out more or less sequentially (e.g. Vanclay 1994; Pretzsch 2001). Now, recent developments in computing technologies allow simultaneous estimation of parameters (e.g. Hasenauer et al. 1998; Johannsen 1999; Hall and Clutter 2004). Considering the multi-dimensional nature of the forest and the simultaneous distribution of related variables this should be the preferred approach. Due to the potentially large number of within-tree and within-stand correlations this recommendation holds especially for individual tree models.

8.2.2
Variable Selection and Model Simplicity

Individual tree growth models often use ‘independent’ variables such as site index, tree characteristics and competition indices for modelling tree growth and stand dynamics. Predictor variables are often derived from other variables that are measured directly (for example, crown length as a predictor variable may be derived from tree height which, in turn, is derived from measured diameter at breast height). To reduce error propagation, collinearity, variance inflation and similar problems, predictor variables should be chosen as close as possible to originally measured variables. Nevertheless, derived variables will continue to play an important role as predictors in forest growth models because they themselves meaningfully integrate and reflect site, stand or tree characteristics. This stresses the need for professional insight as well as statistical skills when selecting relevant variables.

A range of different statistically based methods are available for variable selection, including tests for the need to transform variables. Often, variable selection is carried out in several, sequential steps, beginning with relatively simple univariate considerations for individual model components, leading to a final, more complex compromise for the whole model. In this process, the best combination of variables from univariate selection procedures does not automatically lead to the ‘best’ combination for the model at large. This depends on the correlation structure in the overall model.

With mixed models many of the graphical methods and diagnostics appropriate for the general linear (and non-linear) model extend to the mixed model setting as well. Furthermore, a likelihood-based approach provides several statistical measures of model adequacy. The most common of these are the likelihood ratio test and Akaike’s and Schwarz’ criteria.

In practice, more than one method is often used for each model component in order to contrast different combinations of predictors arising from different selection criteria. Threshold values for entry of a variable may be relaxed to ensure practical relevance (e.g. Skovsgaard 1997a). Finally, variables and variable combinations included in or omitted from the model (as a result of the parameterisation process) should be compared with expectations and reviewed for plausibility and practical relevance.

Following the dictum of Ockham’s razor (“entities should not be multiplied beyond necessity”) the quest for simplicity has become a basic principle in the natural sciences (e.g. Keuzenkamp and McAleer 1995; McAllister 1996). With forest growth models simplicity generally refers to the logical behaviour of a model, the number of state variables, and the number and nature of estimated parameters relative to the model’s predictive ability. The number of state variables and parameters should be kept to a minimum. Mathematical operators and functions should be as elementary as possible and prediction accuracy maximised (e.g. Burkhart 2003; García 2003). As projection period increases model dimensionality should usually decrease to give the same level of prediction accuracy (Kahne 1976). This relation is well known in other areas of science, but except for some few examples (e.g. Leary 1979; Burkhart 2003) it has not received much attention in forest modelling.

The number and combinations of predictor variables should be restricted to relevant biological or silvicultural characteristics or those that improve prediction accuracy considerably. Although derived quantities such as site index or wood volume may be relevant predictors, originally measured variables should be preferred whenever possible. Usually, the magnitude in changes of certain model statistics is used to control whether the improvement caused by a predictor reaches threshold values for its inclusion or exclusion.

8.2.3
Biological Realism

Similar to the arts, realism in modelling implies an accurate, detailed, unembellished depiction of nature or of contemporary life; realism rejects imaginative idealisation in favour of a close observation of outward appearances (cf. Encyclopædia Britannica 2003). Scientifically, realism implies that the model or theory is objectively true (or false) based on its correspondence (or lack of it) to an independently existing reality. So, obviously realism in modelling strives for a faithful representation of the object in question.

In the context of forest growth models biological realism refers to biological growth per se as well as modelling of the site-specific response of trees and stand to silvicultural practices. It should be noted, however, that most management-oriented forest growth models lack links to the underlying causes of productivity and growth. This need not hamper an evaluation of other aspects of biological realism, but definitely sets certain limits.

In addition to the plausibility of predictor combinations a model evaluation should check whether the model predicts sensible responses to management actions over the range of growth conditions. This is controlled by the sign and magnitude of parameter estimates. Implausible model behaviour is usually easier to detect qualitatively than quantitatively. Qualitative implausibility often results from incorrect coefficient sign and may be detected by comparing model behaviour with expectations based on current understanding of growth processes. Quantitative plausibility may be investigated using matrix plots of prediction results calculated by varying each predictor variable within its biological range, retaining all other predictors as constant (e.g. Soares et al. 1995; Leary 1997; Vanclay and Skovsgaard 1997).

Implausibility may result from inadequate model specification (including over-parameterisation) or limitations in calibration data. This implies that all relevant data should be used for calibration, while evaluations should be carried out using independent data (if available) and resampling procedures such as cross-validation, boot-strapping and jack-knifing (Vanclay and Skovsgaard 1997). Independent data may, for example, originate from other growth regions, differently managed stands, more recent data collection or other forest administrations. An important variation on single-observation resampling is to omit groups of data, for example, according to geographic location, age class, management regime or other criteria (e.g. Tarp-Johansen et al. 1997). It is a well-known fact that model evaluations based on resampling provide more optimistic evaluations of realism than when based on independent data (e.g. Reynolds and Chung 1986; Huang et al. 2003).

Biological realism obviously depends highly on data quality, but often data quality is not considered sufficiently (e.g. Vanclay et al. 1995). A model evaluation should also include aspects of data quality, and specifically the identification of areas where remedial sampling may be desirable or further experimentation is needed (e.g. Beetson et al. 1992).

Due to more details in the model the identification of relevant test quantities (and qualities) is especially critical with individual tree models. Again, matrix plots may be helpful to trace relevant issues as well as unexpected or undesired model behaviour. Modelling at a more detailed level often leads to greater flexibility in model behaviour and increasing risk of fitting some parts of the model to random fluctuations in tree growth and stand dynamics. This should be avoided by choosing robust model functions, examining sensitivity to model input and testing for robustness at different modelling levels (e.g. Huber 2004).

Because of the increasing complexity of forest models, numerical methods and Bayesian methods are becoming more and more important in model evaluation. As an example, Monte Carlo simulations have been successfully used for detecting the uncertainties and sensitivities of growth models (e.g. Verbeeck et al. 2003). As another example, Bayesian methods, which are based on prior information on input distributions and correlations between input variables, have been used for assessing the uncertainties of different model types (Gertner et al. 1999; Green et al. 2000; Radtke et al. 2002).

A special aspect of biological realism for individual tree models is the spatial dimension. Except for very simple spatial patterns, this obviously involves geostatistical methods. When spatial information is not available some models initially derive this from inventory data at hand, rely on simulation runs, predict the development of individual trees and, if required, aggregate results back to the stand level. Although this process may seem a bit odd, it is generally believed to provide suitable results and more insight than may be achieved from ordinary stand level models. Spatially explicit studies and models have been available almost since the advent of classical yield tables, while suitable calibration and evaluation methods are only just beginning to emerge (e.g. Gertner 2003; Watt et al. 2004; Brunner et al., this Vol.).

Since forest growth models are often used for long-term forecasts, it is particularly important that they extrapolate well beyond the calibration range. This is stressed by the fact that model calibration almost inevitably is carried out using historical data records. These may not reflect future climate and changing silvicultural practices. This calls for a new generation of management-oriented forest growth models capable of adapting to changing growth conditions and management practices (Skovsgaard and Vanclay 2001). Otherwise, we risk reality becoming an approximation to our model and not vice versa.

8.2.4
Compatibility

In the context of forest growth models, compatibility implies mathematical consistency within a given model or between different models. The idea of compatibility within a model is that yield estimates can be derived from growth estimates (and vice versa) and that estimates of composite variables (for example, volume) are calculated from more basic variables (for example, basal area, height and form factor) rather than modelled independently. Moreover, if a composite variable may be derived in different ways, these should provide identical estimates. These principles have been fundamental in forest growth modelling in Europe since the first scientifically based yield tables emerged in the late 1700s and for subsequent mathematical models. Often, stand level estimates of basal area, height and volume were given highest priority in terms of accuracy, with unexplained error 'hidden' in the form factor or elsewhere.

With the advent of mathematical forest models in North America, compatibility was rediscovered (Buckman 1962; Clutter 1963) and subsequently expanded to refer also to the consistency of estimates from different model types. When models are compatible from individual tree level through various aggregations to the stand level, providing consistent estimates of tree and stand properties, they are said to form an integrated system of forest growth models (Daniels and Burkhart 1988). Such a system provides good opportunities to compare management alternatives at different levels of resolution. For individual tree models compatibility of stand level estimates is a desirable property that should be tested during and after construction.

Compatibility in a strict sense is possible only for deterministic models. With stochastic models realisations will differ between simulation runs. Consequently, an evaluation of compatibility for stochastic models requires predefined limits for the acceptable, most likely deviation, for example based on end-user requirements of prediction accuracy. Compatibility for different projection length is a special variation of this theme (e.g. Soares et al. 1995). Differences occur and possibly accumulate when the predicted values after each stochastic simulation step are used as input for the next step of simulations. This may affect growth predictions less than the prediction of additionally derived variables such as wood quality (Schmidt 2001). As an advantage, this kind of evaluation provides useful information on suitable projection length.

Compatibility between models often leads to the selection of non-linear model forms and analytically solved conditions for model parameters. This means that systems of compatible models are more complex than independent models for different characteristics. In the latter case, models are not mutually conditioned and do not necessarily yield a logical system of prediction equations for the phenomenon of interest.

Another aspect of compatibility is the reliability of reasonable transformations of model predictions. Many individual tree models use static instead of dynamic model components to forecast, for example, stand height or the development of crown base, crown width or branch diameter. Static model approaches suffer the disadvantage that reasonable estimates at two points in time for the same object do not automatically lead to a reasonable estimate of change or growth. In the absence of appropriate time series data, such models should be calibrated based on suitable chronosequences, specifying extrapolation boundaries in the implementation process to ensure biologically reasonable estimates.

Finally, compatibility is often a problem for forest models that include size class distribution or similar information. This may be alleviated in the construction through the use of parameter recovery techniques, which generally aim to ensure that the sum of basal area predictions for individual trees equals stand basal area (e.g. Hyink and Moser 1983).

Information on size class distribution is particularly valuable when evaluating silvicultural alternatives, but often the usual goodness-of-fit tests are not appropriate (e.g. Reynolds et al. 1988; Vanclay and Skovsgaard 1997). One problem is the lack of a specified theoretical alternative to test against, i.e. there is no clear null-hypothesis. Another problem is that standard tests attribute equal importance to errors in different size classes, for example errors for trees with a diameter of 10 cm are rated equally to those for trees of 40 cm although the latter is more serious from a forestry perspective. This has been alleviated through the construction of alternative tests specifically for forestry purposes (e.g. Reynolds et al. 1988; Skovsgaard 1997a; Zucchini et al. 2001). Some of these are based on an error-index that better reflects the forestry importance of different size classes.

8.2.5
Reliability

The objective of model evaluation is to assess the reliability of predictions from the model and, more generally, the model's potential for its intended use. The assessment should depend on modelling or user objectives and be based on specified requirements of accuracy and precision. For forest models, such specifications are often lacking or quite vague. This may be due to the complexity of the issue or of forest ecosystems, but most likely the tradition of a pragmatic approach to modelling and model use also plays a significant role when setting the agenda. The ultimate assessment of model reliability rests with the end-user, so the end-user should help specify accuracy and other requirements even at an early stage of model construction. Although such specifications may be hard to quantify in an operational context, the alternative of no specifications is generally worse and may lead to unacceptable models or waste of modelling efforts.

The evaluation of model-internal properties is mainly a matter of scientific research, guided partially by managerial and other practical considerations. The evaluation of model-external properties is highly dependent on model documentation, but eventually rests with the end-user. From an end-user perspective models that are easily adjusted or recalibrated will generally seem more attractive and reliable than 'black box' models.

For management-oriented forest models, model construction is often divorced from operational forestry. This stresses the need for efficient communication between science and forestry practice, to ensure high and relevant modelling standards and well-targeted use of research grants. The complexity of individual tree models further stresses the need for mental and other interactions between modeller and end-user.

8.3
Conclusion

During recent years the evaluation of forest models has received much attention (e.g. Skovsgaard 1997b; Pretzsch et al. 2002), and the question has emerged of whether there is more to be said.

One argument to do more is that the technicalities, i.e. development and tests of methods and criteria, are a continuously ongoing process in a constantly developing field of research. This depends mainly on developments in other branches of science (logic, statistics, computer technology, etc.), but there are also examples of more specific forestry approaches. Some of these have been mentioned in this chapter. Another argument is that forest models develop. Following some decades of courageous attempts, many failures and some few examples of success, forest modelling finally seems to be moving successfully in the direction of individual tree models. In many parts of the world, this coincides with contemporary developments in silviculture and forest management, aiming for more complex, uneven-aged mixed-species forest types that better fulfil the demands of sustainable forestry.

In conclusion, we believe that more comprehensive evaluations of sustainability are an upcoming issue, but at this stage it is hard to think of a unifying evaluation concept for this purpose. With specific reference to individual tree models there seems to be an urgent need to address model dimensionality in relation to prediction accuracy and to identify or develop relevant tests for the representativeness of spatial dimensions in such models. We envisage that these topics will be researched in the near future. Links to the fundamental causes of forest growth most likely lie still further ahead.

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Demonstraiting the Problem Solving Potential of Tree Growth Models

Modeling Regeneration in Even and Uneven-Aged Mixed Species Forests

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Abstract. Regeneration establishment and juvenile tree height growth are important to ensure sustainability within forest stands. In this chapter, we demonstrate how routine inventory data may be used to assess the probability of regeneration within the last 5 years, the species composition and the regeneration density within pure and mixed as well as even and uneven-aged forests. We also propose an approach for predicting juvenile tree height growth and mortality. Finally, we demonstrate the applicability of our regeneration models using independent data sets, which were not used for model calibration. The results of the study suggest that our regeneration assessment routines and the height growth predictions were unbiased and exhibited consistent results. The equations are simple and require only routine inventory data and can be easily adapted to any other forest type if regeneration data are available.

9.1
Introduction

With the shift from even-aged pure to uneven-aged and/or mixed forest management practices, regeneration establishment and juvenile tree growth are of increasing importance to ensure sustainability. In general, trees may be classified as (1) overstory trees and (2) understory and/or juvenile trees which are considered as regeneration. The threshold level for a particular tree to belong to the over- or understory depends on predefined criteria often derived by the data sampling design. For example, regeneration may include all juvenile trees below a certain height (i.e. <1.3 m) or a certain breast height diameter (DBH) (<5 cm, e.g. the Austrian National Forest Inventory).

One method to predict the recruitment of overstory trees is based on so-called ingrowth models (Ledermann 2002). Such models predict the probability that trees exceed the predefined threshold level (i.e. 5 cm) using forest inventory data. With this method the number of ingrowing trees (in the overstory) during a given time period (e.g. 5-year growth period) is predictable. The approach is simple;

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however, it ignores the regeneration dynamics (seedling establishment and juvenile tree growth) below the threshold level (e.g. 5 cm in DBH).

Many silvicultural management systems focus on regeneration dynamics. This requires adequate data and an approach that allows us to explicitly assess forest regeneration, by looking at processes such as seedling establishment, juvenile tree growth and mortality. Previous attempts by Mitchell (1975) suggested regeneration inventories, while Shugart et al. (1973) used the development stages of regeneration as prognostic tools. Other authors (Shifley et al. 1993; Solomon et al. 1995) used regression analyses based on a combination of recent and previous site parameters to estimate the number of ingrowing trees in the overstory. Ek and Monserud (1974) suggested the Markov chain approach, Moser (1972) differential equations and Hett (1971) so-called life tables to describe regeneration. Recent research aimed at improving our understanding has split regeneration processes into predicting regeneration establishment (Pukkala and Kolström 1992; Ribbens et al. 1994; Schweiger and Sterba 1997; Hasenauer et al. 2000; Kindermann et al. 2002) and regeneration growth (Golser and Hasenauer 1997; Hasenauer and Kindermann 2002).

An important problem in assessing regeneration processes is the availability of data and/or the data collection design. Sometimes routine inventories collect information only if a certain regeneration density is evident (e.g. the Austrian Forest Inventory – FBVA 1994). This excludes plots where no or only little regeneration exists. However, from a silvicultural prospective it is important to understand why no or only little regeneration is available. Regeneration information should not be assessed visually because personal opinions of the field crew strongly bias the recording of data (Wildt 1995). Only a reproducible inventory design allows us to enhance our database for studying regeneration processes (Hasenauer et al. 2000).

In this chapter, we demonstrate the applicability of regeneration models so that they can be used within tree growth modeling using only routine inventory data. We split the regeneration process into four steps: (1) for situations where no regeneration information is available we suggest a simple method to predict the regeneration situation in order to assess regeneration dynamics as they depend upon silvicultural treatments; (2) where information on regeneration establishment is available (either from step 1 or from inventory data) we demonstrate how juvenile tree height growth and mortality can be assessed so that they can be easily implemented in a tree growth-modeling environment; (3) we validate our model calibrations using independent data sets. Because browsing is a key component within regeneration, we (4) explore how browsing impacts may affect regeneration establishment.

9.2
Data

For model building and validation two different types of data were used: (1) routine inventory and (2) permanent research plots. The data came from five different regions in Austria: (1) the University's Experimental Forest, (2) Litschau,

(3) Kammer, (4) the Hirschlacke in the Bohemian Massive and (5) the Limestone National Park in upper Austria.

The first data set was obtained from the permanent sample plot inventory of the University's Experimental Forest in the Rosalien Mountains in the southeastern part of Austria. The elevation ranges from 400–900 m, with mainly west-facing slopes. The main forest type is a mixed Norway spruce (*Picea abies* L. Karst), silver fir (*Abies alba* Mill.), common beech (*Fagus silvatica* L. Karst) forest with some Scots pine (*Pinus silvestris* L.). The Experimental Forest covers about 1000 ha and consists of pure even-aged but also mixed species stands with a wide variety of stand structure and density due to intensive forest management operations. The inventory has a grid size of ~ 141.4×141.4 m = one point per 2 ha, and is a combination of angle count sampling with a basal area factor of 4 (Bitterlich 1959) for all trees with a DBH >6 cm, and a fixed sample plot of 16 m^2 for collecting regeneration information. The fixed sample plot consists of four subplots 4 m^2 each. On these regeneration plots all trees were recorded and assigned by tree species and four height classes: 0–20, 21–50, 51–100 and 101–130 cm. For each species and height class one representative tree for measuring height and the height increment for the past 5-year growth period was selected. The periodic potential height increment rates for common beech were obtained using the site index function from Kennel (1972); for all other species the site index functions of Marschall (1975) were used.

Within the limit of twice the dominant stand height (60 m) the distance between the center of the sample plot and the stand edge was recorded in order to assess possible edge-effected incidence of light as it may affect seedling establishment and juvenile tree growth (Flemming 1962). Site information was recorded according to the Austrian National Forest Inventory (FBVA 1994). Two of the subplots were oriented along the slope and two perpendicular to it (Fig. 9.1).

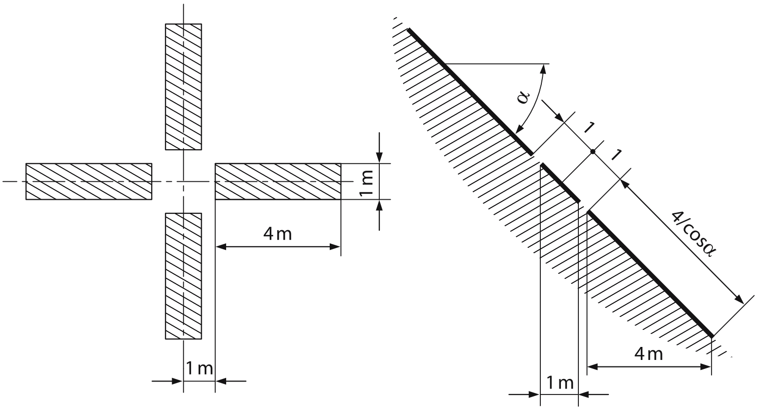

Fig. 9.1. The inventory design for collecting regeneration information on our inventory plots. At each plot center an angle count sampling with a basal area factor of 4 was carried out. On the four subplots (total size of 16 m^2) regeneration information was recorded by height class and tree species

The inventory of the research forest had been carried out since 1989 with a 5-year interval. Each year a fifth of the 558 grid points were remeasured by the angle count sampling method. Since 1998, a regeneration inventory has been added to the permanent grid points according to the design given in Fig. 9.1. In addition, 12 long-term permanent research plots located within this area are available for our study.

The second and third data set came from Litschau in 'Lower Austria' and Kammer in 'Upper Austria' consisting of 21 and 12 permanent research plots, respectively. The plots in Litschau are located near the border with the Czech Republic at an elevation of about 1,000 m. The typical stand type ranges from a pure Norway spruce to a mixed and uneven-aged Norway spruce–Scots pine forest. The plots in Kammer are located in a typical structured and mixed Norway spruce, fir, common beech forest (compare with the University's Experimental Forest) growing on very good sites between 600 and 1,100 m in elevation.

All 45 permanent research plots (12 from the Experimental Forest, 21 in Litschau, 12 in Kammer) include 6 subplots (total 270). On these regeneration plots all tree and site information including possible edge effects were recorded as previously described. Unlike the inventory design, these research plots have not been selected randomly. They were chosen to represent stands covering low as well as high regeneration densities in order to study the potential range of growing conditions for regeneration establishment and juvenile tree growth. Data collection for all trees >1.3 m in height was carried out on fixed sample plots (35×35 m) with a core zone of 15×15 m. In the non-core zone only trees with a DBH >10 cm were sampled.

The fourth data set – Hirschlacke – consists of 43 regeneration plots in a 3.6-ha permanent research site in the Bohemian Massive. The dominating tree species is Norway spruce with some Scots pine and silver fir. The research site was established in 1977 for studying target diameter cuttings. On this site all trees with a DBH >5 cm were recorded. The remeasurement interval was 5 years. The 43 permanent subplots, with a plot size of about 5 m^2 (r=1.27 m), for collecting regeneration information were recorded twice: at the second remeasurement in 1987 and during the last remeasurement in 2002. The data collection system including the assignment of the humus, soil and site data was identical to the system previously described (FBVA 1994).

The fifth data set came from a permanent forest inventory in the Limestone National Park in upper Austria. The national park is located in calcareous mountains and includes the Sensen Mountains as well as the Raichraminger Mountains. The elevation ranges from 700–2,000 m. The dominating stand type is similar to the University's Experimental Forest – a mixed Norway spruce, fir, common beech forest with some Scots pine and larch (*Larix decidua*) at higher elevations. In 1996 a permanent inventory, 300×300 m raster = one point per 9 ha, was established. So far 676 plots have been recorded which are available for our study.

The inventory collects numerous very detailed soil, site and stand information (Eckmüllner et al. 1999). The stand information needed for this study includes overstory information for all trees with a DBH >5 cm recorded on a plot size of 78.54 m^2 (r=5 m) and regeneration information from four subplots ranging in size between 2 and 4 m^2 each. Similar to the previously described data, we used the available detailed soil and site information and derived from this the information needed according to the definitions of the Austrian National Forest Inventory (FBVA 1994). This ensured consistent definition of the data set throughout the study.

The five different data sources have been used for calibrating and validating the regeneration establishment and juvenile tree height growth and mortality models by species (Tables 9.1 and 9.2). The data set covers the main tree species as well as forest types in Austria and comes from different regions within the country. Note that none of the validation data have been used for calibration.

To assess browsing impact as it may affect regeneration establishment an excellent data source provided by the Austrian Federal Forest Company (ÖbfAG) was available. The ÖbfAG owns 15% of the forest-covered land area in Austria. In 2001 the company established 50 permanent research plots within each of their 25 management districts to study browsing impacts. Each plot consists of an area 2 m in radius. Each year all juvenile trees less then 3 m in height are counted and recorded by tree species, height class (10–30, 31–50, 51–90, 91–150, 151–300 cm) and browsing damage of the terminal leader. In addition, site conditions, relief, harvesting method on the site, etc. are recorded. For details we refer to Posch (2003). For our analyses a total of 66,865 individual juvenile tree observations recorded on the 1,250 permanent plots in 2001 and 2002 were available (Table 9.3).

9.3
Methods

9.3.1
Regeneration Assessment

The basic concepts for modeling regeneration assessment and juvenile tree growth developed by Hasenauer and Kindermann (2002) and Kindermann et al. (2002) predict that the probability of regeneration is a function of

$$p = f\,(COMP, DBH_{max,\,Sp}, HT, ST, VT, EDGE$$

where p is the probability of regeneration within a 5-year growth period, $COMP$ the competition index according to Eq. (9.2), $DBH_{max,Sp}$ the maximum breast height diameter (cm) by species, HT one of the six humus types, ST one of the 26 soil types and VT one of the 53 vegetation types according to the definitions of the National Austrian Forest Inventory (FBVA 1994), as well as $EDGE$ a 'dummy variable' or Boolean variable for a stand edge within the doubled stand height of a mature forest (about 60 m). An important parameter in Eq. (9.1) is the overstory competition $COMP$, which can be derived from routine inventory data:

$$COMP = \frac{\sum (a \cdot mdbh)^{b} \cdot n_{Rep} \cdot c}{10000}$$

Table 9.1. Number of angle count sampling plots (WZP) with the regeneration data used for parameterization and model validation of the regeneration establishment models. $EDGE_{yes}$ and $EDGE_{no}$ indicate the number of plots with and without edge-effected incidence of light, respectively

Variable	Spruce	Fir	Beech	Others	With regeneration	Total
Data for parameterization: inventory plots of the Experimental Forest until 2000						
WZP	294	44	278	173	233	422
Regeneration	104	83	160	101	233	422
Mull	23	8	29	29	48	65
Mull/moder	29	29	61	34	80	153
Moder	48	44	68	37	100	193
Rohhumus/torf	4	2	2	1	5	11
$EDGE_{yes}$	24	10	31	26	51	82
$EDGE_{no}$	80	73	129	75	182	340
Data for validation: inventory plots of the Experimental Forest 2001 and 2002						
WZP	139	24	163	125	113	214
Regeneration	60	55	72	69	113	214
Mull	19	15	17	18	24	37
Mull/moder	19	17	27	29	45	84
Moder	22	23	28	22	44	91
$EDGE_{yes}$	20	16	20	25	38	58
$EDGE_{no}$	40	39	52	44	75	156
Data for validation: subplots at the Hirschlacke 1987 and 2002						
WZP	86	46	66	4	78	86
Regeneration	77	47	7	3	78	86

Table 9.1. Continued

Variable	Spruce	Fir	Beech	Others	With regeneration	Total
Data for validation: inventory plots at the Limestone National Park						
WZP	514	101	439	406	500	676
Regeneration	255	181	308	467	500	676
Mull	134	88	161	249	266	338
Mull/moder	37	30	54	81	84	106
Moder	84	63	93	138	151	233

$$mdbh = \begin{cases} dbh + 1.3 : if\ h > 1.3\ m \\ h : if\ h \leq 1.3\ m \end{cases}$$

where *mdbh* is the modified *dbh* given in Eq. (9.3), n_{Rep} the stem number per hectare, *h* the tree height, and *a*, *b*, and *c* the species-specific coefficients (Table 9.4). The final decision whether regeneration is modeled or not is derived by a comparison of the predicted value for *p* with an equally distributed random number.

Once the decision has been made that in a particular stand regeneration occurs during a 5-year growth period, the species proportion or mixture of the regeneration is estimated using the same basic concept as given in Eq. (9.1):

$$p_{Sp} = f\,(COMP, DBH_{max,Sp}, HT, ST, VT, EDGE)$$

where p^{Sp} is the proportion of a species within the regeneration (between 0 and 1) and all other variables are as previously defined. Note that each species proportion is assessed separately to keep the error components of the model predictions independent. Thus summing up the estimated proportions may result in numbers less than or greater than 1, which requires a weighting of the estimated proportions so that the summary of all species is equal to 1.

The final step of the regeneration assessment during the last 5 years is the estimation of its density. According to Eq. (9.5) a Poisson model of the following form is used:

$$1n\ (n/m^2) = f\,(COMP, DBH_{max,Sp}, HT, ST, VT, EDGE)$$

where $ln(n/m^2)$ is the logarithm of the number of trees in the height class ≤ 20 cm and all variables are as previously defined (Kindermann et al. 2002). Once

Table 9.2. Summary statistics of the calibration and validation data set for the species-specific juvenile tree height increment models. Data for parameterization are from the 12 permanent research plots at the Experimental Forest, 12 plots in Kammer and 21 research plots in Litschau. Validation data are the height increment measurements of the permanent inventory design at the University Experimental Forest. *N* Number of trees with observed 5-year height increment; h_{Reg} height of the juvenile tree; *ihist* observed 5-year height increment; N_{taller}/m^2 number of trees per m^2, which are taller than the subject tree; *CCF* distance-independent crown competition factor (trees >6 cm DBH); *SUMD* edge-effected incidence of light

Variable	Spruce Mean (min. – max.)	Beech Mean (min. – max.)	Fir Mean (min. – max.)	Scots pine Mean (min. – max.)
Data for parameterization: permanent plots Litschau, Kammer, Experimental Forest				
N	610	479	324	66
h_{Reg}.(m)	0.27 (0.00–1.30)	0.43 (0.00–1.30)	0.27 (0.00–1.28)	0.16 (0.00–0.96)
ihist (m)	0.24 (0.03–2.15)	0.43 (0.01–1.97)	0.26 (0.03–1.97)	0.36 (0.12–0.93)
N_{taller}/m^2	2.13 (0.00–31.5)	1.81 (0.00–15.2)	2.63 (0.00–15.2)	1.86 (0.00–7.50)
CCF	158 (28–563)	184 (59–826)	175 (28–826)	144 (29–291)
SUMD	0.48 (0.00–3.52)	0.51 (0.00–3.52)	0.50 (0.00–3.52)	0.72 (0.00–1.73)
Data for validation: inventory plots from the Experimental Forest				
N	210	489	72	–
h_{Reg}.(m)	0.17 (0.00–1.15)	0.25 (0.00–1.29)	0.08 (0.00–0.66)	–
ihist (m)	0.14 (0.03–0.86)	0.29 (0.01–1.43)	0.10 (0.03–0.36)	–
N_{taller}/m^2	1.16 (0.00–13.7)	1.19 (0.00–13.7)	1.04 (0.00–13.8)	–
CCF	295 (0–1858)	312 (0–1858)	275 (0–1858)	–
SUMD	0.16 (0.00–2.28)	0.33 (0.00–2.50)	0.07 (0.00–1.38)	–

the regeneration density is available it can be multiplied by the species proportion (Eq. 9.4) to produce the final regeneration density (trees ≤ 20 cm) by species.

Due to the high random impacts, density predictions are the most difficult part in assessing regeneration establishment. To provide some simple alternatives compared to the formulation given in Eq. (9.5), we have also tested several combinations of random numbers: the first option would be to define a maximum

Table 9.3. Summary statistics of juvenile trees recorded by species to assess browsing impacts. The trees were recorded on the permanent plots in 2001 and 2002

	Species					
	Spruce	Fir	Larch	Scots pine	Arolla pine	Others
Number of juveniles	21,791	3,009	2,379	522	179	90
Number of plots	1,894	588	638	113	39	23
	Beech	Maple	Ash	Hornbeam	Rowan	Others
Number of juveniles	15,523	9,877	8,450	1,899	1,592	1,554
Number of plots	1,008	856	497	114	313	479

Table 9.4. Coefficient estimates for driving the competition index by tree species

Coefficient	Spruce	Fir	Scots pine	Larch	Beech
a	0.9	0.9	0.5	0.5	1.0
b	1.2	0.7	1.1	1.1	1.0
c	1.5	1.7	1.2	1.2	1.0

number of juveniles by species in the height class ≤ 20 cm. As a second option we suggest a random number x (between 0 and 1) for the height class ≤ 20 cm weighted according to the following form:

$$\text{In}\ (n/m^2) = -3.394 + 4.859 \cdot x$$

9.3.2
Juvenile Height Growth

If the density of the regeneration is known, a juvenile tree height growth model is needed to predict the regeneration growth until a given threshold to enter the overstory (trees ≤ 1.5 m). For this purpose Golser and Hasenauer (1997) introduced an approach that predicts the height growth of a representative tree for each species and height class of tree ≤ 1.3 m using: (1) the competition of the remaining overstory (*OCI*), (2) the intra- and interspecies competition among the regeneration itself (*RCI*), and (3) a modifier for the edge-effected incidence of light (*EIL*). This modifier is needed because competition-induced decline in height increment may be reduced or even compensated for by possible edge-effected incidence of light. The original model has the following form:

$$ih_{obs} = ih_{pot} \cdot \left(1 - \frac{-1}{e^{a \cdot OCI + b \cdot RCI}} + c \cdot EIL\right)$$

where ih_{obs} is the current periodical 5-year height increment of a representative tree and ih_{pot} is the potential height growth determined from site index curves.

The competition of the remaining overstory is assumed to be similar for all juvenile trees on a given micro site within the stand (Chazdon 1988) and is calculated as the overlap of the potential crown area between the jth tree and the regeneration plot of 4 m^2 (2×2 m) (Bella 1971). For each sample plot the OCI is constant.

Intra- and interspecies competition among juvenile trees is defined as a competition measure for each height class and species representative and can be calculated as follows: the potential area of influence for open-grown trees (Hasenauer 1997) is multiplied by the number of individuals and by species within a given height class. These results are added for all height classes greater or equal to the height class of a given representative tree.

Edge effects are considered within the limit of twice the stand height (see also Flemming 1962; Canham et al. 1990) by calculating the maximum angle of incidence of light and a weighted sum of the distances to the stand edges. For further details related to the original model, we refer to Golser and Hasenauer (1997).

Although the study by Golser and Hasenauer (1997) explored successfully the deriving variables for assessing juvenile tree height growth, the implementation of this algorithm in a tree growth modeling environment (e.g. MOSES) turned out to be rather complex. Consequently Hasenauer and Kindermann (2002) adopted the model by keeping the data required as simple as possible to ensure easy implementation in existing tree growth.

The following changes were applied to achieve this goal: (1) the distance-dependent competition measure *OCI* was replaced by a distance-independent competition measure *CCF* according to Krajicek et al. (1961); (2) the complex calculation of the *RCI* for each representative tree (Golser and Hasenauer 1997) was replaced by the number of juveniles taller than the subject tree N_{taller}.; (3) *EIL*, the modifier for edge-effected incidence of light, was substituted by the sum of the distances *DIST* to the stand edges (< 60 m) in eight possible directions (N, NO, O, SO, S, SW, W, NW). The final new simplified equation for predicting juvenile tree height growth had the following form:

$$ih_{obs} = ih_{pot} \cdot \left(1 - \frac{-1}{e^{a \cdot CCF + b \cdot N_{taller}}} + c \cdot \sum SUMD\right)$$

where ih_{obs} is the current periodical 5-year height increment of a 'representative tree' by species and height class, ih_{pot} is the potential height growth determined from site index curves and all other parameters are as previously defined.

Using the identical data set for calibrating the models by species, we assessed the change in the resulting predictions between the original model structure (Eq. 9.7) and our new simplified version (Eq. 9.8).

Figure 9.2 gives the results for the overstory competition index for Norway spruce and common beech as well as Scots pine and silver fir. The bold lines indicate the relationships between relative height increment and the original distance-dependent competition measure *OCI* (the overstory competition index) as used in Golser and Hasenauer (1997). The dashed lines give the relationship for the same relative height increments and the distance-independent overstory competition measure *CCF* (crown competition factor) according to Krajicek et al. (1961). Note that a *CCF* times 0.4 is similar to the *OCI* for a given overstory situation. Similar results were also evident for Scots pine and fir.

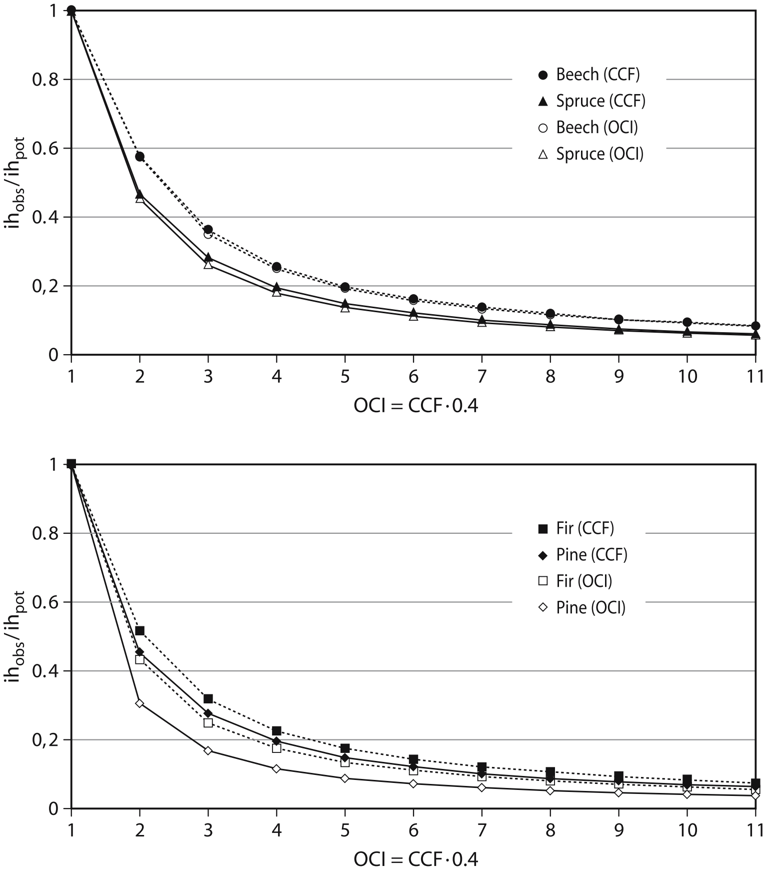

Fig. 9.2. Comparison of the relationships between the distance-dependent overstory competition (*OCI*) and the distance-independent measure (*CCF*) versus the relative 5-year height increment ih_{ist}/ih_{pot} for spruce and beech (*above*) and pine and fir (*below*). Note that at a given stand density the *OCI* is similar to a *CCF* times 0.4 (conversion factor)

Figure 9.3 shows the effect of our changes to the inter- and intraspecific competition measure for beech and four given overstory competition situations. The RCI represents the inter- and intraspecific competition measure within the regeneration as developed by Golser and Hasenauer (1997). The same overstory competition is assumed and the juvenile tree height growth relationship versus the new simplified competition measure N_{taller} (all trees that are taller than the subject tree) is depicted. Note that a $OCI=1$ is similar to a CCF of 0.40, and an RCI of 5 is similar to N_{taller} of 10, respectively.

Figure 9.4 gives the results of possible edge effects for silver fir at a given overstory competition index ($OCI=9$ which is similar to $CCF=3.56$). The original mod-

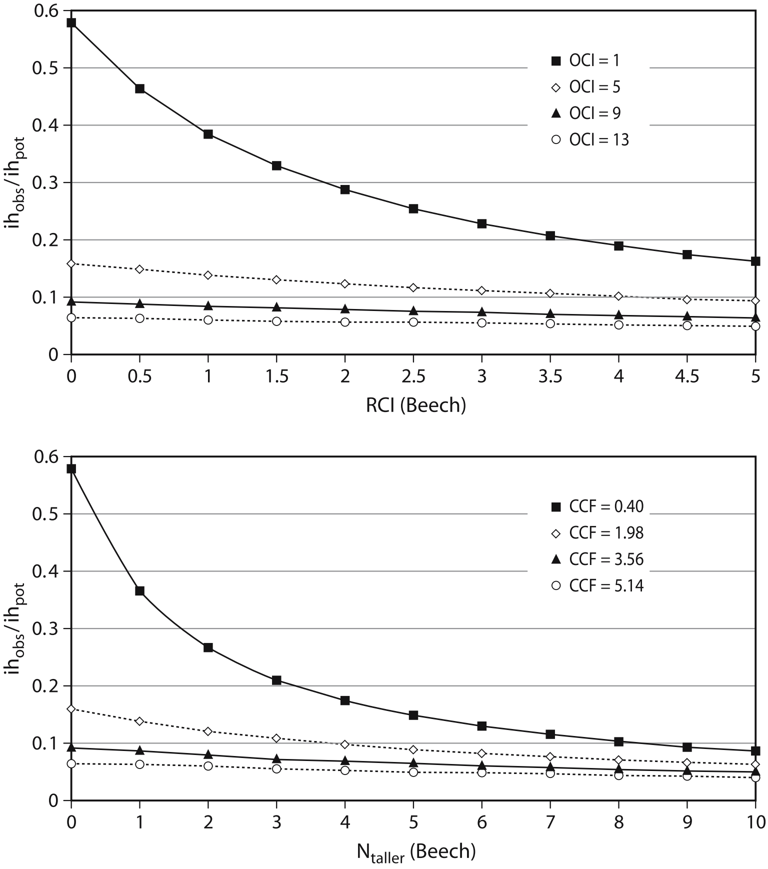

Fig. 9.3. Comparison of the intra- and interspecies competition measure on the resulting relative proportions of the 5-year height increment ih_{ist}/ih_{pot} for beech according to Golser and Hasenauer (1997) and the simplification expressed by the total number of trees taller (N_{taller}) than the subject tree. Four different overstory competition scenarios are presented. Note that an $OCI=1$ is similar to a $CCF=0.4$. No edge-effected incidence of light is assumed

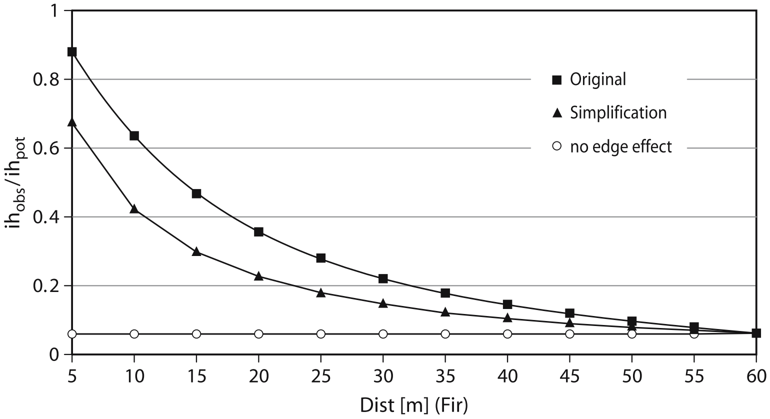

Fig. 9.4. Comparison of the edge-effected incidence of light between the original approach developed by Golser and Hasenauer (1997) and our simplifications, using the sum of the distances (*Dist*) if the stand edge is <60 m in the eight possible directions. The results give the relationship for silver fir at a given overstory competition (*OCI*=9 which is similar to a *CCF*=3.56). Note that the difference between the lines *no edge effect* and *Original* and *Simplification*, respectively indicates the relative improvement or compensation in the height increment due to edge-effected incidence of light

el uses the distance-dependent competition measure *OCI* and *EIL*, the multiplier for assessing edge effects due to incidence of light (Golser and Hasenauer 1997). The adapted simplified version is based on the distance-independent competition measure *CCF* plus the sum of the distances to the stand edge in eight possible directions (N, NO, O, SO, SW, W, NW) if the stand edge is <60 m. Note that the difference between the lines *no edge effect* and *Original* and *Simplification* (Fig. 9.4) indicates the relative improvement or compensation in the height increment ratio due to available edge-effected incidence of light versus no edge effects. The differences in the presented relationships between the approach developed by Golser and Hasenauer (1997) and the adapted version according to Eq. (9.8) may be considered as the loss in accuracy due to simplification. Similar results have been presented for all other tree species (Kindermann 2004).

9.3.3
Juvenile Tree Mortality

Juvenile tree mortality is modeled in two steps: (1) for each species, the maximum density or maximum competition factor (Eq. 9.2) that defines the threshold for starting competition-induced mortality is defined. The individuals beyond this limit die. The smallest trees die first; (2) the second possibility for mortality is induced by random effects, which take into account that trees may also die due to pathogens, snow or other environmental risks (Leak and Graber 1976). For this purpose we use an equally distributed random number between 0 and 1. In Eq. (9.9) x is <0.98 and in Eq. (9.10) x is ≥ 0.98.

$$P_{mort} = \frac{\mathrm{x}}{50}$$

$$P_{mort} = (\mathrm{x} - 0.98) \cdot 50$$

Equations (9.9) and (9.10) are based on the following idea: choosing a random number between 0 and 1 means that half of the trees would die, which is incorrect. If we assume that the average annual randomly induced mortality is 1% (Eq. 9.9), the maximum random mortality will be 2%. This can be interpreted as the density-related random reduction of juveniles. To additionally account for other random effects which deviate from the average random mortality as given by Eq. (9.9) we calculate the mortality according to Eq. (9.10).

9.4
Analyses and Results

In this section we (1) present the final models as they are currently available and used in our tree growth modeling environment, (2) perform the validation analyses, (3) show results of how potential browsing may be addressed, and (4) give some demonstrations and examples of modeling regeneration within uneven-aged mixed species stands using the distance-dependent growth simulator MOSES (Hasenauer 1994). Note that the equations for regeneration assessment validated in this study include only those parameters that entered the models significantly (α=0.05). This is important because if this approach had been calibrated using data from other regions, the resulting significant model parameters may have been different.

9.4.1
Assessing Regeneration

The first model needed to assess regeneration is the probability of regeneration within a 5-year growth period. In Eq. (9.1) the left-hand side of the formulation is a dichotomous variable because only two situations are possible: regeneration yes or no (1 or 0). Such equations are referred to as quality response (QR) models (Cuthbertson et al. 1992). The estimation of coefficients using OLS methods is not applicable since: (1) no normal distribution of the residuals can be assumed, (2) no homogeneity of the variance exists, and (3) it is not assured that the predictions range between 0 and 1.

In such situations the coefficients are estimated with the maximum likelihood (ML) method of the logistic transformation for an existing binomial distribution (Cuthbertson et al. 1992). This method determines the coefficients by maximizing the probability of the occurrence of the dependent values (0 and 1) as it may be derived by the vector of the independent variables. The likelihood of regeneration [P(Y=1)=F(bx)] or no regeneration [P(Y=0)=1–F(bx)] needs to be assessed. The inverse transformation of the density function is commonly referred to as the LOGIT. The final model for assessing the probability of regeneration including all variables and coefficients which entered the model significantly (α=0.05) has the following form (see also Kindermann et al. 2002):

$$p = \frac{1}{1 + e^{0.414 \cdot COMP - 0.0289 \cdot DBH_{max,\,Sp} - 0.0384 \cdot DBH_{max,\,Be} - 0.064 \cdot DBH_{max,\,Fi} - 0.0026 \cdot DBH_{max,\,Ot}}}$$

where p is the probability of regeneration within a 5-year growth period, $COMP$ the competition index as given in Eq. (9.2), and $DBH_{max,Sp}$, $DBH_{max,Be}$, $DBH_{max,Fi}$ and $DBH_{max,Ot}$ are the maximum breast height diameter for spruce, beech, fir and all other species. The 422 inventory plots (Table 9.1) of the University's Experimental Forest were used for calibration.

To validate the developed relationships we employed the 214 remaining inventory plots of the Experimental Forest, the 86 observations from the Hirschlacke as well as the 676 inventory plots from the Limestone National Park (Table 9.1). The results are given in Table 9.5: where Δ (%) gives the difference in percent for pre-

Table 9.5. Results of the validation runs for assessing the probability of regeneration. The data were not used for calibrating the models. *N* Number of sample plots; N_{Reg} number of sample plots with observed regeneration; N_{Model} number of sample plots with predicted regeneration; Δ (%) relative difference between predicted and observed regeneration [$(N_{Model}–N_{Reg})/N_{Reg}$]; *Regen–yes* (%) percentage of correctly classified plots, e.g. on 80.1% of the plots in the experimental forest with regeneration the model also predicted regeneration; *Regen–no* (%) percentage of correctly classified plots with no regeneration; *All* (%) percentage of correctly classified plots with or without regeneration

	Location Experimental Forest	Hirschlacke	National Park
N	214	86	676
N_{Reg}	113	78	500
NModel	121	67	533
Δ (%)	7.1	–14.1	6.6
Regen–yes (%)	80.1	82.1	81.0
Regen–no (%)	70.8	62.5	27.3
All (%)	75.6	80.2	67.0

Table 9.6. Results of the coefficient estimates to assess the species proportion of regeneration if regeneration occurs. $^+$ Significant with $\alpha=0.10$; *COMP* competition index according to Eq. (9.2); *EDGE* edge effect within twice the dominant tree height in one of the eight directions (60 m); $DBH_{max,Sp}$ maximum diameter at breast height for spruce; $DBH_{max,Be}$ maximum diameter at breast height for beech; $DBH_{max,Fi}$ maximum diameter at breast height for fir; $DBH_{max,Ot}$ maximum diameter at breast height for all other species

Variable	Spruce	Beech	Fir	Others
COMP	–0.245	–	0.086^+	–
COMP if EDGE = yes	–	–	–	0.47^+
COMP if EDGE = no	–	–	–	0.03^+
$DBH_{max,Sp}$	0.0007^+	–	–	–
$DBH_{max,Be}$	–	0.0483	–	–
$DBH_{max,Fi}$	–	–	0.57^+	–
$DBH_{max,OT}$	–	–	–	0.0138
$EDGE_{no}$	–	–	–0.90	–1.07
$EDGE_{yes}$	–	–	–1.65	–1.75
Mull	-0.55^+	–1.53	–1.02	1.18
Mull-moder	-0.03^+	-0.56^+	-0.22^+	0.37^+
Moder	0.64^+	-0.58^+	–	–

dicted versus observed regeneration; *Regen–yes* (%) the number of correctly classified plots with predicted regeneration on plots with observed regeneration; *Regen–no* (%) the number of correctly classified plots with predicted no regeneration on plots with no regeneration; and *All* (%) the relative proportion of correctly classified plots with and without regeneration.

Equation (9.4) gives the species proportion. With the data from the University's Experimental Forest (Table 9.1) for each species a separate LOGIT model using the ML estimation method was calibrated. The results of the model predictions for spruce, beech, fir and all other species are given in Table 9.6. The validation results by species are given in Table 9.7. On plots with regeneration *N*, we compare the predicted N_{Model} versus observed plots with regeneration N_{Reg}, the relative differences between predicted and observed plots with species regeneration Δ (%), the percentage of correctly classified plots with *Reg–yes* (%) or with-

Table 9.7. Results of the model validation predictions for assessing the species proportion on a given plot with regeneration. The data were not used for calibrating the models. *N* Number of sample plots with regeneration; N_{Reg} number of sample plots with observed regeneration of the species; N_{Model} number of sample plots with predicted regeneration of the species; *Δ (%)* relative difference between predicted and observed regeneration of the species [$(N_{Model}-N_{Reg})/N_{Reg}$]; *Regen–yes* (%) percentage of correctly classified plots, e.g. on 60% of the plots with spruce regeneration the model has predicted spruce regeneration; *Regen–no* (%) percentage of correctly classified plots where no spruce regeneration occurs; *All* (%) percentage of correctly classified plots with or without spruce regeneration

Location	Species	N	N_{Reg}	N_{Model}	Δ (%)	Reg–yes (%)	Reg–no (%)	All (%)
Experimental Forest	Spruce	113	60	53	-11.7	60.0	67.9	63.7
	Beech	113	72	85	18.1	83.3	39.0	67.3
	Fir	113	55	19	–65.5	23.7	89.6	57.5
	Others	113	69	44	–36.2	44.9	70.5	54.9
Hirschlacke	Spruce	78	77	43	–44.2	55.2	100.0	59.9
	Beech	78	7	58	728.6	85.7	25.8	30.6
	Fir	78	47	44	–6.4	61.7	49.6	56.2
	Others	78	3	0	–100.0	0.0	100.0	96.5
National Park	Spruce	500	255	394	54.5	80.4	22.9	52.2
	Beech	500	308	317	2.9	71.4	49.5	63.0
	Fir	500	181	73	–59.7	25.4	91.5	67.6
	Others	500	467	273	–41.5	54.6	45.4	54.0

out *Reg–no* (%) of a given species regeneration as well as for all correctly classified plots *All* (%).

The last step in the assessment of regeneration is the estimation of its density. Following Eq. (9.5) the multiple linear regression of the formulated Poisson model resulted in significant (α=0.05) coefficients for

$$in(n/m^2) = -0.0037 \cdot DBH_{max,Sp} + 0.0099 \cdot DBH_{max,Be} + 0.0060 \cdot DHD_{max,Fi} \\ +0.0051 \cdot DBH_{max,Ot} - 0.56 \cdot EDGE_{no} - 0.69 \cdot EDGE_{yes}$$

where $ln(n/m^2)$ is the logarithm of all new juveniles in the height class ≤ 20 cm/m^2, $DBH_{max,Sp}$, $DBH_{max,Be}$, $DBH_{max,Fi}$ and DBH_{maxOt} are the maximum diameters at breast height for spruce, beech, fir and all other tree species (in cm), and $EDGE_{no}$ and $EDGE_{yes}$ are the dummy variables for an existing stand edge in one of the eight directions and within the limit of twice the dominant stand height (60 m).

The validation of this density function by comparing predicted versus observed regeneration densities per square meter for the inventory plots revealed the following results: (1) the 113 inventory plots with observed regeneration at the University's Experimental Forest exhibited a significant relationship (r=0.30, t-value=3.4 > $t_{\alpha=0.05,\ FG=112}$=1.96); and (2) the 500 inventory plots with observed regeneration from the Limestone National Park also showed a significant relationship between predicted and observed juvenile tree densities (r=0.15, t-value=3.3 > $t_{\alpha=0.05,\ FG=499=1.96}$).

9.4.2
Height Increment Predictions

Since the expected reduction in accuracy is relatively small between the distance-dependent incremental height growth model and the distance-independent model (Hasenauer and Kindermann 2002) we next validated the simplified height increment model by comparing predicted versus observed 5-year height increments using the height increment observations from the inventory plots of the University's Experimental Forest (Table 9.2). The species-specific parameter estimates of the corresponding height increment models, which were developed using height increment data from our permanent research plots (Table 9.2), are listed in Table 9.8.

Table 9.8. Coefficient estimates for the species-specific juvenile tree height increment models. $^+$ Significant with α=0.10; *CCF* crown competition factor according to Kraijecek et al. (1961); N_{taller} number of trees taller than the subject tree; *SUMD* sum of the distances to the stand edge

Variable	Spruce	Beech	Fir	Scots pine
CCF *a*	0.039	0.0264	0.0342	0.0379
N_{taller} *b*	0.740	0.870	1.740	0.060$^+$
SUMD *c*	–0.066	–0.057	–0.091	–0.105
Number of observations	589	456	303	62
Standard error (m)	0.17	0.34	0.20	0.15

We started the validation using a paired t-test to test whether significant differences (α=0.05) between predictions and observations may exist as well as the expected error range of the model predictions. For this purpose the confidence, prediction and tolerance interval (Reynolds 1984) were determined for each species and height class. The confidence interval (*CI*) for the mean of the differences can be used to evaluate the discrepancies between expected differences and the mean estimator, while the prediction interval (*PI*) assesses the range of each single difference between the predicted vs. observed height increments for future predictions (for instance, at a 95% or 1-α confidence level). The tolerance interval (*TI*) provides the limit that contains a specified proportion (e.g. 95%) of the distribution of the differences when the model is used repeatedly (Reynolds 1984). The results of the confidence, prediction and tolerance interval for each species and height class are presented in Table 9.9. For example, the statistics for spruce in the height class ≤ 20 cm can be interpreted as follows: with a probability of 95% we can be confident that no bias in the height increment predictions exists because the mean of the differences will be between –0.02 and +0.01 m. With a probability of 95%, the errors in the future height increment predictions will be between –0.16 and +0.15 m and if the equation is used repeatedly 95% of all errors in this height class will be between –0.18 and +0.17 m.

9.4.3
Assessing Browsing Impacts

One of the main threats to regeneration in central Europe is deer damage due to browsing. Besides habitat suitability issues, deer density is the key factor whether browsing impacts are considered as damage or not. In this section we will provide a simple guideline characterized by the mean stem number per height class and species for different levels of deer damage as it may be assessed by the number of damaged juvenile trees (terminal leader) versus the total number of juveniles within a given height class. This allows us to compare the change in the mean stem number by height class according to the proportion of damaged terminal leaders.

The data set used consists of 66,865 individual juvenile tree observations from ÖbfAG (Austrian Federal Forest Company) across Austria. The idea is to provide estimates of the stem number reduction due to deer damage according to the following criteria: if we know for a given height class and species the total stem number at a given percentage of damaged juveniles (from field observations), we can assess the mean impact of deer damage as it may affect the establishment of juveniles by species. Figure 9.5 gives the mean results across all available data by height class and proportion of damaged terminal leaders for Norway spruce, common beech, silver fir and maple. These numbers give the means by damage class.

Next we were interested in whether species mixture affects browsing. Possible variation would suggest that certain tree species within a mixed regeneration may be more attractive for browsing versus others and this may be different according to the dominance of the species.

Table 9.9. Mean of the differences between predicted and observed height increment rates by tree species and height class. The confidence interval (*CI*, α=0.05) gives the mean of the differences between predicted and observed 5-year height increment, the prediction interval (*PI*, α=0.05) indicates the range of the differences among the predicted vs. observed height increment, and the tolerance interval (*TI*, γ=0.95 and α=0.05) provides the limit that contains a specified proportion (e.g. 95%) of the distribution of the differences when the model is used repeatedly (Reynolds 1984). * Significant with α=0.05; *n* number of trees; *CI* confidence interval (α=0.05); ih_{obs} mean observed 5-year height increment; *PI* predictions interval (α=0.05); D_i mean difference; *TI* tolerance interval (γ=0.95 and α=0.05); s_D *standard deviation*

Species	Height class (cm)	*n*	$\overline{ih}_{obs}$ (m)	$\overline{D}_i$ (m)	s_D (m)	*t*-val.	*CI* (m)	*PI* (m)	*TI* (m)
Spruce	< 21	155	0.11	–0.04	0.08	1.97	–0.02 to 0.01	–0.16 to 0.15	-0.18 to 0.17
	21–50	38	0.33	–0.02	0.13	2.02	–0.07 to 0.02	–0.31 to 0.26	–0.37 to 0.33
	≥ 51	17	0.81	–0.12	0.22	2.11	–0.24 to –0.01*	–0.61 to 0.36	–0.77 to 0.51
Fir	< 21	66	0.06	0.01	0.06	1.99	0.00 to 0.03	–0.12 to 0.15	–0.14 to 0.17
	21–50	5	0.28	0.04	0.11	2.77	–0.10 to 0.19	–0.32 to 0.41	–0.56 to 0.65
	≥ 51	1	No statistical analyses possible						
Beech	< 21	304	0.07	0.01	0.19	1.96	–0.01 to 0.40	–0.38 to 0.53	–0.41 to 0.43
	21–50	105	0.31	–0.06	0.32	1.98	–0.12 to 0.00	–0.70 to 0.58	–0.78 to 0.66
	≥ 51	80	0.82	–0.20	0.38	1.99	–0.29 to –0.12*	–0.99 to 0.57	–1.09 to 0.68

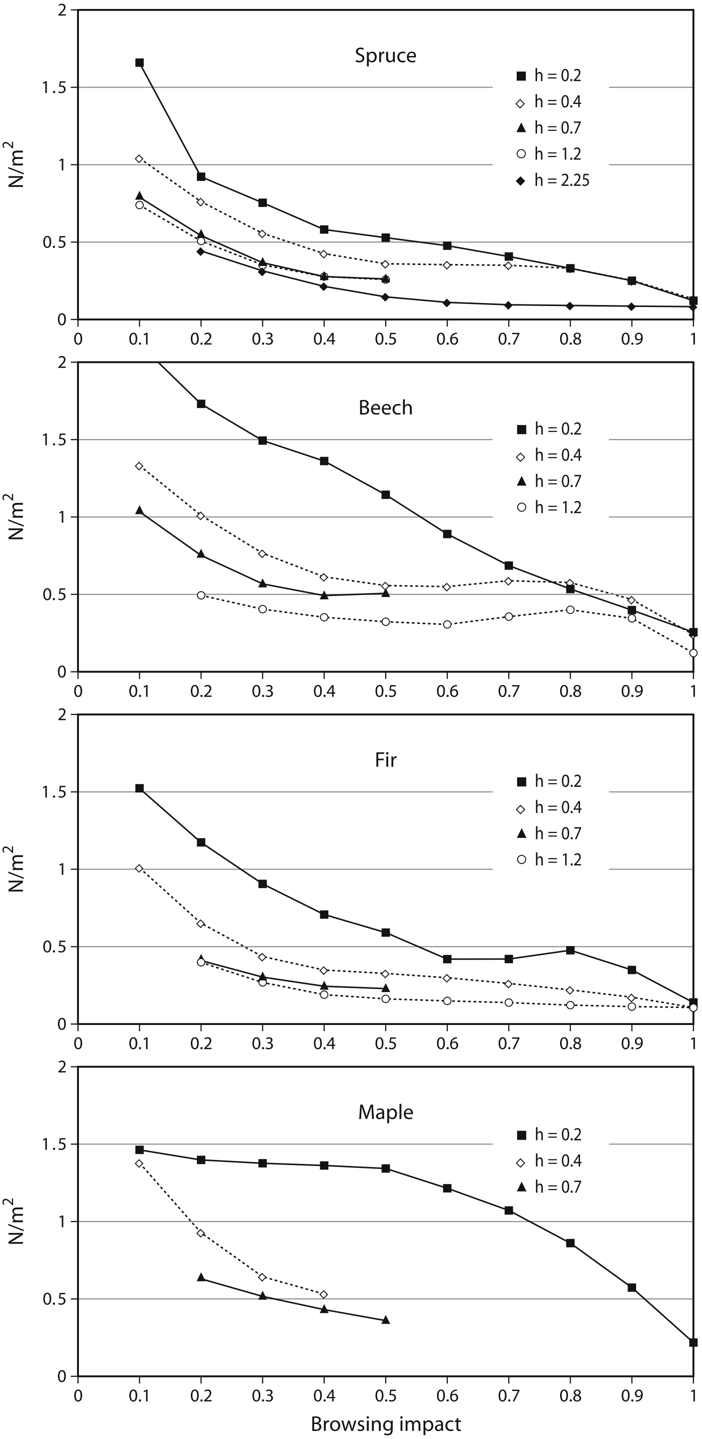

Fig. 9.5. Stem number (*N*) reduction versus deer damage percentage by height class. Deer damage is expressed by the ratio of juvenile trees with a damaged terminal leader to the total number of juveniles

9.5
Discussion and Conclusion

The regeneration models described and validated in this study explicitly assess the probability of regeneration, species mix, density, juvenile tree growth and mortality within a 5-year growth period. Such information is needed if no regeneration information is available and if forest growth simulators are applied for silvicultural scenario analyses. The equations for predicting the probability of regeneration, species mix and density were developed for Norway spruce, silver fir, common beech and for 'all other trees' using only data from the University's Experimental Forest in the Rosalien Mountains. Since not all possible site conditions were found in this area, only a limited number of humus, soil and vegetation types entered the model formulations significantly ($\alpha=0.05$). This is important because if data from other regions are used, the site variability (e.g. humus, soil and vegetation types) and its influence on the regeneration establishment, species mix and density will be different. Nevertheless, the general approach as it is presented in this study is simple, robust and can be easily adjusted for any other regeneration data set.

The probability of regeneration within a 5-year growth period (Eq. 9.11) depends mainly on the overstory competition and the largest tree by species. Although this model was calibrated with inventory data from the University's Experimental Forest, the validation results using data from this forest but also from two different regions – the Hirschlacke and the Limestone National Park – suggest that consistent predictions of the probability of regeneration establishment can be expected (Table 9.5). The difference between the number of plots with predicted and observed regeneration varied only between −14.1 and 7.1% (Table 9.5) and no systematic under- or overestimation was detectable. More important, the percentage of correctly classified plots (with or without regeneration), an indication of the random error component in the resulting predictions, exhibited approximately 70% correctly classified plots [with or without regeneration – see *All* (%) in Table 9.5], suggesting a relative small random error component and thus a stable model approach.

An important aspect of our work is to demonstrate the problem solving potential. In Fig. 9.6 a typical stand situation as it may be generated within the tree growth model MOSES is demonstrated.

Figure 9.7 illustrates how the regeneration tool may be used within a tree growth modeling environment to test silvicultural management in the University's Experimental Forest: first, the probability of regeneration according to the current overstory competition is predicted using Eq. (9.11). Then a silvicultural management scenario is assumed which reduces overstory competition across all sites by 30%. Next, with the tree growth model the overstory stand situation for the two different management types is simulated for 10 years. Finally, again Eq. (9.11) is applied to predict the regeneration probability according to (1) the variant no change in the overstory competition and (2) the probability of regeneration 10 years after 30% overstory removal (Fig. 9.7).

In the model of species proportion (Eq. 9.4 and Table 9.6), overstory competition, the largest tree by species but also the humus type and a dummy variable

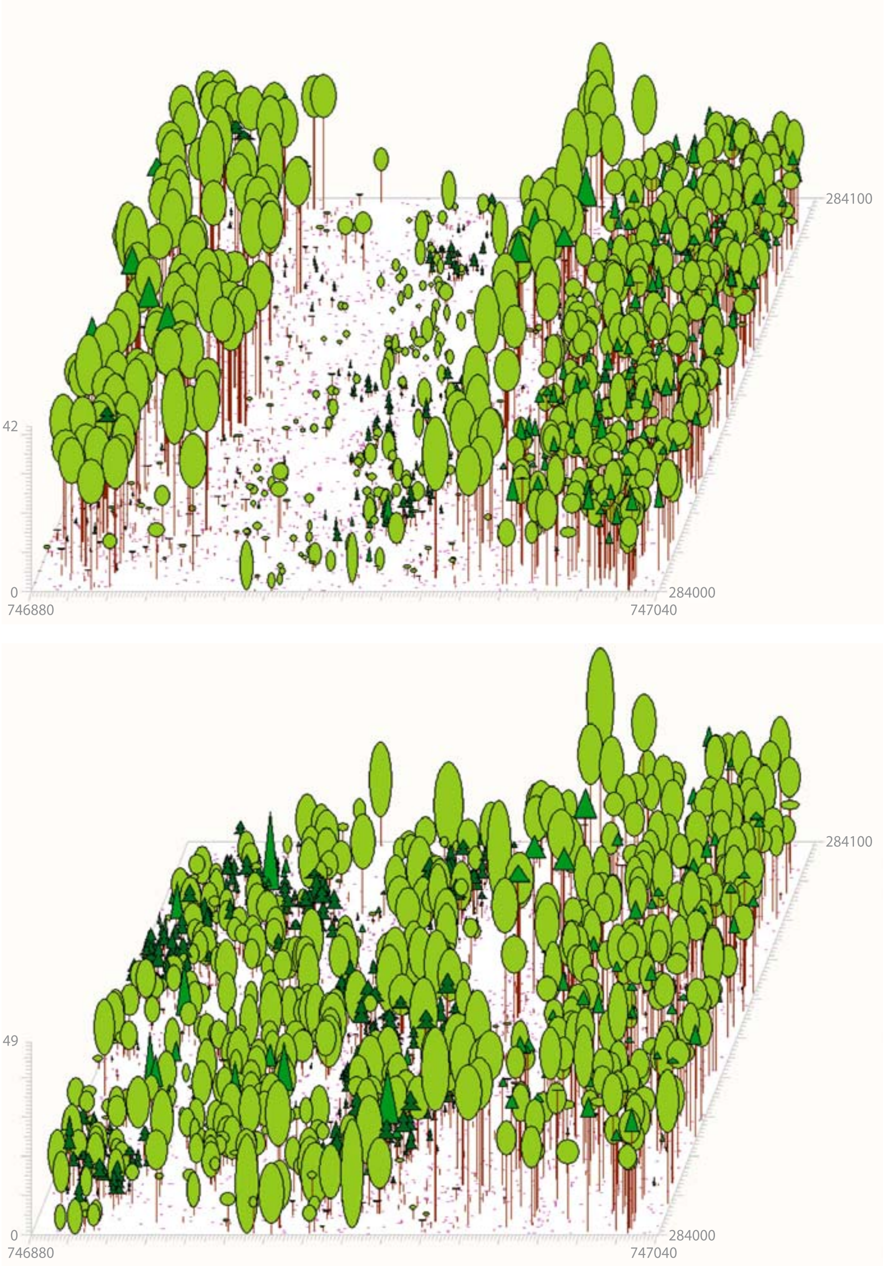

Fig. 9.6. Visualization examples of the implemented regeneration module in the tree growth modeling environment MOSES. The theoretical framework may be recalibrated for different locations and may be implemented in any other tree growth modeling environment

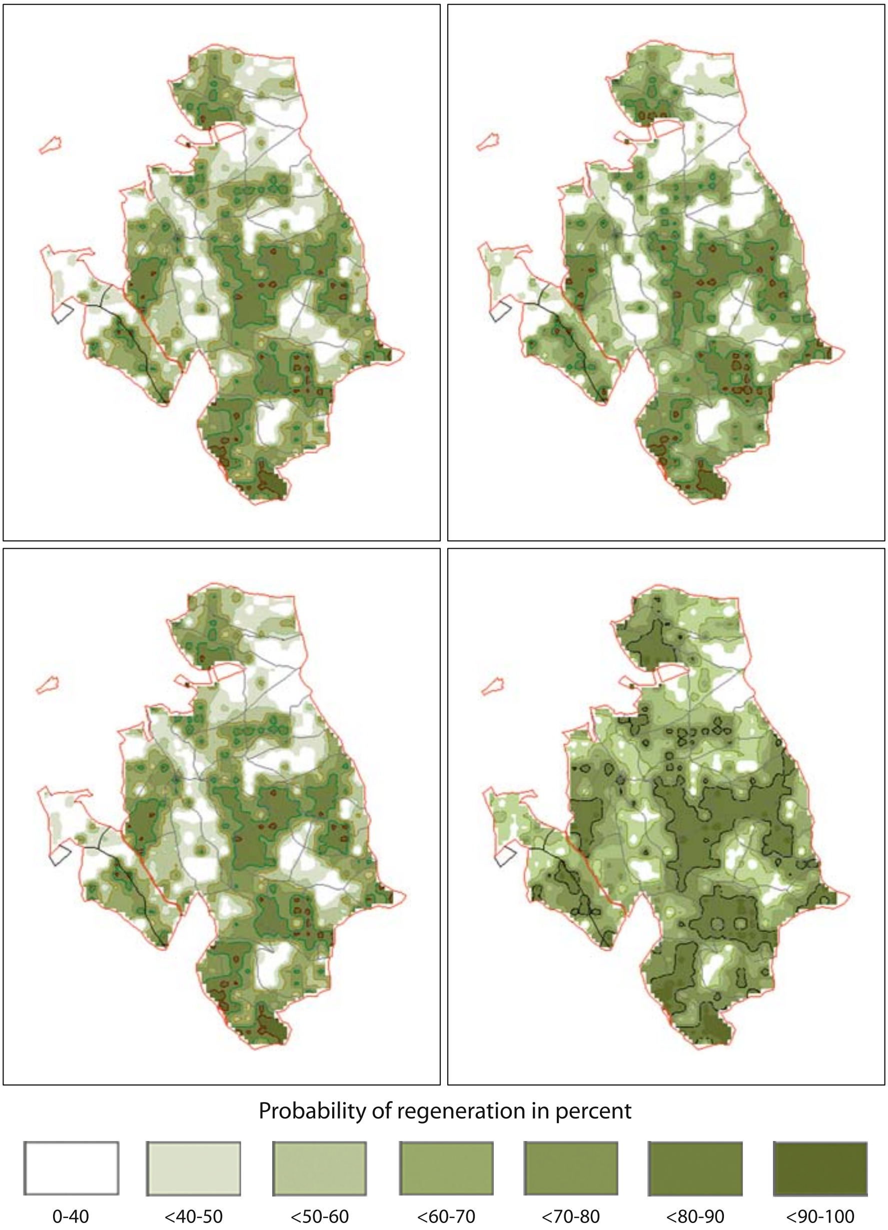

Fig. 9.7. Results of the regeneration assessment in combination with the tree growth model, which was used to assess the change in the overstory according to different management assumptions. The *upper left plot* gives the estimated current probability of regeneration. The *upper right plot* would be the average situation if all stands had their stocking density reduced by 30% compared with the current situation. The *lower left and right plots give the change in the probability of regeneration after 10 years according to variant (1) – no change in density – and variant (2) – a 30% reduction in stand density – respectively.*

for the edge-effected incidence of light with its compensatory effect for overstory competition are important (Flemming 1962; Canham et al. 1990). Even though the variability of site and vegetation types (with the exception of humus type) is relatively small and hence the likelihood is low that they are significant ($\alpha=0.05$), these site conditions are important for the correct prediction of regeneration. This confirms findings by Gasch (1995), which report a significant impact of aspect, slope, site and vegetation type on the species mix.

The validation results (Table 9.7) indicate a higher variation and a lower percentage of correctly classified plots versus the regeneration probability predictions; however, with more than 50% correctly classified plots the models are stable and useful. Only if the number of plots for a given species and region was very low (e.g. beech and other species from the Hirschlacke site) would the random error increase (Table 9.7).

The simplification of the height increment growth model (Hasenauer and Kindermann 2002) to predict the 5-year height growth produced consistent and unbiased results since none of the confidence, prediction and tolerance intervals by species and height classes exhibited biased results (Table 9.9). Only for spruce in the height class ≥51 cm did the *CI* suggest a significant difference. Compared with the *CI* using the original model with the distance-dependent competition indices (Golser and Hasenauer 1997) the error range is slightly but not systematically different. Thus, the change from distance-dependent to -independent competition indices and the replacement of the inter- and intra-species competition indices (Golser and Hasenauer 1997) by the sum of all juvenile trees taller than subject tree did not lead to a systematic deviation in the 5-year growth increment predictions. Similar findings have been reported by Biging and Dobbertin (1995) who compared various competition indices and their influence on the 5-year height increment growth. Their results showed that no major differences between distance-dependent and -independent indices exist.

A major focus of our work was the integration and assessment of the compensatory effects on competition due to edge-effected incidence of light and its impact on juvenile tree growth. The introduced simplification in accounting for edge effects by summing up the distances to the stand edge versus the original approach (Golser and Hasenauer 1997; Hasenauer and Kindermann 2002) did not result in any systematic deviation from the expected predictions.

Our data do not include repeated regeneration inventories. Thus, this study does not address the temporal issues such as the question how long it will take until a silvicultural management operation has lead to a certain regeneration result. Such information would allow us to assess time horizons according to certain management practices (= dynamic components). In 2004 we started with the first remeasurement of the regeneration inventory at the University's Experimental Forest; appropriate data for studying temporal effects will be available soon.

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Evaluating Management Regimes and Their Impact on Commercial Timber Supply Using an Individual-Tree Growth Model and Scenario Analysis

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Abstract. In this chapter we demonstrate different management regimes and their impact on commercial timber supply using the individual-tree growth simulator PrognAus for Windows 2.2. We thereby address two frequently discussed scenarios: (1) the conversion of even-aged pure species stands into uneven-aged mixed species stands and (2) how to deal with a forest stand whose trees are damaged by bark peeling. For both scenarios we show how growth and yield, timber supply and commercial assortments change under different management regimes. In addition we provide an economic evaluation of these management regimes. The results of our demonstration runs indicate that a thoroughly developed individual-tree growth simulator is an excellent tool for scenario analysis.

10.1
Introduction

The management of forests has a long tradition in European forestry (Richter 1996). However, the reasons why forests are managed have clearly changed. While in the past forest management was mainly focused on timber production, recent management strategies emphasise the multiple-use concept of forests, which is characterised by timber production and by the conservation of species and wildlife habitat. Forests that are managed according to the multiple-use concept are renewable resources producing essential raw material for several purposes. They are also rich in wildlife habitat and species diversity and may therefore contribute to increased ecosystem stability (Söderbergh and Ledermann 2003).

For many forest managers uneven-aged mixed species stands are considered to comply better with the requirements and restrictions of the multiple-use management concept. Hence, it is not surprising that the national forest inventories of some central European countries show an increasing proportion of uneven-aged mixed species stands (Smaltschinski 1990; Schieler and Schadauer 1993; Monser-

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Growth Models for Europe

ud and Sterba 1996), indicating that forest managers and forest owners are willing to convert even-aged pure species stands into uneven-aged mixed species stands. This also supports the results of Sagl et al. (2000), who reported that more than 80% of interviewed forest managers intend to increase or at least to retain the proportion of uneven-aged mixed species stands in their forest enterprises. However, Sagl et al. (2000) further reported that all of the interviewed forest managers referred to profit as the basic forest management objective, indicating that commercial timber supply is still the major incentive in forest management. This is especially true if timber production is the main source of the forest owner's income. Hence, many forest owners and forest managers are only willing to convert even-aged pure species stands into uneven-aged mixed species stands if a sustainable income is guaranteed during and after the conversion period. Furthermore, changing the forest management regime affects not only the financial issues of individual forest enterprises but also the timber industry if the change in the management strategy occurs on a large (regional) scale. Therefore, in changing the management regime, it is useful to predict its impact on timber production and revenues. From an economic point of view, we are faced with the following questions:

1. How does growth and yield change under different management regimes?
2. Does the amount of timber supply change ? If yes, to what extent?
3. How do commercial assortments change under different management regimes?

In this chapter we demonstrate different harvesting scenarios and their impact on commercial timber supply, thereby addressing two scenarios that are often discussed among forest practitioners: (1) the conversion of even-aged pure species stands into uneven-aged mixed species stands and (2) how to deal with a forest stand whose trees are damaged by bark peeling. By means of these scenarios (CONVERSION-Demo and PEELING-Demo) it is shown how an individual-tree growth simulator can be used for decision support in answering questions that are relevant to forest managers and forest owners.

10.2
The Individual-Tree Growth Simulator

The crucial point at the beginning of each scenario analysis is the selection of the appropriate growth simulator. All of the existing simulators have some particular merits, making them more or less suitable for a specific application. Hence, in this regard, special care is appropriate. In order to evaluate different management regimes with regard to economical aspects, an individual-tree growth simulator is a very useful tool if the following conditions are met: (1) it must provide the possibility to simulate different stand treatment and forest management regimes, (2) the output must be in terms of commercial assortments, specifically in volume per size and quality class and (3) the simulator must include models to predict stem and wood quality of standing trees in order to reflect the influence of different management regimes on the log quality distribution.

In our demonstration we decided to use the individual-tree growth simulator PrognAus for Windows 2.2. The model predicts basal area and height increment (Monserud and Sterba 1996; Schieler 1997; Hasenauer 2000), mortality (Monserud and Sterba 1999) and ingrowth (Ledermann 2002a). It also predicts stem damage caused by harvesting and skidding operations, bark peeling by red deer (*Cervus elaphus* L.), rockfall in steep terrain and a tree's probability of belonging to a specific log quality class (Sterba et al. 2003). Moreover, it has assortment tables (Sterba et al. 1986; Eckmüllner and Sterba 2002) and the needed thinning and harvesting algorithms (Söderbergh and Ledermann 2003). Thus, the model fully complies with the model capabilities required for a comprehensive economic evaluation – usually the main issue in the decision-making process of forest managers and forest owners.

Because PrognAus for Windows 2.2 is a distance-independent growth simulator the model can be set up to accept either conventional inventory data [e.g. data from variable radius sample plots (Bitterlich 1948) or fixed radius sample plots], or data from research plots and entire stands. Due to a method introduced by Ledermann and Eckmüllner (2004), the model can also project small sample plots during long-term simulations. The ability to set up the simulator on inventory data is particularly important because we wanted to demonstrate the conversion strategy not only for a particular stand, but also at the level of a forest management district, thus covering several hundreds of hectares. For such a large area the only way to obtain individual-tree data efficiently is the application of a method of plot sampling, thus requiring this specific property of the individual-tree growth simulator PrognAus for Windows 2.2.

10.3
Model Calibration

When applying an individual-tree growth simulator to a specific region, it is possible that the real growth conditions regarding site quality are not well represented by the site variables included in the growth model. Hence, whenever possible, an individual-tree growth simulator should be calibrated before scenario analyses are performed. However, this requires repeated observations of individual trees, made available, for example, by a continuous forest inventory. Using these repeated observations we can calculate the basal area increment (BAI) of those trees remaining in the stand. We also know which trees were removed from the stand and which trees died during the observation period. By providing an individual-tree growth simulator with this information, i.e. which tree has to be removed at what time, it is possible to imitate the growth conditions with regard to competition. The predicted BAI of the remaining trees can then be compared with the observed BAI obtained from the repeated observation of the continuous forest inventory. For each tree species k the mean ratio MLP_k can be calculated as follows:

$$MLP_k = \frac{1}{N}\sum_{i=1}^{N}\frac{BAI_{observed_i}}{BAI_{predicted_i}}$$

where *N* is the number of sample trees for species *k*.

In the course of a simulation run the predicted BAI of each individual tree will then be multiplied by the specific multiplier MLP_k at the end of each 5-year projection cycle. Because the BAI sub-model in PrognAus for Windows 2.2 is a log-linear multiple regression model, this approach amounts to an adjustment of the intercept of the respective species-specific growth function.

10.4
Defining Stand Management Objectives and Management Regimes

The stand management objective describes a stand with regard to species composition and stand structure (e.g. diameter distribution) at a specific point in time, which can be, for example, the end of the rotation period or the end of a special treatment phase. This very general definition of the stand management objective can also be extended by some desired stand characteristics or tree attributes (e.g. a specific volume per hectare, a tolerable proportion of damaged trees), and can also be formulated for a larger area, for example, an any-aged continuous cover forest ("Plenterwald"). However, referring to management objective rather than to stand management objective makes more sense in this case because the usual definition of a stand, which is based on the vegetation, is not appropriate in an any-aged continuous cover forest. A clearly defined (stand) management objective is important for two reasons: (1) it is closely related to the management regime that on its own part determines the appropriate thinning and harvesting algorithms to be applied and (2) it facilitates the evaluation of the different management alternatives.

10.5
Evaluation of Management Alternatives

Evaluating different management alternatives is one of the most important procedures in scenario analyses. At this step it must be determined whether the defined management objective was achieved under a specific management regime. Specifically, the results of a given scenario must be checked if they fulfil all the criteria that were defined in the management objective.

Nevertheless, such analyses are not sufficient for an economic evaluation. We also have to consider that additional costs may arise when we follow a specific management regime. If this is the case, then we have to consider these additional costs as some kind of investment. Hence, we must compare the costs of this investment with the added value gained at that time when the decision on this investment has to be made. According to Schulte and Buongiorno (1998), the net present value (NPV) is an appropriate economic criterion for the comparison of different management regimes. The NPV is the value of harvests over a long time horizon, net of the costs and discounted to the present. From an economic perspective the management regime with the largest (positive) NPV should be selected:

$$NPV = \sum_{i=1}^{C} \frac{CM_i}{(1 + p/100)^{TP_i}}$$

where:

C the number of cuttings;
CM_i revenues net of costs (contribution margin) of the i^{th} cutting;
TP_i the time period from the present to the i^{th} cutting (in years);
p the interest rate per year (in %).

In order to calculate the contribution margin (CM=revenues minus costs) timber prices with regard to size and quality classes rather than average prices are needed. This is for the following reason: if there is only a weak impact on commercial timber assortment, this impact can hardly be detected if average prices are used. For our demonstrations we used the timber prices given in Table 10.1. However, due to their small proportion, we used the prices of Norway spruce also for white fir and Scots pine. For the same reason, we applied the prices of beech to all other broadleaved species.

However, not only timber prices but also the costs of felling and skidding are relevant for the calculation of CM. Using the models of Daxner et al. (1999) and current wages of forestry employees, we developed a simple function for estimating the costs of felling and skidding dependent on the quadratic mean diameter of the harvested trees (Fig. 10.1).

Although we know that both timber prices and costs of felling and skidding change over time, they were held constant as this was done in similar analyses (e.g. Schulte and Buongiorno 1998). Using constant timber prices is mainly due to the fact that prices cannot easily be predicted because of changing markets owing to several reasons, for example, large-scale natural disturbances such as windthrow, snow breakage or bark beetle attacks.

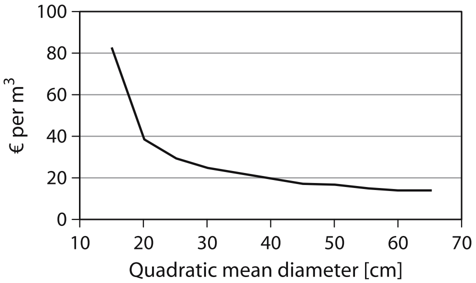

Fig. 10.1. Costs of harvesting (felling and skidding) depending on the quadratic mean diameter of the harvested trees

Table 10.1. Timber prices (EUR m^{-3}) used in the economic evaluation of the different management regimes. *A* best quality; *B* medium quality; *C* worst quality

Tree species	Quality	Saw timber by size class (cm) 20–24	25–29	30–34	35–39	40–49	50–59	60–69	70–79	>79
Norway spruce	A	104	126	131	142	142	142	142	142	142
	B	58	70	73	79	79	79	79	79	79
	C	48	60	63	69	69	69	69	69	69
	Pulpwood	32	32	32	32	32	32	32	32	32
Beech	A	65	83	95	116	131	138	146	150	150
	B	54	58	68	76	83	89	106	110	110
	C	33	36	40	43	47	48	51	51	51
	Pulpwood	30	30	30	30	30	30	30	30	30
Maple	A	108	127	145	165	185	220	250	280	280
	B	56	65	90	105	120	135	150	165	165
	C	32	35	55	60	70	75	85	90	90
	Pulpwood	30	30	30	30	30	30	30	30	30

10.6
CONVERSION-Demo

10.6.1
Data

Input data for this demo example came from the continuous forest inventory of the forest management district Sonnenwald (*Prämonstratenser monastery Schlägl*). The data set was comprised of 159 permanent sample plots with 1,454 repeatedly observed sample trees, which were recorded by variable radius plot sampling (Bitterlich 1948) using a basal area factor of 4 m^2 ha^{-1}. The BAI model of the individual-tree growth simulator PrognAus for Windows 2.2 was calibrated to the regional growth conditions by calculating species-specific multipliers (Table 10.2). In setting up the simulator on the initial data in 1988, each individual

Table 10.2. Multipliers (*MLP*) used in the basal area increment (BAI) model to calibrate the individual-tree growth simulator PrognAus for Windows 2.2 to the regional growth conditions of the forest management district Sonnenwald. s^2 variance; *n* number of observations

Tree species	MLP	s^2	n
Norway spruce (*Picea abies* L. Karst.)	0.92	0.64	1002
White fir (*Abies alba* L.)	0.78	0.69	25
Scots pine (*Pinus sylvestris* L.)	1.28	1.17	7
Beech (*Fagus sylvatica* L.)	0.42	0.06	5
Maple (*Acer pseudoplatanus* L.)	1.16	2.37	135
Other broadleaved trees	0.45	0.23	17

sample plot was simulated for a period of 120 years, applying two different management regimes. For the sake of evaluation and interpretation, the results were aggregated to the level of the entire forest management district.

10.6.2
Stand Management Objective

All stands of the forest management district Sonnenwald should be converted from even-aged into uneven-aged forest stands aiming for a negative exponential diameter distribution, the equilibrium state of an any-aged continuous cover forest ("Plenterwald"). The volume should be 350–400 m^3 ha^{-1} and the tree number 500–600 ha^{-1}. A specific species composition is not desired.

10.6.3
Management Regimes

In this demo example we tested two different management regimes for their ability to achieve the defined management objective. The regular harvesting strategy in the management district Sonnenwald is the diameter-limit cutting system according to Reininger (2000). This harvesting strategy is characterised as follows: in stands that are older than 100 years all trees above 45 cm in breast height diameter (DBH) should be cut, while stands younger than 100 years should be thinned from above. Because diameter-limit cutting is considered to be a strategy to convert even-aged into uneven-aged stands, it was obvious to test whether the defined management objective can be achieved. Although the definition of this harvesting strategy is quite clear, it can be possible that the actual harvesting strategy does not fully conform to the regular one. Therefore, we used the harvesting algorithm developed by Ledermann (2002b). This algorithm was also derived from the continuous forest inventory of the management district Sonnenwald, and clearly depicted the recently applied harvesting strategy, specifically the tree selection preferences for harvesting.

The second alternative of the management regime in the CONVERSION-Demo is the application of a standard equilibrium curve. In an any-aged continuous cover forest ("Plenterwald") this equilibrium curve is represented by a negative exponential diameter distribution. Through comparing the actual diameter distribution with the standard equilibrium curve, it can be seen from which diameter classes trees have to be removed (Söderbergh and Ledermann 2003). In our demonstration, the standard equilibrium curve was calculated according to Cancino and Gadow (2002) based on a q-value of 1.3, a residual stem number of 45 trees ha^{-1} in the largest DBH class of 49 cm and a class width of 8 cm. This equilibrium curve was applied in stands older than 100 years. In stands younger than 100 years, the slope of the applied stem number–diameter curve was steeper, but was decreased algorithmically during the simulation until the stand reached

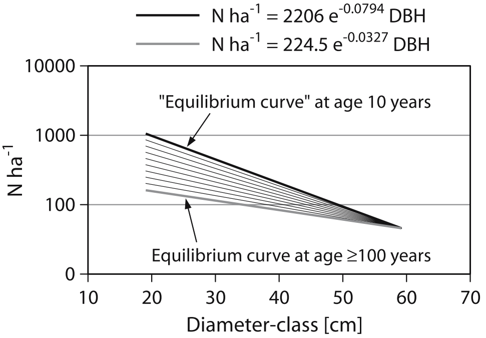

Fig. 10.2. Second alternative of the management regime in the CONVERSION-Demo for a forest stand at age 10 years. *Thin lines* represent equilibrium curves at age 20, 30, 40, etc. years

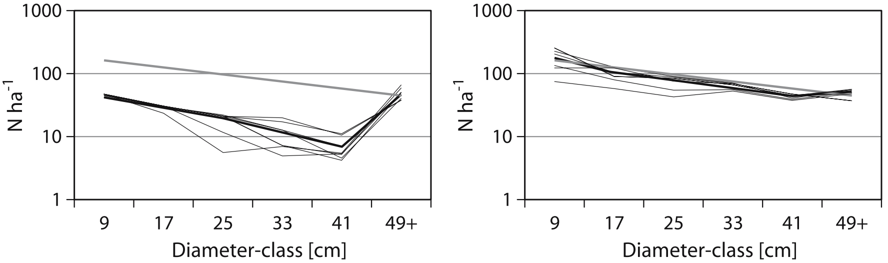

Fig. 10.3. Diameter distributions at the end of a 120-year simulation period for the entire management district Sonnenwald. Continuation of the recent management regime (*left*) and applying a standard equilibrium curve (*right*). *Thick grey line* indicates the standard equilibrium curve, *bold black line* depicts the actual DBH distribution. *Thin lines* represent DBH distributions in the strata of the former age classes

the age of 100 years. At this age the slope was equal to the slope of the equilibrium curve and therefore kept constant until the end of the simulation run. The concept of this harvesting strategy is presented in Fig. 10.2, where it is applied to a 10-year-old stand.

10.6.4
Evaluation of the CONVERSION-Demo

At the end of two 120-year simulation runs the evaluation of the different management regimes applied in the CONVERSION-Demo was based on the comparison of the final DBH distributions, the development of the growing stock, and the development of the annual increment and removals. The results of the simulation runs presented in Figs. 10.3–10.6 indicate that the desired DBH distribution of an any-aged forest ("Plenterwald") cannot be obtained if the recent harvesting strategy is continued. This is due to the fact that there are too many trees in the highest DBH class, resulting in a very low total tree number per hectare of only

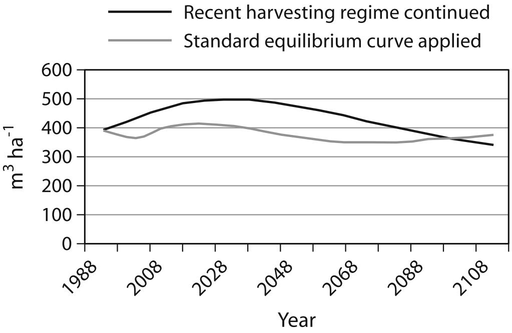

Fig. 10.4. Development of the growing stock in the management district Sonnenwald during a simulation period of 120 years

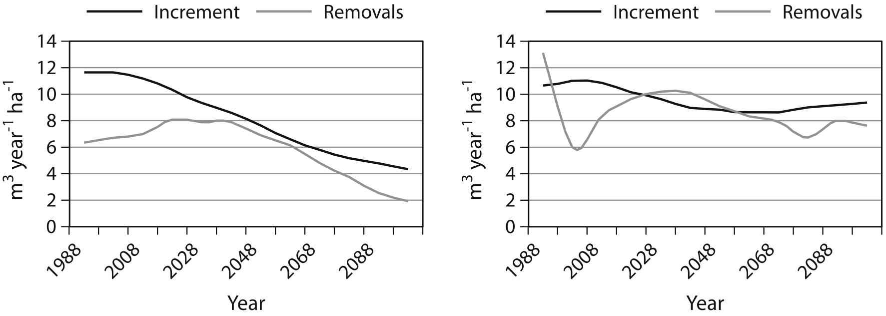

Fig. 10.5. Development of annual increment and removals in the management district Sonnenwald. Continuation of the recent management regime (*left*) and applying a standard equilibrium curve (*right*)

163. In contrast, the application of the standard equilibrium curve provides a final DBH distribution that is very close to this desired equilibrium curve (Fig. 10.3), and the total number of trees per hectare (533) is within the defined range of the management objective. Also the volume per hectare of the growing stock varies only within the range of 350–400 $m^3 ha^{-1}$, as it was defined in the management objective, but increases to 496 $m^3 ha^{-1}$ and subsequently decreases to 339 $m^3 ha^{-1}$ if the recent harvesting strategy is continued (Fig. 10.4).

However, from an economic point of view the main difference in the two management regimes is the fact that on average, over the whole simulation period, the mean annual removals are 49% higher when the standard equilibrium curve is applied (Fig. 10.5). This is even more obvious if the development of the contribution margins is considered (Fig. 10.6). Using an interest rate of 3% per year, the NPV of the equilibrium curve approach is 95% higher than the NPV of the recent management regime continued (12,156 vs. 6,222 EUR ha^{-1}), emphasising the economic superiority of the equilibrium curve approach.

10.7
PEELING-Demo

10.7.1
Data

The input data for this demo example came from a thinning experiment that was established in 1970 by the Institute of Forest Growth Research (BOKU University of Natural Resources and Applied Life Sciences, Vienna) in a pure stand of Norway spruce (*Picea abies* L. Karst.). The stand was 35 years old when this 0.45-ha research plot was established. For our demonstration we used the initial data before the first treatment had been performed. In order to obtain a specific number of peeled trees, we applied a static model predicting a tree's probability of

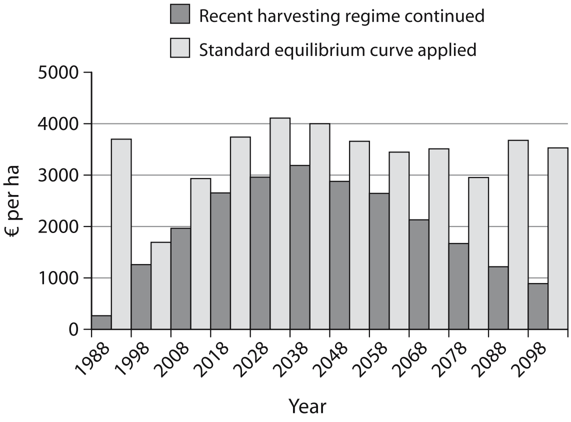

Fig. 10.6. Development of the contribution margin (CM) (revenues net of costs) in the management district Sonnenwald during a simulation period of 120 years

exhibiting damage caused by bark peeling (Sterba et al. 2003). The model predicted that 20% of the trees were peeled. Because this stand is located near the forest management district Sonnenwald, the same multipliers as presented in the CONVERSION-Demo (Table 10.2) were used for the simulation runs. We simulated a period of 85 years, finally resulting in a rotation period of 120 years.

10.7.2
Stand Management Objective

At the end of the rotation period of 120 years, this specific Norway spruce stand should have as few damaged trees as possible, and a high proportion of top-quality timber.

10.7.3
Management Regimes

Because in this stand 20% of the trees were damaged by bark peeling, we tried to determine the effect of the preferred removal of peeled trees when a thinning had to be performed. Hence, we also formulated two different management regimes for this stand. The first alternative was characterised by following a basal area–dominant height curve. When the stand basal area exceeded the basal area according to the yield table, the stand basal area was reduced to the critical basal area (Fig. 10.7).

This procedure resulted in three thinning operations, removing 169, 116 and 146 $m^3\ ha^{-1}$ at the age of 35, 50 and 70 years, respectively. The stand volume was removed without any regard to tree attributes. Following the second alternative, each thinning was performed at the same point in time as was done in the first management alternative. However, in each thinning we tried to remove the total number of peeled trees. Undamaged trees were only removed when the volume of the peeled trees was not enough to achieve the same amount of removed volume as it was under the first management alternative. On the other hand, if the total volume of the peeled trees exceeded the amount of volume to be removed, the surplus number of peeled trees remained in the stand.

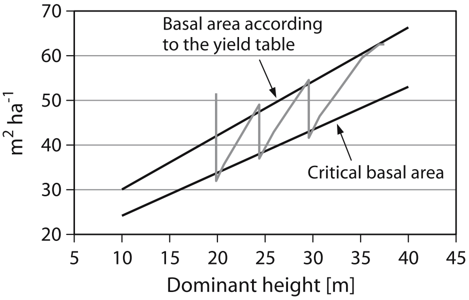

Fig. 10.7. Basal area-dominant height guideline to define the management regime in the PEELING-Demo. When stand basal area exceeded basal area according to the yield table [Weitra, dGZ_{100}=15 $m^3\ ha^{-1}\ year^{-1}$ (Marschall 1992)], a thinning operation was performed

10.7.4
Evaluation of the PEELING-Demo

The evaluation of the two different harvesting strategies revealed that the management regime has quite a strong impact on the commercial timber supply. From an initial proportion of 20% peeled trees at the age of 35 years, this proportion increased to 58% at the age of 120 years, if in thinning operations trees were removed without any regard to stem damage (scenario 1, Fig. 10.8). In contrast, if peeled trees were preferably removed in thinning operations, the proportion of peeled trees at the end of the rotation period was only 5% (scenario 2, Fig. 10.8).

From these results it can be seen that there must be an impact on the log quality distribution, which is depicted in Fig. 10.9. Thus, following the management regime of scenario 2, the proportion of quality class A (best quality) increased by 3% while the proportion of quality class C (worst quality) decreased by 3%.

The economic evaluation of these two management regimes is presented in Table 10.3. It can be seen that in both scenarios the contribution margin (CM) per hectare of the first thinning is negative. However, if damaged trees are preferably removed, the contribution margin is less (213 EUR ha^{-1}) due to the bad log quality of the damaged trees. Performing the second and the third thinning at the age

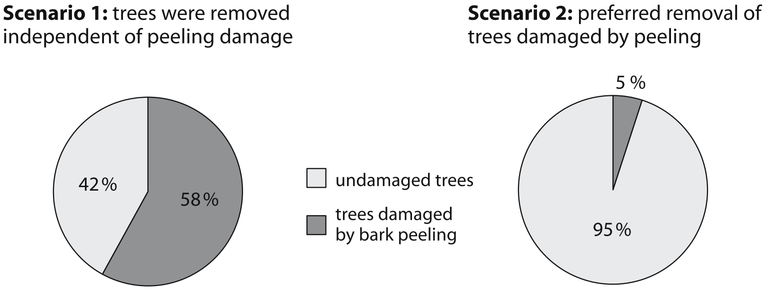

Fig. 10.8. Proportion by stem number of peeled trees at the end of the rotation period of 120 years

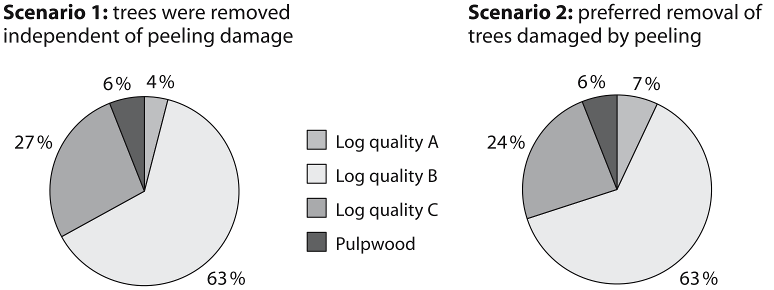

Fig. 10.9. Log quality distribution by volume at the end of the rotation period of 120 years. Quality class *A* (best quality), quality class *B* (medium quality) and quality class *C (worst quality)*

of 50 and 70 years, respectively, the contribution margins are still less if damaged trees are preferably removed (43 and 23 EUR ha^{-1}). Finally, comparing the contribution margins of the two different management regimes at the end of the rotation period (42,150 vs. 40,503 EUR ha^{-1}), it becomes clear that the value of the remaining stand can be increased by the preferred removal of damaged trees, although the total volume is lower (739 vs. 744 m^3 ha^{-1}). Hence, the increased value of the stand is solely a result of the improved commercial timber assortment achieved under this management regime.

In order to check whether this management regime was profitable as well, we also calculated the NPV. However, instead of calculating a NPV for each scenario, we rather calculated one NPV considering the differences of the contribution margins of the two management regimes as additional costs and added values, respectively:

$$\mathrm{NPV} = \frac{1647}{\left(1+\frac{p}{100}\right)^{(120-35)}} - \frac{23}{\left(1+\frac{p}{100}\right)^{(70-35)}} - \frac{43}{\left(1+\frac{p}{100}\right)^{(50-35)}} - 213$$

where p is the interest rate (in % per year).

Table 10.3. Economic evaluation of two different management regimes of the PEELING-Demo. *dg* Quadratic mean diameter of harvested trees; *CM* contribution margin (revenue minus costs)

Treatment		Scenario 1: trees were removed independent of peeling damage			Scenario 2: preferred removal of trees damaged by peeling			
	Age (years)	Volume (m^3 ha^{-1})	dg (cm)	CM (EUR ha^{-1})	Volume (m^3 ha^{-1})	dg (cm)	CM (EUR ha^{-1})	ΔCM (EUR ha^{-1})
First thinning	35	131	18.1	–1,589	130	17.9	–1,802	–213
Second thinning	50	91	23.3	1,454	92	23.1	1,411	–43
Third thinning	70	115	30.4	4,016	116	30.1	3,993	–23
Final harvest	120	744	47.0	40,503	739	47.6	42,150	1,647
Total	–	1,081	–	44,384	1,077	–	45,752	–

Table 10.4. Net present values (NPV) depending on different interest rates (*p*) for the example presented in the PEELING-Demo

	Interest rate *p*					
	2.0%	2.1%	2.2%	2.3%	2.4%	2.5%
NPV (EUR ha^{-1})	49.52	25.92	4.28	−15.57	−33.78	−50.47

In any case of a positive NPV the investment is profitable. However, the NPV depends on the interest rate p as presented in Table 10.4. Thus, as long as we assume an interest rate $p < 2.3\%$, the investment in terms of the preferred removal of damaged trees can be considered profitable. In other words, the preferred removal of damaged trees in the course of thinnings will result in an appreciation of the stand that amounts to an internal rate of return of 2.22% at maximum.

10.8
Summary

A thoroughly developed individual-tree growth simulator intended to help forest managers in decision support should be both flexible regarding the data that should be used in the simulation runs and sensitive to stand treatment in order to determine the impact of different management regimes on commercial timber supply. Both of these desired properties were demonstrated in this chapter. The CONVERSION-Demo showed on the level of an entire forest management district how an individual-tree growth simulator can be used to control sustained commercial timber supply during the conversion from an even-aged to an uneven-aged forest management system. In the PEELING-Demo the impacts of different treatments on a specific stand were demonstrated. The results of this demo example clearly show the sensitivity of the new models for predicting tree attributes and their importance for the economic evaluation of different stand management regimes.

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A Decision Support System for Multi-Criteria Forest Estate Planning, Integrating a Forest Growth Simulator, Fuzzy-Inference Techniques and a Heuristic Optimisation Approach

Rainer M. Sodtke[1], Heinz Utschig[2], Hans Pretzsch[3]

Abstract. The extended perception of sustainable forest development (MCPFE 2000) demands the integration of multiple management functions and criteria into strategic forest enterprise planning and decision making. Decision support systems (DSS) with effective model and method components can effectively support this planning procedure. For this, DSS must integrate tree growth simulators in order to run scenario simulations of stand dynamics, to project the long-term consequences of management alternatives and to scale stand dynamic processes at different spatial and temporal levels. Furthermore, DSS must include evaluation models capable of incorporating expert information and fuzzy reasoning. DSS should also integrate appropriate optimisation algorithms to identify optimal problem solutions dependent on multiple objectives. This chapter presents a DSS approach intended to support strategic multi-criteria forest planning and management at stand and estate levels. The DSS is aimed at forest enterprise managers as well as at the forest management planning services. Technically, the DSS integrates the individual tree-growth simulator SILVA 2.2 (Pretzsch 2001) and combines it with fuzzy-inference techniques and a heuristic Tabu Search optimisation approach. The main parts of the DSS concerning the technical structure, the database, the decision space, the objective system and the evaluation system will be presented as well as the main fuzzy-inference algorithms and utility functions. The heuristic multi-criteria optimisation approach developed for the specific DSS requirements will be shown. In addition, some example results demonstrating the DSS's plausibility and sensitivity will be given. Finally, the chapter concludes with a brief discussion of the DSS approach and outlines perspectives for further research.

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Hubert Hasenauer (Ed.)
Sustainable Forest Management
Growth Models for Europe

11.1
Introduction

Long-term forest planning aims at the sustainable development of forests. This task is becoming increasingly difficult because the demand for sustainability applies not only to timber production, but also to multiple ecological and socio-economic silvicultural functions, for example protection of soil and ground water and the aesthetics of natural scenery, and should be integrated into management decisions. These functions can address forest resources, forest ecosystem health and vitality, biological diversity, protective functions or socio-economic forest functions (MCPFE 2000). Therefore, certain criteria must be introduced into forest planning and decision making (Sodtke et al. 2004). This extended perception of sustainability is associated with the transition from pure to mixed stands (Pretzsch et al., this Vol.). However, this process requires information that cannot be provided by the model of ideal forests or yield tables. Today, much information is available from sample plots, site classification, etc. which could be better utilised if the planning procedure was improved (Hanewinkel 2001; Spellmann et al. 2001; von Gadow 2003). Furthermore, increasing public interest in forests demands participative planning methods. Subject to the extended tasks of today, DSS (e.g. Bonczek et al. 1981) can effectively support long-term forest planning (e.g. Rauscher 1999).

DSS are interactive computer-based systems intended to help decision makers utilise data and models to identify and solve badly structured problems and make effective decisions (Bonczek et al. 1981; Zimmermann 1987; Turban 1990). According to their application purposes, DSS can integrate various model and method components, covering different tasks such as communication, data and knowledge management, numerical simulation and problem solution (scenario evaluation, optimisation) (Rauscher 1999; Power 2001). Technically, a DSS should be structured in accordance with the theory of a rational (i.e. objective-orientated) decision and therefore organised into a decision space, an objective space, a problem solution component and a dialogue component (user interface) (Laux 1982; Mag 1990; Kelling 1991; Bamberg and Coenenberg 2002). As the main tools to set up the decision space, forest growth models can be applied. These models can be utilised to run scenario simulations of stand dynamics, to project the long-term consequences of management alternatives and to scale stand dynamic processes at different spatial and temporal levels. Evaluation models are required for structuring and evaluating the results, and for conducting multi-criteria plausibility and sensitivity analyses. Combined with appropriate optimisation algorithms, optimal problem solutions for multiple objectives can be identified.

The objectives of our research work are to design and develop a DSS to assist in the strategic management planning of forest enterprises and test it by using forest inventory data. The main focus is to combine a forest growth simulator with inventory databases, geographical information systems, visualisation routines and algorithms for evaluation and optimisation (Pretzsch and Seifert 2000; Pretzsch 2003). Such a system will be useful for teaching and training as well as for practical use in long-term forest planning. To simulate characteristic indicators of forest stand dynamics, the forest growth simulator SILVA 2.2 (Pretzsch

2001) will be used running in batch mode. Management objectives based on uncertain expert knowledge and requirements specified by our practical partners (The Count's Arco-Zinneberg Forest Enterprises, Moos, Bavaria, and the Municipal Forest of Traunstein, Bavaria) will be integrated into the objective system of the DSS. For problem solution, specific evaluation algorithms and optimisation procedures have to be combined and implemented into the DSS's problem solution component. For practical application, an adequate user interface will be programmed as well as links for use with a graphical information system and visualisation routines. Finally, the DSS will be tested by using inventory data from our forest enterprise partners.

11.2
The DSS Approach

11.2.1
Fields of Application

This approach of a forestry DSS is aimed at forest enterprise managers as well as forest management planners (for example, private or state-based forest planning services). While the former need an evaluation of different management alternatives at estate level subject to multiple management objectives, the latter rely on the identification of optimal treatment strategies in specific situations (stand level). Both managers and planners are interested in long-term strategic planning (silvicultural management strategies) and less in short-term operational planning (e.g. use of machines, labour organisation). The aim is to objectify the decision making processes and to make them more understandable. For this, growth simulations based on management scenarios are as significant as instruments for enhancing the transparency of silvicultural decisions and the possibilities for public participation. This may be of interest in, for example, municipal forests or areas protected by Natura 2000 or Fauna Flora Habitat designation. From this, there is a demand in developing DSS not only able to simulate long-term scenarios but also to evaluate different management alternatives with respect to multiple criteria, to consider various spatial (stand, enterprise sub-unit, enterprise) and temporal levels, and be able to visually represent alternative results in a suitable manner. Finally, such a system also introduces forestry students – the future decision-makers – to computer-aided management planning and decision-making.

11.2.2
Data

Through several interviews (based on questionnaires) of our practical partners (G. Fischer, Municipal Forest of Traunstein, Bavaria and W.-D. Radike, The Count's Arco-Zinneberg Forest Enterprises, Moos, Bavaria), information for identifying relevant characteristics of the decision process (objectives/criteria and specific indicators), as well as for deriving functional relations between objectives and indicators, was gained. The acquired information was generally given as vague or uncertain statements. Relevant variables (objectives, indicators) were usually expressed as linguistic variables with vague or fuzzy values [e.g. 'narrow height/dbh (hg/dg) ratio' (dbh, breast height diameter; hg/dg, height/diameter of a stem representative of the whole stand); 'very poor vertical structure'; see Table 11.1]. With the use of fuzzy logic, specifications of the linguistic variables could be described by fuzzy sets (see, e.g., Zimmermann 1996). The acquired expert knowledge was transferred into rules and integrated into fuzzy inference systems (Matlab Fuzzy Toolbox, The Math Works). The gained information could also be used to define utility functions for the evaluation of management alternatives at different spatial levels.

To construct a data pool with resulting forest state characteristics (i.e. indicators for evaluating multi-criteria objective fulfilment, e.g. dbh, height of dominant trees, etc.) depending on different management alternatives and environmental situations (sites, stands) various scenario simulations were carried out with the forest growth simulator SILVA 2.2. These scenarios included sets of different mixed stands of Norway spruce and common beech, several sites according to the enterprises of our practical partners and sets of different management alternatives.

For DSS evaluation and validation, our practical partners supplied us with inventory data from their forest estates. These data included information about the site characteristics at district level (Bayern-Forst 1993), as well as forest planning maps with geometric information and data about tree species composition and growth characteristics (stand age, height, dbh, etc.) at stand level.

11.2.3
DSS Structure

The technical structure of the DSS 'Silva Support' is closely orientated to the theory of objective-orientated decision making (Bamberg and Coenenberg 2002; Sodtke 2003). In order to create a stand-alone software – independent of the programming software and the operating system – the DSS architecture was developed with the programming language C++ (Borland). In order to make the decision making process rational and comprehensible, the DSS integrates the following main components: an interface with the existing forest growth simulator SILVA 2.2 (Pretzsch 2001), a database for storing simulation results, a sub-system for the organisation of knowledge-based objective functions and the definition of respective objective preferences, a sub-system for multi-criteria evaluation and identification of optimal management alternatives, and a graphical user interface as a dialogue and knowledge acquisition component (Fig. 11.1). Furthermore, possibilities were created for direct and indirect linking with the GIS ArcView (ESRI) and with other visualisation systems (Pretzsch and Seifert 2000), allowing an appropriate visualisation of result and evaluation measures. A management sub-system contains algorithms for linking and running all DSS components and for processing the data input and output via the user-interface and/or data files.

Table 11.1. Management objectives and respective indicators for evaluation according to the Pan-European criteria of sustainable forest management (MCPFE 2000) and relevant to our associate forest enterprises, Municipal Forest Traunstein, Germany, and The Count's Arco-Zinneberg Forest Enterprises, Germany

Management objectives	Indicators (dynamic forest state variables)
Timber production (commercial efficiency)	Net return from timber sale
	Growing stock dynamics (balance between wood growth and removals)
	Timber assortment (quality) structure
	Rotation time
Stand stability	Tree species composition (share of deep rooters)
	Crown length/stand height ratio
	Stand height (dominant trees)
	Slenderness (h/d ratio)
Biodiversity (habitat quality, species richness)	Number of tree species
	Horizontal intermingling (index by Clark and Evans)
	Vertical structure (species profile index by Pretzsch)
	Share of dead wood (woodpecker stems, standing trees with dbh >20 cm)
Protective functions (soil, ground water protection)	Tree species composition (share of deep rooters)
	Period with continuous soil cover
	Vertical structure (species profile index by Pretzsch)
Aesthetics (recreational function)	Number of tree species
	Horizontal intermingling (index by Clark and Evans)
	Vertical structure (species profile index by Pretzsch)
	Frequency of management actions
Habitat quality for game (hunting opportunity)	Supply of area (spruce clear-cutting system)
	Share of borderlines between stands and clearance areas

With the graphical user interface (GUI), the system user is able to communicate with the DSS, to provide input data or information (such as values of decision variables, state variables or management objectives) or to export output data or information (such as indicator or utility variables). Furthermore, via the interface, the user can obtain additional or auxiliary information about the system or system status.

The growth simulator SILVA was suited for integration into the DSS because of its following properties: (1) as a distant-dependent individual tree-growth simulation model, SILVA permits simulating the development of complexity structured even and uneven-aged pure and mixed stands; (2) as defined by the parameterisation data, SILVA is reliable for most German site conditions; (3) it covers the most common German tree species; and (4) it is possible to run SILVA in a batch operation mode for enterprise simulation and external use by a DSS software (Pretzsch et al., this Vol.). Because of the growth simulator's spatial specificity, the DSS is also applicable to a wide range of forest sites in central Europe ranging from Denmark to the Swiss Alps, and particularly to site conditions found in southern Germany.

The database contains simulation results from a multitude of management scenarios generated with the growth simulator SILVA under predefined conditions (defaults). Simulation results consist of complete tree lists as well as characteristic indicators of forest state dynamics used for evaluating the objective

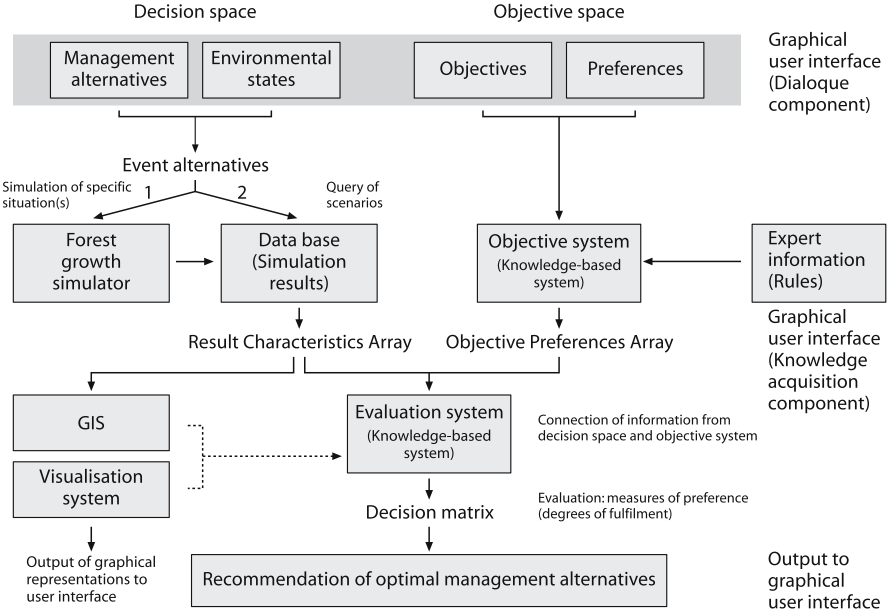


Fig. 11.1. Structural scheme of the decision support system (DSS) SILVA Support. *Boxes* represent the main DSS components. *Arrows* denote data exchange between components and the system's data input and output. For more information refer to the text

fulfilment. In the example of a 19-year-old mixed stand of Norway spruce and common beech with the management alternatives 'no thinning', 'moderate' and 'strong thinning from above', Fig. 11.2 shows the temporal dynamics of the indicators growing stock, height/diameter (hg/dg) ratio, vertical structure as expressed by the species profile index (Pretzsch et al., this Vol.) and net return from timber sales calculated from average German timber prices between 1990 and 1999. The chosen management scenarios were selected in agreement with our practical partners and address one of their main management dilemmas. In the case of no thinning, the h/d (height/diameter of an individual tree) ratio indicating stand stability evolves most unfavourably, whereas the vertical structure as an indicator of biodiversity shifts from beneficial to adverse values at the age of 34 years. Positive financial return occurs earliest with strong thinning. However, compared with the alternatives, this management technique results in lower net returns in the long run.

These simulation results can be taken from the GUI for further evaluation. Alternatively, information on site attributes and stand structure, as well as management specifications, can be supplied to the DSS by data files or via direct GUI input. Using this method, results of scenarios not yet simulated can be calculated with the growth simulator. Afterwards, the result variables (indicators) of all calculated alternatives are evaluated by the evaluation sub-system according to multiple objective preferences. These preferences result from the objective sub-system processing knowledge-based information about the management objectives (objective characteristics, weights, etc.) also specified in the GUI by the user. Finally, for each management alternative a so-called degree of fulfilment will be assigned to each management objective, plus an evaluation of the total utility as a measure of preference of an alternative.

11.2.4
Decision Space

The decision space of the DSS contains decision variables and state variables defined by specifying the range of values of the management alternatives (e.g. thinning grade) and the environmental states (e.g. site conditions, tree species composition/growth characteristics before management operations). The current DSS version integrates the following decision variables regarding intermediate thinnings and final cutting: thinning type, thinning frequency and thinning grade, as well as type and intensity of final cutting. The temporal application of these variables may be defined differently according to variable thinning schemes. Decision variables referring to stand regeneration (choice of tree species, type of regeneration) will be integrated into a future DSS version. Furthermore, a set of management constraints, such as the maximum thinning volume per hectare and period, can be defined.

The initial environmental state results from site and stand structure and is identified by a set of characteristic state variables. Site conditions are characterised by several specifications of climate and soil, such as forest growth region, precipitation, soil nutrient content, slope, exposure, etc. The properties of the initial

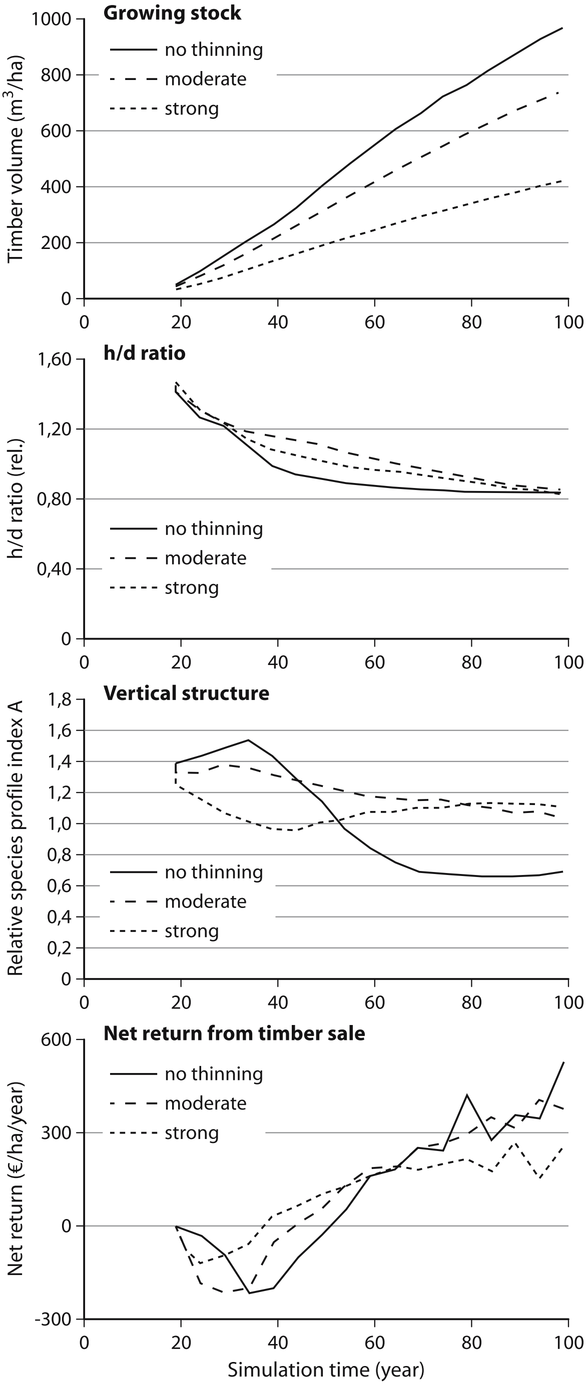


Fig. 11.2. Dynamics of characteristic indicators of forest stand dynamics simulated with the growth simulator SILVA 2.2 and used for evaluating multi-criteria objective fulfilment. In the case of a 19-year-old mixed stand of Norway spruce and common beech (80:20) with the management alternatives no thinning, moderate or strong thinning from above applied, the figure displays the temporal dynamics of growing stock, height/diameter (*hg/dg*) ratio, vertical structure as expressed by the species profile index, and net return from timber sales calculated from average German timber prices between 1990 and 1999

stand or enterprise sub-unit are denoted by tree lists or can be described by the aggregated variables tree species, stand structure, age and age structure. If information about a particular environmental state cannot be provided with certainty, each state variable can also be specified with its degree of certainty (within the interval [0, 1], where 1 = certain, 0 = totally uncertain) to be processed by fuzzy inference techniques within the evaluation sub-system.

11.2.5
Objective System

For evaluation of the management alternatives, various management objectives can be selected as well as preferences defined by the user. According to the Pan-European criteria for sustainable forest management (MCPFE 2000; see also Pretzsch et al., this Vol.) and as agreed with our practical partners, six management objectives were integrated into the objective system (Table 11.1). These objectives comprise economic as well as ecological and social aspects of forest management, which occasionally conflict. Objectives and preferences can be selected by the user from a predefined list via the DSS interface and can be assigned to the total estate, singular stands or enterprise sub-units. The objective system consists of a knowledge base representing objective contents (objective variables and their attributes = indicators), and an inference component (rule system) integrating quantitative relations (preferences) between objectives and objective variables (indicators). Indicators characterising one specific objective were also defined at the Pan-European level (MCPFE 2000). For example, forest biodiversity is characterised by indicators such as tree species diversity, vertical stand structure, share of dead wood, etc. (Table 11.1). Objective preferences refer to type, value, time and uncertainty of the indicators. If the user has stated more than one objective he/she may also specify the objective's relevance by weighting them.

The rules of the objective system were acquired from scientific literature and from interviews with our practical partners and will be supplemented by additional interviews with other experts. Such data are usually imprecise assessments characterised by linguistic terms which can be analysed as qualitative answers. Therefore, with the aid of fuzzy logic (e.g. Rommelfanger 1994; Zimmermann 1996), these variables were assigned to fuzzy sets, and the relational information between objectives and indicators (set of rules) was utilised to configure fuzzy inference systems (Matlab Fuzzy Toolbox, The Math Works; Sodtke 2003). Thus, the degree of fulfilment u_i for management objective i referring to management alternative x at stand/stratum level can be formalised by the fuzzy inference graph $\mu^Y(x)$ representing a maximum–minimum combination of the fuzzy result variable matrix μE and the fuzzy relation R (rule system) (Eq. 11.1):

$$\mathrm{u_i} = \mu^Y = \mu^E \cdot R$$

with

$$\mu^E = \begin{bmatrix} \mu^{E_1}_{A_1}(E_1(x)), \mu^{E_1}_{A_2}(E_1(x)), & \dots & \mu^{E_1}_{A_m}(E_1(x)) \\ \vdots & \ddots & \vdots \\ \mu^{E_n}_{A_1}(E_n(x)), \mu^{E_n}_{A_2}(E_n(x)), & \dots & \mu^{E_n}_{A_m}(E_n(x)) \end{bmatrix}$$

and

$$\mu^{E_j}_{A_k} = \left\{\left(e_{xst}, \mu_{\tilde{A}_k}(e_{xst})\right) \mid e \in E\right\}$$

where e_{xst} is the value of result variable E_j of management alternative x, stratum s and time t and $\mu^{E_j}_{A_k}$ is the membership function denoting the membership of values e_{xst} to the fuzzy set A_k. In the example of the management objective stand stability, Fig. 11.3 shows a scheme of a fuzzy inference system transforming crisp input information to fuzzy sets, processing them in a rule base and calculating information on the degree of objective fulfilment. The effects of changed inputs and weights may be analysed rule by rule as well as by plotting the fuzzy inference graph. Figure 11.4 displays the simulated dynamics of objective fulfilment of the management objectives timber production (commercial efficiency), stand stability and biodiversity in the example of a mixed spruce–beech stand and the management alternatives 'no thinning', 'moderate' or 'strong thinning from above'. According to the indicator variable 'net return', in the first simulation periods commercial efficiency of timber production is greatest with strong thinning. Stand stability is also best with strong thinning. With no thinning, biodiversity shifts from beneficial to adverse values in the long run; strong thinning from above shows the opposite behaviour.

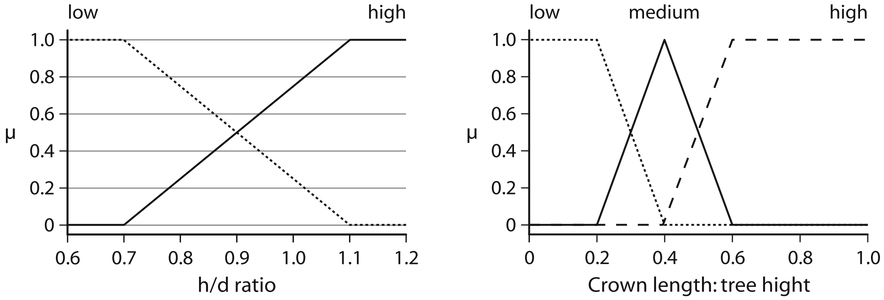
11.2.6
Evaluation

Within the evaluation sub-system, management alternatives are evaluated according to their degree of objective fulfilment. The total utility U^T for each management alternative can be determined from the user-defined objective weights a_i and the (objective-referring) partial utility $U_i(x)$ by additive utility functions (Pukkala and Miina 1997):

$$U^T(x) = \sum_{i=1}^{z} a_i \, U_i(x)$$

The total utility allows comparison of the alternatives and ranking according to their preference. If the user prefers, the DSS can alternatively offer the best management option or a set of possible alternatives sorted by objective fulfilment. The partial utility $U_i(x)$ referring to a singular objective may be represented by the weighted average of sub-utilities u_{its} per growth period t and stratum s (Eq. 11.5):

Fuzzy sets



Rule system

h/d ratio	Age	Crown length/ tree height	Objective fulfilment with share of deep rooters is		
			low	medium	high
low	low	low	medium	medium	high
		medium	medium	medium	high
		high	medium	high	high
	high	low	low	low	medium
		medium	low	medium	medium
		high	medium	high	high
high	low	low	low	medium	medium
		medium	low	medium	medium
		high	medium	medium	medium
	high	low	low	low	low
		medium	low	low	medium
		high	low	medium	high

Fuzzy inference graph

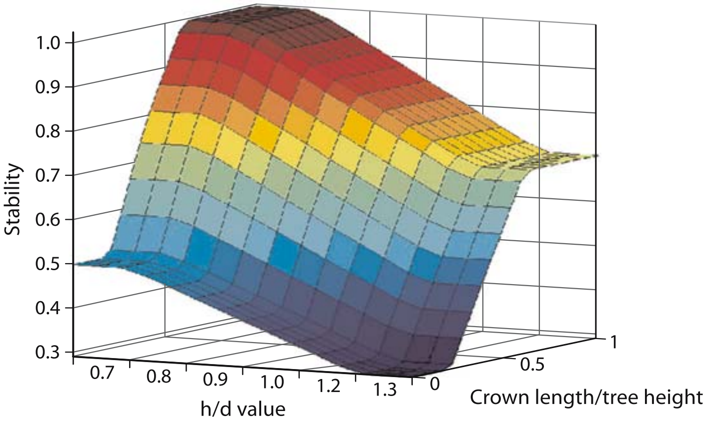


Fig. 11.3. Fuzzy inference scheme for the management objective stand stability. *Above* Fuzzy sets of input variables h/d ratio and crown length/tree height ratio. Input values are calculated with the rule system (*centre*) and result in characteristic degrees of objective fulfilment as shown by a surface plot (fuzzy inference graph, *below*).

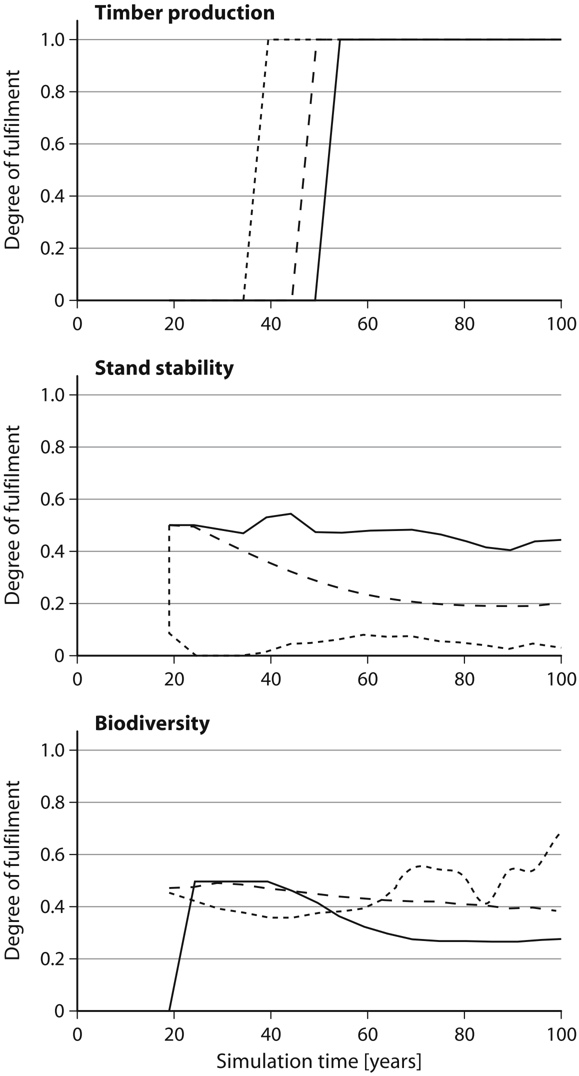


Fig. 11.4. Dynamics of objective fulfilment of the management objectives timber production (commercial efficiency), stand stability and biodiversity evaluated with DSS SILVA Support. Results refer to the example of a spruce-beech mixed stand and the management alternatives no thinning, moderate or strong thinning from above, applied as presented above (Fig. 11.2)

$$U_i(x) = \frac{1}{\sum b_t \sum c_s} \sum_{t=t_1}^{t_n} b_t \sum_{s=s_1}^{s_m} c_s \cdot u_{its}(x) \text{ with } u_{its}(x) \geq d_{is}$$

where d_{is} is the lower limit of sub-utility u_{its} (constraint), and b_t and c_s are weights.

Table 11.2 shows the results of a multi-criteria evaluation of the management alternative 'moderate thinning from above' at stratum and enterprise levels. The results are given for five different age strata of mixed stands from Norway spruce and common beech. The results also refer to the strata's spatial extension at estate level. Hence, in this example an ideal estate with equally sized strata is assumed.

Figure 11.5 presents the respective results comparing several strata differentiated by age (20–100 years) and tree species composition (pure Norway spruce and Norway spruce–common beech mixed stands), and three management alternatives (no thinning, moderate and strong thinning from above).

Table 11.3 displays results aggregated at estate level. The presented results refer to two different kinds of estates, one dominated by pure Norway spruce stands, the other by spruce–beech mixed stands. For both estates, and with the given objectives' weighting, highest total utilities are achieved with strong thinning. However, with pure spruce, estate differences between the management alternatives are not very large.

The DSS comprises two relevant spatial levels of silvicultural decision support: the stand level or stratum level, on the one hand, is characterised by a multi-criteria evaluation of alternative stand/stratum treatment decisions (thinning type and intensity, planting, etc.). Forest stands that are comparable according to site, tree species composition, development state and the like are combined into enterprise sub-units (strata; Durský 2000) to which the DSS will apply the same management schemes and resulting indicator values. Table 11.4 gives the criteria and characteristic values for strata definition classified by tree species composition and stand age.

The enterprise (or regional) level, on the other hand, requires an estate-orientated strategy of forest management activities relating to the spatio-temporal order of actions. To identify this strategy, an appropriate combination of stand/stra-

Table 11.2. Evaluation results of objective fulfilment at stratum level according to the objectives 'timber production', 'stand stability' and 'biodiversity' in the example of a spruce--beech mixed stand with moderate thinning from above applied and five strata of different age presented above (simulation with natural regeneration, simulation period: 30 years; see Fig. 11.5). For aggregation at estate level, the objective-referring results are weighted by the strata's spatial extension (Eq. 11.4)

Stratum (age class) (years)	Area (ha)	Objectives Timber production	Stand stability	Biodiversity
20	100	0.0	0.42	0.48
40	100	0.67	0.28	0.45
60	100	1.0	0.21	0.42
80	100	1.0	0.20	0.40
100	100	1.0	0.23	0.38
Estate result		0.73	0.27	0.43

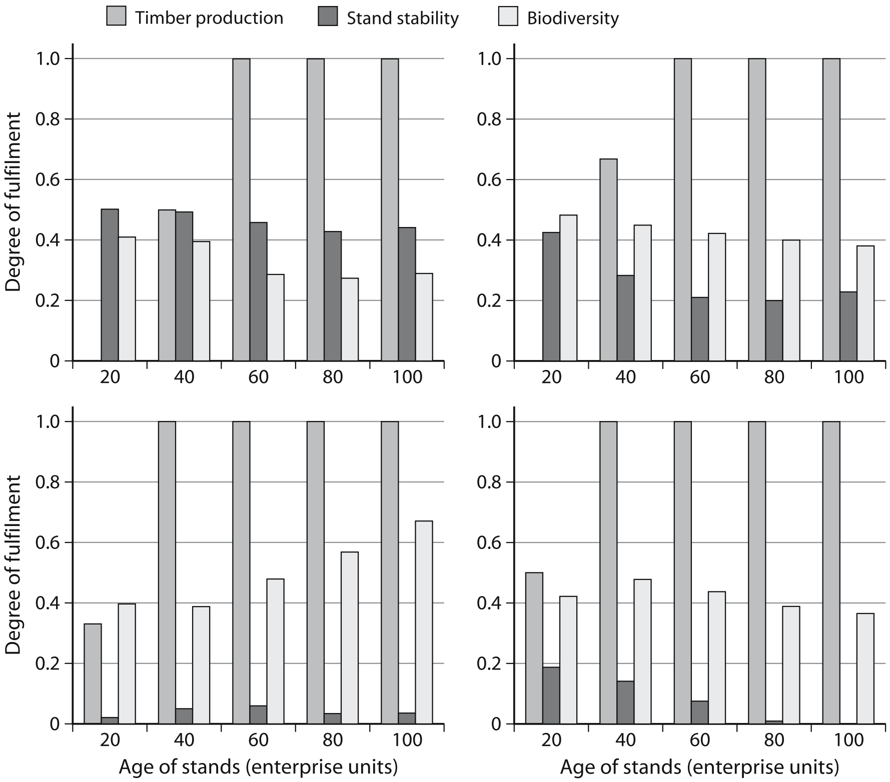


Fig. 11.5. Evaluation results of objective fulfilment regarding timber production, stand stability and biodiversity and five strata of different age (20, 40, 60, 80 and 100 years old). *Upper graphs* represent mixed strata from Norway spruce and common beech (80:20) with no thinning (*left*) and moderate thinning from above (*right*) applied (see Figs. 11.2 and 11.4). *Lower graphs* show results in the cases of a spruce-beech mixed stratum with strong thinning from above (*left*), and a pure Norway Spruce stratum with moderate thinning from above (*right*). Each simulation calculated with natural regeneration, simulation period: 30 a.

tum-level scenarios is processed at estate level. The linking of both levels of decision support is accomplished by the utility functions shown above (Eq. 11.5). Beneficial and adverse (conflicting) utilities per stratum and period may therefore 'compensate' each other in time and space. Compensations in this respect may be described as trade-offs between conflicting utilities depending on the user's preferences (weights).

Table 11.3. Evaluation results of objective fulfilment at estate level according to the objectives 'timber production', 'stand stability', and 'biodiversity' and the management alternatives no thinning, moderate thinning and strong thinning from above. Results are shown in the example of an estate consisting of five spruce–beech mixed strata of different age presented above (see Table 11.2 and Fig. 11.5), and in the example of a respective estate consisting of pure Norway spruce strata (simulation with natural regeneration, simulation period: 30 years)

	Management alternative	Objectives Timber production Weighting	Stand stability	Biodiversity	Total utility
		0.3	0.6	0.1	
Spruce–beech mixed estate	No thinning	0.70	0.47	0.33	0.52
	Moderate thinning	0.73	0.27	0.43	0.42
	Strong thinning	0.87	0.04	0.50	0.34
Pure Norway spruce estate	No thinning	0.72	0.06	0.24	0.28
	Moderate thinning	0.78	0.06	0.28	0.30
	Strong thinning	0.81	0.07	0.38	0.32

11.2.7
Optimisation

The utility functions presented above were integrated into an optimisation algorithm (heuristic Tabu Search approach). By this means, the DSS is able to identify mathematically optimal management alternatives – at stand level as well as at estate level – within a short time. Tabu Search was introduced as a heuristic optimisation algorithm to solve packing problems such as the 'knapsack or smuggler's problem' (Domschke et al. 1996). Changing a decision variable within the optimisation procedure (e.g. putting an object into or taking it out of the knapsack) sets this particular action tabu and adds it to a tabu list for a predefined time span (tabu duration). This means that this action cannot be carried out (or revised) until the number of iteration steps exceeds the tabu duration.

This procedure was applied to the problem of optimising forest management alternatives. Here, several decision variables (e.g. thinning type, thinning grade) exist which may be applied to a forest at different time periods as well as to different enterprise strata. Figure 11.6 graphically displays the Tabu Search optimisation scheme implemented in the DSS. Optimisation refers to a combination of decision variables, which may be expressed by a decision tree. In period (1) a stra-

Table 11.4. Criteria and characteristic values for stratum definition classified by stand stage and age, and share of the tree species composition. *Spr* Norway spruce; *Fir* silver fir; *Dgl* Douglas fir; *Bch* common beech; *Oak* sessile oak; *Mpl* common maple (Sycamore); *Ash* common ash; *Elm mountain elm (wych)*

Stratum	Stage	Age (years)	Tree species	Share (%)
1.1–4	Brush stage	<20/25	All species	–
2.1	Young thinning	20–40	Spr, Fir, Dgl	>80
2.2		25–45	Bch, Oak	>80
2.3		20–40	Mpl, Ash, Elm	>70
2.4		20–40	All species	–
3.1	Old thinning	40–60	Spr, Fir, Dgl	>80
3.2		45–90	Bch, Oak	>80
3.3		40–70	Mpl, Ash, Elm	>70
3.4		40–70	All species	–
4.1–4	Final cutting + regeneration	>60/90	All species	–
5.1–4	Selection forest	–	All species	–

tum's initial state may be changed by a selected thinning type and a selected thinning grade. In period (2) the stratum's resulting state again may be changed by a selected thinning type and a selected thinning grade and so on. With this procedure, the number of possible management alternatives can easily be calculated as follows (Eq. 11.6):

$$N_s = \left[\prod_{i=1}^{n} x_i \right]^p$$

where N_s is the number of possible management alternatives per stratum, x_i is the number of stages of the decision variables, n is the number of decision variables and p is the number of periods.

In case of constrained alternatives (e.g. no thinning implies no differentiation according to thinning grade), Eq. (11.6) reads as follows:

$$N_s = \left[\prod_{i=1}^{n} x_{u,i} + \prod_{j=1}^{n} x_{c,j} \right]^p$$

where $x_{u,i}$ is the number of decision variable stages with unconstrained management alternatives and $x_{c,j}$ is the number of decision variable stages with constrained management alternatives.

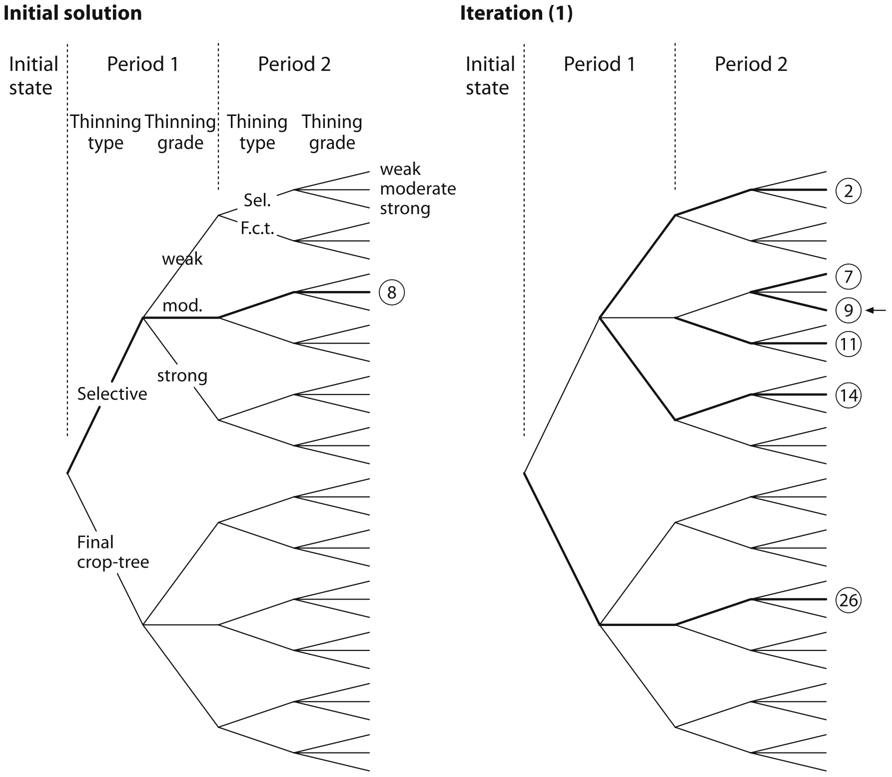
The optimisation algorithm proceeds as follows: first, a randomly chosen or predefined initial solution [alternative (8) in the example denoting moderate selective thinning in periods 1 and 2] is calculated with the growth simulator – or taken from a stored example in the database – and evaluated by the DSS referring to preselected objectives. Afterwards, this solution is set tabu within the tabu list for a predefined time span (tabu duration), during which this solution cannot be selected again. In iteration step (1), the solutions neighbouring the initial solution are calculated and evaluated. A neighbouring solution is characterised by changes in only one decision variable in the whole decision tree (e.g. changing the thinning grade in period 2). The alternative evaluated best [alternative (9) in Fig. 11.6] is selected as the actual solution and also set tabu in the tabu list. In iteration step (2), the solutions neighbouring the best alternative from the previous iteration step are calculated and evaluated. Neighbouring solutions are those alternatives that differ from the previous best solution only in one changed decision variable (e.g. thinning type). Again, the best alternative is selected as the actual solution and set tabu. This procedure continues until a predefined maximum number of iterations is achieved. The identified alternative with the result evaluated best within all iteration steps is taken as the optimal solution.

In the case of optimising management alternatives applied to different strata of an estate, the above procedure is extended in the following manner. For each stratum an initial solution is defined (e.g. by random selection) and set tabu. In the following iteration steps, only one decision variable in the whole estate-level decision tree can be altered. Therefore, the neighbouring solutions to a whole set of initial solutions (referring to each stratum) are calculated and evaluated at estate level. That alternative leading to the best evaluation at estate level (e.g. belonging to stratum 1) is selected as the actual solution and set tabu. The management alternatives according the other strata remain unchanged. In the next iteration step, again, the whole set of actual solutions is calculated and so on. In this case, the number of possible management alternatives is calculated as:

$$N_E = \left[\left[\prod_{i=1}^{n} x_i \right]^p \right]^s$$

or

$$N_E = \left[\left[\prod_{i=1}^{n} x_{u,i} + \prod_{j=1}^{n} x_{c,j} \right]^p \right]^s$$



Initial solution: ⑧

Multi-criteria evaluation: 0.66

Tabu list: [(1; 2);
(1; 2), (1; 2)]

Calculation of neighbouring solutions:
2; 7; 9; 11; 14; 26

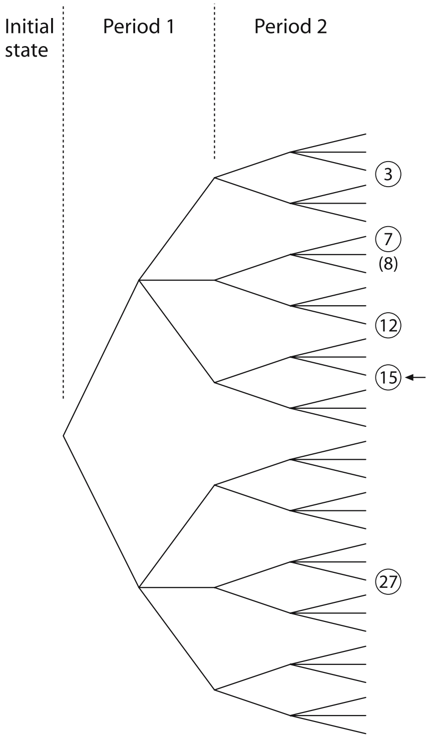
Multi-criteria evaluation:
0.21; 0.54; 0.78; 0.45; 0.75; 0.40

Selection of best alternative: ⑨

Tabu list: [(1; 2);
(1; 2), (1; 2; 3)]

Fig. 11.6. Tabu Search optimisation scheme within DSS SILVA Support. Figure shows a decision tree within four iteration steps by an optimisation example referring to a management recommendation for two 5-year periods, two thinning types (selective thinning, final crop-tree thinning) and three thinning grades (weak, moderate, strong). *Solid lines* in the decision tree refer to possible management alternatives within the two periods. *Bold line in left-hand picture* shows the randomly chosen initial solution [alternative (8): moderate selective thinning in periods 1 and 2]. This solution is calculated with SILVA 2.2 and evaluated by DSS referring to preselected objectives. Afterwards, this solution is set tabu within the tabu list for a predefined time span (tabu duration) of more than three iterations, during which this solution cannot be selected again. The tabu list reads as follows: 'In period (1), moderate selective thinning is set tabu (first line); in period (2) with moderate selective thinning in period (1) applied, moderate se-

Iteration (2)



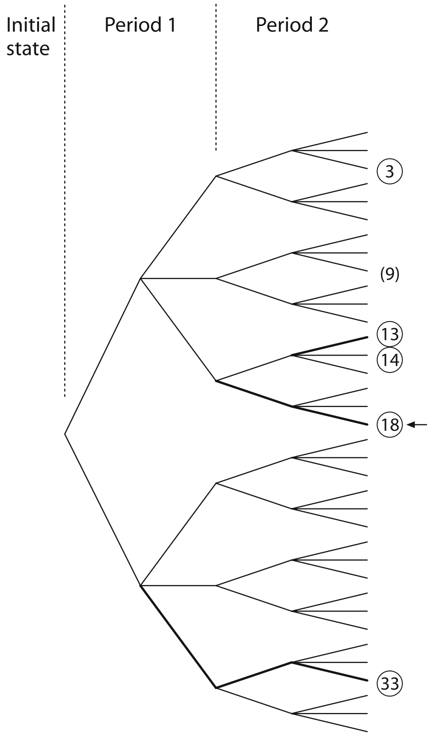
Calculation of neighbouring solutions:
3; 7; (8); 12; 15; 27

Multi-criteria evaluation:
0.25; 0.54; 0.66; 0.55; 0.81; 0.44

Selection of best alternative: ⑮

Tabu list: [(1; 2; 3);
(1; 2), (1; 2; 3);
(1; 3), (1; 3)]

Iteration (3)



Calculation of neighbouring solutions:
3; (9); 13; 14; 18; 33

Multi-criteria evaluation:
0.25; 0.78; 0.68; 0.75; 0.76; 0.48

Selection of best alternative: ⑱

Tabu list: [(1; 2; 3);
(1; 2), (1; 2; 3)]
(1; 3), (1; 3);
(1; 3), (2; 3)]

lective thinning is set tabu (second line)'. *Black bold lines* in iteration 1 denote the neighbouring solutions now to be calculated and evaluated. The alternative evaluated best (9) is selected and also set tabu afterwards. In iteration 2, the neighbouring solutions of alternative (9) are calculated and evaluated (*black bold lines*). Again, the best alternative is selected and set tabu within the tabu list. This procedure continues until the maximum number of iterations (in this example more than three iterations) is achieved. The identified alternative with the result evaluated best within all iteration steps is taken as the optimal solution where N_E is the number of possible management alternatives per estate and s is the number of strata.

The CPU time required to solve a specific problem depends on the number of decision alternatives, strata and time periods to be considered. Previously stored solutions in the database will slow down the system. If appropriate solutions can be found in the database, CPU time for optimisation may only take a few seconds. If there are no previously calculated solutions, alternatives have to be simulated by the growth simulator and evaluated by the DSS in the manner described above. In this case, CPU time may increase by several minutes or longer. This is especially true for the simulation/evaluation of young stands/strata consisting of many individual trees, the growth simulation of which is fairly time-consuming.

11.3
Demonstration

The DSS was tested with inventory data from our practical partners in order to examine the plausibility and sensitivity of the DSS results. As an example, data from The Count's Arco-Zinneberg Forest Enterprises, Germany, in the forest district of Künzing, are presented. The forest district is located on a hillside at an altitude of 345–410 m above sea level in the region 'Niederbayrisches Tertiärhügelland' (German forest growth district 09.12.09) in south-eastern Bavaria, and covers an area of 535 ha. The soils are sandy loams (medium or profound brown earths or lessivés, partially gleyic soils). The annual average temperature is 7.5 °C and the annual average precipitation is about 800 mm (Bayern-Forst 1993).

For testing the DSS, several enterprise sub-units (strata) were defined according to the criteria and characteristic values of stand age and tree species composition (a fairly even split of deciduous and coniferous trees), as given in Table 11.4. For simplification, these stands were represented as pure and mixed stands of Norway spruce and common beech. Next, various management alternatives at strata level were calculated with SILVA 2.2 and evaluated at stratum and estate levels. The evaluated management alternatives refer to a 30-year simulation period and the thinning types no thinning, thinning from above and below, selective and final crop-tree thinning, with a stepwise increased thinning grade (100, 80 and 50% of basal-area guide curve), and final linear cutting (equal cutting rates for each cutting period until a stratum is clear-cut) for older stands (>60/90 years old). Again, the management scenarios were selected in accordance with our practical partners and address their current management techniques or potential alternatives. These management alternatives were evaluated according to the management objectives of timber production, biodiversity and stand stability.

With the management objectives 'stand stability' and 'biodiversity', the resulting degrees of fulfilment show only slight differences for each alternative at stratum and estate levels. In the case of timber production there is a decreasing preference of the alternatives from weak thinning from above to heavy final crop tree thinning (Sodtke et al. 2004, not shown here). With young stands (40/45 years old), the objectives 'stand stability' and 'biodiversity' receive higher degrees of fulfilment than the objective 'timber production'. In the case of older stands

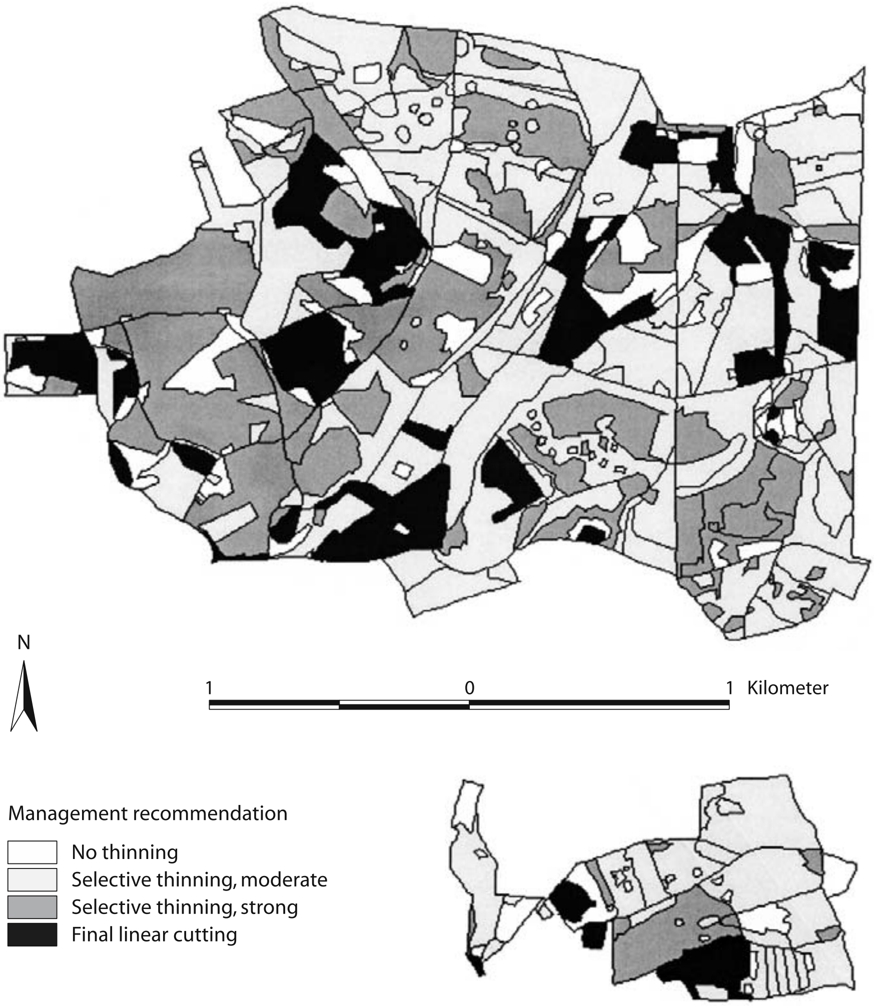


Fig. 11.7. Map of management recommendations for different management strata according to Table 11.4 and a 5-year period after forest inventorying by the example of inventory data from the forest district Kuenzing, The Count's Arco-Zinneberg Forest Enterprises, Germany

(60/90 years old), timber production is better evaluated than the other objectives. For most strata, selective thinning (moderate, strong) was found to best fulfil the desired objectives. In the case of young stands (<20/25 years old), generally no thinning, and in the case of older stands (>60/90 years old), final linear cutting were found to be optimal. Figure 11.7 shows a spatial representation of the identified optimal management for the forest district's strata.

The DSS results were considered to be reasonable and sufficiently sensitive when compared with our research results on trial plots in Bavaria. In addition, our practical partners judged the DSS results and recommendations to comply with their practical experiences in the examined forest districts. Further test runs – for example sensitivity analyses with inventory data from our practical partners – should be carried out in the future in order to search for potential anomalies and to thoroughly validate the DSS.

11.4
Discussion

DSS Silva Support represents a prototype for a decision support system in forestry. Many modifications and improvements of details seem to be possible and necessary before it can be used in practice. However, for us it was important to show the principle and the design of such a tool. In test runs and first applications implausible results will be detected and corrected in an iterative process. For example, the rule system for stand stability has to be thoroughly revised. Further research is necessary to move the system from a demo to a tool for practitioners.

The presented approach of the DSS Silva Support fulfils the general requirements of DSS by using data and models to identify and solve semi-structured problems (e.g. Bonczek et al. 1981; Zimmermann 1987). The DSS enhances strategic forest planning but – as demanded – does not replace managerial judgement (Turban 1990). The provided information can be interpreted easily (Kelling 1991). The DSS is aimed at the planning of medium- and long-term management, and therefore supports decisions concerning silviculture and forest enterprise planning. Possible users are forest planners and forest enterprise managers. By integrating and combining growth simulators with databases, evaluation and optimisation routines, and making use of GIS and visualisation routines, the approach incorporates all-important components of a 'full-service' DSS as mentioned by Rauscher (1999). It compares favourably with forest management DSS developed in North America (Mowrer et al. 1997; Rauscher 1999). Those DSS can be arranged by their spatial applicability – region, estate, project – or by the area of decision support covered, e.g. simulation of vegetation dynamics, economic analysis, disturbance simulation, visualisation, etc. (Sodtke et al. 2004). Respective DSS in central Europe (Thees and Riechsteiner 2001; Vacik and Lexer 2001; Mosandl and Felbermeier 2003) were mostly found to be in an early stage of development. Using individual-tree growth simulators is especially helpful for strata planning and enterprise simulation. Such simulators generate the most accurate solutions, using the individual-tree information provided by enterprise inventories (Pretzsch et al. 1998).

By enabling a user to fix preferences for several management objectives, the DSS allows for a multi-criteria evaluation of management alternatives. Identification of the best management alternative results from a combined procedure of evaluation and optimisation with an adjusted heuristic Tabu Search algorithm. Evaluation comprises fuzzy inferring strategies, enabling the processing of vaguely defined expert knowledge (Zimmermann 1987, 1996). Resulting utility values per management objective are aggregated to total estate utilities, serving as target functions for mathematical optimisation. Evaluation results given by the DSS help with estate-level decisions. However, the DSS does not on its own dictate an optimum strategy to the decision maker. Rather, it allows the decision maker to select the most suitable strategy from a range of alternatives.

11.5
Perspectives

Methodical testing is now complete, but the DSS prototype is not yet fully validated. Further testing with inventory data from our practical partners is currently being carried out. In the future, the presented approach will be developed and advanced, for example, in integrating more decision variables (referring to regeneration, planting, pruning, etc.) and integrating further objectives and indicator variables (economic, structural indicators, etc.). Furthermore, it is planned to convert the program into a stand-alone software – independent of the programming software and the operating system – to be used by forest managers and planners and for education purposes.

The combination of simulators, evaluation and optimisation algorithms and several visualisation systems appears to be trend-setting for decision support at estate level (Pretzsch 2003). Such integrative systems can reveal the objective criteria and preferences of decision makers, and may highlight decision pathways and possible consequences of different management alternatives in the long run. They enable participation of an interested public in the decision processes (Pretzsch 2003; Pretzsch et al., this Vol.) and allow debate over future forest management with politicians and association members, thus paving the way for strategic objective-orientated forest enterprise management.

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The Use of Tree Models for Silvicultural Decision Making

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Abstract. In the last decade, Lower Saxony's forest policy has undergone a major shift from pure stands to mixed-species stands. Consequently the Forest Research Station of Lower Saxony (NFV) focused its research on the construction of a tree growth model. This growth model was incorporated into a computer software program (BWINPro) which allows for forest growth simulation and strategy development. In addition, this program can be used for permanent plot inventory to calculate future growth, thinning and timber harvest at the enterprise level. The thinning and the amount of timber harvested by critical diameter are estimated by a rule-based system. This program has recently been extended to a decision support system (KSP_DSS).

12.1
Introduction

During the last decade, there has been a major shift in Lower Saxony's forest policy goals from creating and maintaining pure stands to encouraging mixed-species stands. This policy is defined by the LÖWE (long-term ecological forest development) program (Otto 1989, 1991). In essence, the LÖWE program can be described by the following rules:

- Soil protection and site-adapted choice of species.
- Enlarging the percentage of broadleaf and mixed forest stands.
- Ecological tolerance.
- Preference for natural regeneration.
- Improvement of stand structure.
- Target diameter harvesting.
- Conservation of old trees, rare and endangered species.
- Establishment of a network of protected forests.
- Guarantee of special forest functions.
- Tending of forest edges.
- Ecological forest protection.

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Growth Models for Europe

- Game management appropriate to the ecosystem.
- Use of forest technology appropriate to the environment.

The 13 rules have created a great deal of uncertainty in forest planning and in the understanding of stand development. Yield tables, designed for pure stands and a fixed treatment, were suddenly rendered obsolete for forest planning and management. At the stand level, most foresters still have a clear idea about their 'right' silvicultural strategy.

Planning at a commercial and ecosystem level, however, is a more complex and confusing process. With its wide-ranging and sometimes conflicting goals, the LÖWE program makes it difficult to determine sustainability and to manage forest districts. New tools were needed for making decisions at the ecosystem level. Consequently the Forest Research Station of Lower Saxony (NFV) focused its efforts on research on mixed forest stands and constructing a tree growth model for nearly all possible mixtures of species using flexible treatments. Previously, the state's Forest Planning Agency (NFP) established management plans by prescribing treatments on a stand-by-stand basis with the help of yield tables. Now the NFP develops management plans that use training plots and permanent inventory plot data to guide decision making. As a result the new planning procedure is more cost effective and better adapted to the LÖWE program (Böckmann 2002). Single tree growth models are the most appropriate tools for updating high resolution single tree inventory data because they allow for growth prognoses without averaging tree level into stand level information (Pretzsch 2001). Therefore a breakdown of updated stand level variables into tree variables, as is required for most planning decisions, is valuable.

12.2
The Growth Model BWINPro

The NFV has a wide net of approximately 750 growth and yield experiments over northwest Germany. These data and the additional data of new mixed species experiments were used to construct a statistical forest tree growth model. The growth of each tree is estimated by regression functions that primarily include the four independent parameters of crown surface area, crown competition and the change of crown competition due to thinning and age. The coefficients of these functions are determined for all major species. The crown parameters were used to make the model sensitive for mixed species stands. Tree coordinates were not used, since they were unavailable for most of the study trees. Therefore the model may be classified as a distance-independent tree model. Mortality is estimated by a critical value of crown competition for each species. Currently an ingrowth model has been added. The first version of the model was released in 1996 (Nagel 1996). In the meantime the model has been reparameterised (Nagel et al. 2002). The model and a detailed user's guide are available on the internet[1]

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[1] http://www.nfv.gwdg.de/A/BwinPro/bwinpro.php

For practical applications the tree growth model was incorporated into a computer software program (BWINPro), which can simulate forest stands. Besides the growth-determining functions, the program consists of many routines for:

- data input and storage;
- generation of missing data;
- thinning;
- selecting crop trees;
- visualisation;
- assortment calculation;
- wood quality;
- various HTML-formatted output;
- user's guide.

Thus far, this program mainly has been used for research and for the development of silvicultural recommendations for stand treatment according to the LÖWE program (Hillebrand 1997; Spellmann 1997; Hauskeller 1998; Konitzer 2000; Rademacher et al. 2001), but it also has been available to foresters in the field. Distributing the program over the internet to the public from the beginning has helped to improve both the growth model and the computer program as external users provide comments and criticisms. Recently, the program has become integrated into the forest planning process of the NFP.

12.3
BWINPro in Forest Planning

In forest planning tree growth models can be used for different reasons (Fig. 12.1). First, they can be used to develop silvicultural strategies for single stands or strata. This is an important task when determining general strategies. However, when setting up management plans, silviculturists cannot develop individually tailored strategies for all stands, because there was no automatic routine to find an optimal treatment for each stand. Interactive simulation of all stands would be too time-consuming. Thus the growth simulator BWINPro is used to conduct growth simulations based on the application of different silvicultural treatments to experimental stands with typical species composition. This procedure enables the forest service to set up main management guidelines for stand types instead of an optimised treatment for each single stand. Single stand optimisation of treatments is limited anyway because of the lack of measured sin-

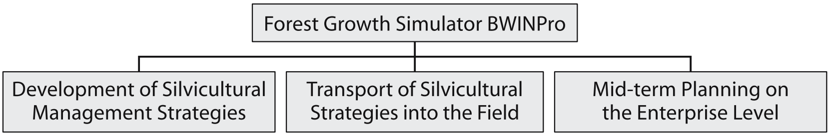
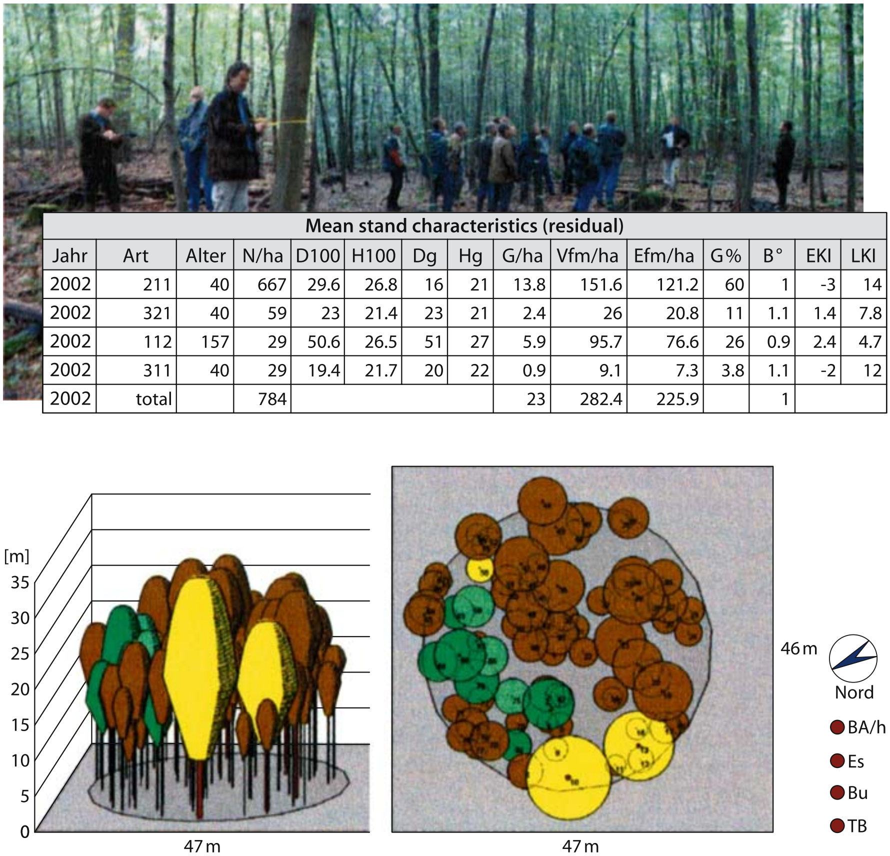


Fig. 12.1. Main application areas of the forest growth simulator BWINPro within the forest planning process of Lower Saxony

gle tree and stand information at the stand level if the sample-based inventory is adapted to the enterprise level, as in Lower Saxony (Böckmann et al. 1998).

Forest growth simulators can also be used in teaching and transferring silvicultural strategies to the field (Fig. 12.2). During the planning process these recommendations are discussed in the field at up to ten training plots per forest district, using the BWINPro program to provide stand information and visualisation. The BWINPro simulation program is used by the NFP as an educational tool, allowing people in the field to visualise and discuss the treatment of the special



Mean stand characteristics (residual)

Jahr	Art	Alter	N/ha	D100	H100	Dg	Hg	G/ha	Vfm/ha	Efm/ha	G%	B°	EKl	LKl
2002	211	40	667	29.6	26.8	16	21	13.8	151.6	121.2	60	1	-3	14
2002	321	40	59	23	21.4	23	21	2.4	26	20.8	11	1.1	1.4	7.8
2002	112	157	29	50.6	26.5	51	27	5.9	95.7	76.6	26	0.9	2.4	4.7
2002	311	40	29	19.4	21.7	20	22	0.9	9.1	7.3	3.8	1.1	-2	12
2002	total		784					23	282.4	225.9		1		

Fig. 12.2. Teaching and discussing silvicultural strategies at a training plot and using the tree growth model for the evaluation of markings of thinnings and crop trees. Abbreviations in table: *Jahr* year; *Art* species code; *Alter* age; *N/ha* number of stems (*n*/ha); *D100* and *H100* diameter (cm) and height (m) of strongest 100 trees; *Dg* and *Hg* diameter (cm) and height (m) of mean quadratic diameter; *G/ha* basal area (m^2/ha); *Vfm/ha* total volume inside bark (m^3/ha); *Efm/ha* harvest volume (m^3/ha); *G%* basal area percentage; *B°* degree of stocking; *EKl* yield class; *LKl* maximum volume increment (m^3/year)

training plots. Crop tree markings and thinnings can be evaluated as well as the future development of the plot.

The effects of different management alternatives can be illustrated, e.g., the improvement of diameter growth of crop trees caused by thinnings from above compared to thinnings from below. Since assortment and wood quality routines have been incorporated, the simulator allows the user to predict the effect of different crop tree selections and thinning regimes on assortment structure and wood quality composition. These empirically well-founded output results are very valuable when comparing the benefits and costs of different treatments and when convincing foresters of the appropriateness of main management guidelines.

Most forest growth simulators have a visualisation routine that can be used in discussions among foresters and when it comes to participation of the public. The graphical output of the program BWINPro has been used very successfully in public hearings regarding communal forests. BWINPro provides three alternative routines for visualisation. The VRML (Virtual Reality Modelling Language) routine allows the user to 'virtually' walk through or fly over the stand. The program has also been used in combination with a geographical information system (GIS) and landscape visualisation program (Knauft 2000).

For mid- and long-term planning the optimal silvicultural treatment of each stand may not be the best solution at the forest enterprise level. For example, if a stand contains a surplus of trees with larger diameter, the best solution at the stand level would be to harvest these within the next few years. At the enterprise level, however, such a decision could lead to problems in manpower and a shortage of merchantable timber of the next management cycles. By applying the growth model to forest inventory data, it is possible to calculate the growth, estimate the amount of thinning and harvest by assortments, and evaluate how much of the forest enterprise area corresponds with the objectives of the LÖWE concept. The extension of the growth simulator from a single stand simulator to a management tool for strategic forest planning based on permanent sample plot inventories is the main topic of the work package 'Policy Demo' within the EU-ITM project. Chapter 4 gives a detailed specification of this growth-simulator-based decision support system KSP_DSS for mid-term forest planning in Lower Saxony (see also Sodtke et al. 2003).

12.4

Decision Support in Forest Planning

Forestry has a long tradition in Germany and this tradition influences the work of foresters and their acceptance of new technology. By integrating the tree growth model BWINPro into forest practice we have gained much experience concerning people's psychology. For instance, we have learned that the tree growth model is accepted only because it provides information and does not provide a solution. The foresters want to understand why a model gives a certain suggestion, and ultimately they want to make the decisions themselves.

The same is true for forest planning and has to be taken into consideration when we think about decision support systems. On the one hand, foresters need support for handling the huge amount of information and restrictions when setting up a management plan. On the other hand, they want to remain in control of the system and need to understand the outcome, so that they can explain it to the people in the field. As a part of the EU-ITM project we had the opportunity to create a decision support system for setting up management plans in close cooperation with our partners from the NFP. The idea was to create a fairly simple, useable, straightforward solution rather than a complete DSS. Therefore, we decided to handle the two tasks 'development of silvicultural strategies, teaching and implementation to the field' and 'mid- and long-term planning on an enterprise level' separately.

Default silvicultural strategies have been developed using the tree growth simulator BWINPro at the stand level with data from experimental and training plots. The scenario simulations for planning purposes result in general recommendations on how to treat a certain management strata, whereas the decision variables are allowed to differ from the defaults. A management stratum or silvicultural unit is defined by the current forest stand type (BT) and the desired forest type of management objective (WET). Together with our partner from the NFP, we identified key questions for the decision support system which the system should solve in order to assist mid- and long-term planning. These are:

- Concerning yield prognosis and scenario simulation:
  - Mid-term amount of thinning?
  - Mid-term amount of timber harvest?
  - Actual and future frequency, volume and basal area distributions by DBH classes?
  - Actual and future amount of regeneration area?
  - Actual amount of habitat (standing dead wood, etc.) trees?
  - Amount of the forest area that is covered by specific BTs, assigned WETs and resulting combinations (management strata, silvicultural units)?
  - Transition status of the BTs compared with the assigned WETs?
  - Actual and future forest area distribution by thinning urgency?
  - Actual and future forest area distribution of different stand structures?
  - Influence of different management strategies applied to the management strata?
- Concerning economical analysis and analysis of sensitivity:
  - Actual and future assortment structure of timber?
  - Actual and future wood quality structure of timber?
  - Influence of different price-cost relations on the operating result?

For the scenario simulation we found that our partner was mostly interested in altering the decision (key) variables target diameter, thinning strength and restrictions of thinnings concerning wood quality, pruned trees and habitat trees. The detailed conceptional framework of the DSS for mid- and long-term planning concerning the specific demands of the forest planning agency (NFP) of Lower Saxony is described below. The framework contains the following sub-systems: a database; analysis of the current situation and the scenarios; updating of the current status considering difference thinning and harvest regimes (scenario simulation); and graphical presentation of simulation results.

12.4.1
Database

The main purposes of the database are to store inventory data and simulation results and provide a standardised data interface for the growth simulator. Different types of tables containing inventory information and simulation results as well as decision variables can be combined within one database file. The permanent sample plot inventory data, consisting of plot and tree information, are organised in a MS-ACCESS database to ensure compatibility with data formats provided by the NFP. Additionally the use of a database allows for database programming using structured query language (SQL) statements, which facilitates multiple stratification by plot and tree variables. These stratification options are part of the main enhancements to extend the growth simulator into a DSS for mid-term forest planning.

Inventoried tree variables are tree species, DBH, age, tree coordinates and representative measurements for tree height and crown base, as well as information about timber quality, pruning height and bark peeling damage. Important plot variables are site, BT and weighting factors from the two-phase inventory design (Dahm and Saborowski 1998). In addition, there is information concerning the height distribution of regeneration (less than 7 cm DBH) differentiated by tree species and regeneration type. The database also provides information about decision variables that define default treatments and the rules for the assignment of the WETs to inventory plots.

12.4.2
Analysis of the Current Situation and Scenarios

The DSS includes a sub-component to analyse the current status and alternative future scenarios. With the conversion from pure to mixed species stands the determination of sustainability has become more complicated. One approach to overcoming the problem of missing optimal guidelines to ensure sustainability is to conduct growth simulations and estimate the future state variables and utilisation potentials of those resources for which sustainability is demanded. Thus, by altering decision variables, users can obtain better adapted management plans in an iterative process. The most important variables in evaluating different aspects of sustainability are tree-species-specific diameter and assortment structures for future states, thinning and harvest amounts. Assortment structures provide the basis for the evaluation of future economical sustainability. However, they can also be used for validation of sustainability concerning ecological aspects such as the impact of harvest alternatives, e.g. different thresholds for upper diameter, on nutrient discharge and supply (Rademacher et al. 2001). Diameter structures are useful for estimating long-term resources for target diameter harvest as well as the amount of very large trees deemed worthy of preservation. The DSS allows for calculation of mean frequency and volume distributions by DBH and assortment classes for multiple stratification options (combinations of site, BT, WET). Assortment settings are adjusted by threshold values for upper diameter and timber length, bark reduction and length/diameter excess (Schmidt 2001; Nagel et al. 2002). The assortment routine is also applied to the estimated amount of thinning and harvest by target diameter. Inventory information concerning timber quality, pruning height and bark peeling damage can be used for a more detailed stratification of inventory information and simulation results.

A further type of information useful in the evaluation of sustainability aspects is that of the current and future proportions of the forest enterprise area which are covered by stands of certain properties. For these requirements the DSS provides frequency distributions of (weighted) sample plots grouped by stand variables such as basal area, total volume, dominant height, volume increment, amount of deadwood, amount of thinning and target diameter harvest, which represent percentages of the forest area. The distribution type that describes the forest enterprise area by classifying sample plots can be calculated for the whole district as well as for individual strata (combinations of site, BT, WET).

As forest enterprise managers endeavour to convert pure stands to mixed-species stands in accordance with the LÖWE program, they must consider how the increased percentages of broadleaved tree species affect calculations of the planting area within planning periods, and the associated quantities of work and costs. The effect of the LÖWE program on tree species composition at the enterprise level can be illustrated in order to support negotiation processes with different forest interest groups. The automatic assignment of WETs is controlled by a decision rule, which includes rankings of feasible WETs by stand and site types. The final selection of a WET results from the intersection of the rankings, which are defined by current stand type and site. An additional analysis provides an area percentage distribution of BTs and WETs within the forest enterprise. The resulting combinations of BTs and WETs are used to stratify sample plots into management units to which specific uniform thinning and harvesting regimes are applied. By comparing the actual and desired species composition for BT–WET combinations, deviations between species composition can be identified and considered in the definition of the thinning and harvest control variables. Based on results from the initial runs, the program user can then adjust the default values for controlling thinning, harvest and artificial regeneration planning in order to accomplish the desired species composition of a WET in a shorter time range. Rare BT–WET combinations (by definition less than 5% of the forest district area) can be combined into categories that are defined by the dominant tree species of a plot.

The conversion process defined by the LÖWE program is affected by the current regeneration status and its future development also. Hence for planning planting activities and illustrating the conversion process to the public, the forest district manager needs information about the current regeneration structure and its development. Another important aspect to consider is the influence of regeneration status on the assignment of WETs to inventory plots. If density and height of the advanced regeneration reach certain threshold values, the assignment is no longer determined by the actual stocking but instead by the composition of the regeneration species.

Regeneration analysis provided by the DSS is based on specific height distributions of inventoried species. The results can also be stratified by site and BT–WET combinations.

Future development of the current regeneration status needs to be forecasted if a comprehensive base for mid-term planning of planting activities and a realistic long-term planning of thinning and harvest amount are to be provided. This part of the DSS is currently under construction and will consist of four sub-components:

1. A component that allows for specification of artificial planting areas and densities for management strata (silvicultural units).
2. A component that forecasts the establishment and structure of regeneration for inventory plots with no current regeneration.
3. A component that forecasts the development of the regeneration structure as shifting of the three inventory height classes over time.
4. A component that estimates the ingrowth rate of trees exceeding a DBH of 7 cm during a prognosis period.

The LÖWE program includes the conservation of old trees and rare and endangered species. Hence trees with specific nature conservation functions and a DBH exceeding 30 cm are assessed in the permanent sample plot inventory in Lower Saxony. For analysis of ecological aspects, the DSS allows for the calculation of frequency, basal area and volume distributions by DBH classes of standing dead trees, trees with cavities and aeries. Multiple stratification of the results by tree and plot variables as described above can then be conducted.

12.4.3

Updating of the Current Status Considering Different Thinning and Harvest Regimes (Scenario Simulation)

After the generation of missing information (i.e. unmeasured heights and crown information of single trees), single tree growth is described using growth functions for DBH and height and static models for crown base and crown width from the growth simulator BWINPro (Nagel et al. 2002). Tree growth is estimated, taking into account a single tree competition index to ensure a prognosis sensitive to different silvicultural regimes.

Thinning type and strength are based on the approach by Spellmann et al. (1999), which defines thinning strength in relation to maximum stand density for different dominant height classes (Döbbeler and Spellmann 2001). Deviation from the appropriate stand density defined by Spellmann et al. (1999) is used to determine priorities of thinning to ensure stability by highlighting critical sample plots. An interface allows for changing the default settings for thinning/harvest regimes by specifying differing threshold values for target diameter, thinning strength, thinning range and maximum harvest and thinning volume. Different settings can be specified for each management stratum (silvicultural unit). This feature is important because different combinations of current and future states require individually tailored silvicultural regimes for a realistic prognosis. For example, after analysing current tree species composition, the decision variables can be modified to exclude particular tree species from thinning if their proportion should be increased with respect to the WET. This type of thinning regime specification could be described as a data-driven approach (Rauscher 1999).

12.4.4
Graphical Presentation of Simulation Results

The output of all the calculated distributions outlined above is displayed as a series of bar charts. Percentages of the forest district area that account for certain BT–WET combinations (silvicultural units) are displayed as pie charts. Scenario simulation results are stored in a compressed form, including the associated silvicultural regimes, in an MS-ACCESS database. These results allow for advanced analyses such as the multi-criteria validation of different management options (Albert 2003) and the identification of optimal solutions using external software packages (e.g. JLP, Lappi 1992). Figure 12.3 shows a flow chart for the application of the DSS in mid-term planning and scenario simulation.

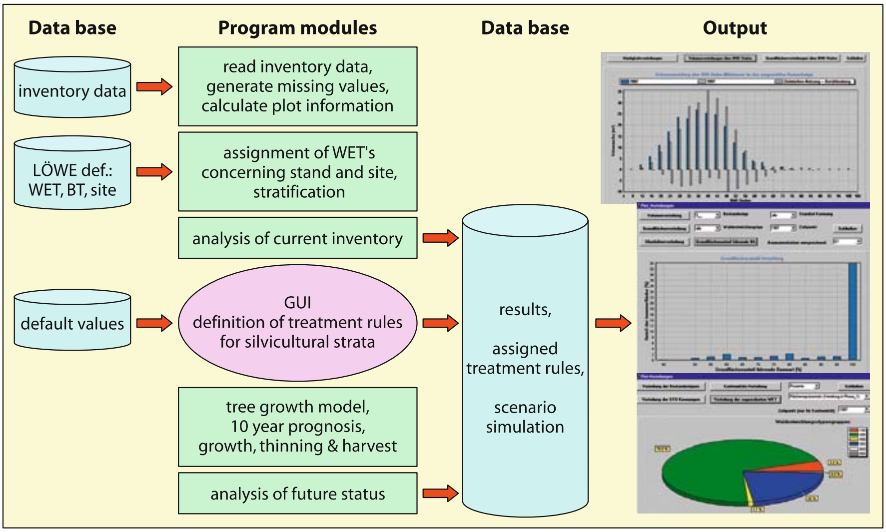


Fig. 12.3. Program organisation of the decision support system KSP_DSS. *GUI* Graphic user interface

12.5 Examples

12.5.1 Automatic Assignment of Forest Types of Management Objective (WET) and Stratification of Silvicultural Units

First we want to illustrate the influence of specific conversion rules that ensure the achievement of the goals and objectives of the LÖWE program, such as increasing broadleaf percentage and percentages of site-adapted tree species. We use permanent sample plot inventory data from three different forest districts located in southern Lower Saxony on predominantly variegated sandstone (I) and limestone (II) and in the 'Lüneburger heathlands' on predominantly sandy soils of glacial origin (III). Results of the automatic assignment of WETs concerning site

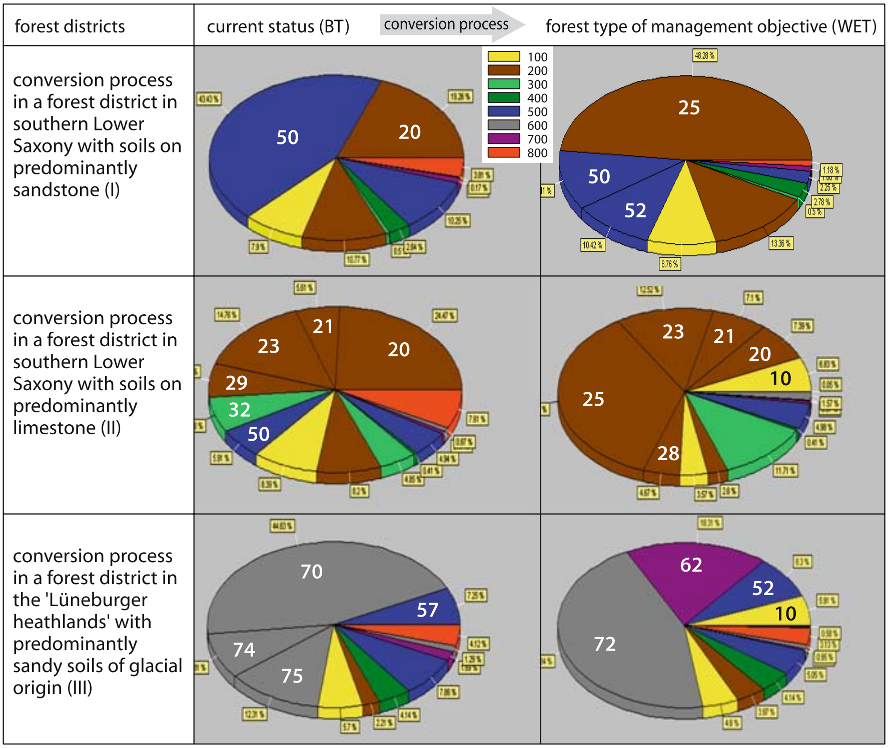


Fig. 12.4. Proportions of forest district area covered by forest types of management objective (WETs) as a result of an automatic assignment using the decision support system KSP_DSS in three different forest districts. Additionally, the distribution of forest district area proportions that are covered by different actual stand types (BTs) is calculated

Table 12.1. Coding of current stand types, management objective, forest types and silvicultural strata as used in Figs. 12.4 and 12.5

Coding	Tree species combination in BTs and WETs (Fig. 12.4)
100	All types with dominant species ‚oak‘
200	All types with dominant species ‚beech‘
300	All types with dominant species ‚broad-leaved species with high rotation age‘
400	All types with dominant species ‚broad-leaved species with low rotation age‘
500	All types with dominant species ‚Norway spruce (all spruces)‘
600	All types with dominant species ‚Douglas fir‘
700	All types with dominant species ‚Scots pine (all pines)‘
800	All types with dominant species ‚European larch (all larches)‘
900	All types with dominant species ‚white fir (all firs)‘
20	pure beech type
25	Dominant beech with Norway spruce type
52 etc.	Dominant Norway spruce with beech type
	Tree species combination in silvicultural strata (Fig. 12.5)
50_25	Conversion from pure Norway spruce to dominant beech with Norway spruce
20_25	Conversion from pure beech to dominant beech with Norway spruce
1_1 etc.	Dominant oak which remains dominant oak

properties and the current stand type (BT) are presented in Fig. 12.4. The coding of current stand types (BT) and stand types of management objective (WET) is described in Table 12.1. All segments in the pie charts that are not designated with highlighted numerals represent species combinations of minor importance, which therefore are grouped by dominant species. Minor importance for BTs and WETs is defined as a percentage of less than 5% of forest district area before grouping by dominant species.

Because of the different site conditions and current stand composition of the forest districts, widely varying distributions of WETs result. At present, forest district I is primarily composed of stand types with dominating Norway spruce. Prospectively the main changes are a heavily increased proportion of stands dominated by beech. Norway spruce-dominated stands are decreased from approximately 50 to 25% of the forest district area. Stand types dominated by oak or Douglas fir are slightly increased. In the limestone-dominated forest district II, the high proportion of stands that are dominated by broadleaved tree species is increased even more by enlarging the proportion of stand types that are dominated by beech. The proportion of stand types dominated by oak is also increased slightly. Stand types dominated by conifer trees, especially Norway spruce, are decreased even though their current proportion is only around 20% of the forest district area.

Nevertheless, there are major differences between the forest districts I and II due to the rule-based selection of the additional tree species for the beech-dominated stands. As outlined in the Introduction to this chapter, one main aim of the LÖWE program is enhancing the proportion of mixed species stands. On sandstone (typical for forest district I) the additional tree species in most beech-dominated stands is Norway spruce, and where Norway spruce is the dominant species, it is very often combined with beech also. However, in forest district II the variety of additional tree species in beech-dominated stands is larger. In forest district II beech is often combined with Norway spruce, oak, European larch and broadleaved tree species with high rotation age.

Forest district III is dominated by pure Scots pine stands and mixed stands of Scots pine and Norway spruce. The conversion process according to the LÖWE program will lead to WETs that are still dominated by conifer tree species and the percentage of Douglas fir-dominated stands is increased heavily. In all WETs of higher importance, beech is used as an additional tree species. There is a higher percentage of WETs with dominant oak compared to forest districts I and II.

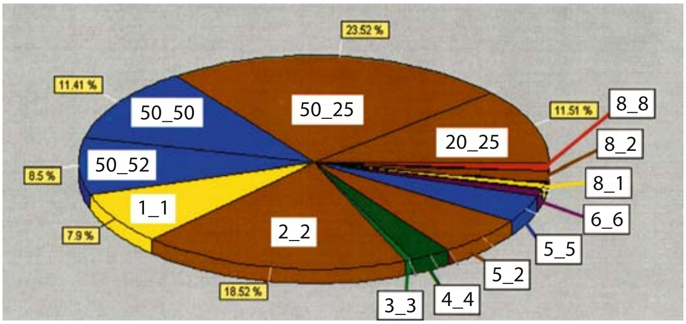


Fig. 12.5. Automatic stratification of silvicultural units (combinations of BT and WET) and associated proportions of forest district area using the decision support system KSP_DSS for forest district I

The illustrated assignment of WETs provides the basis for a stratification of silvicultural units (management strata). All inventory plots with the same combination of current stand type (BT) and stand type of management objective (WET) are classified into the same silvicultural unit (Fig. 12.5). For one silvicultural unit the same set of values for the decision variables (e.g. target diameter) is applied. The differences in age within a stratum are considered directly using the thinning and harvest rule base (Spellmann et al. 1999) by definition of different dominant height classes for which different treatments can be applied. The classification of separate BTs and WETs combinations of less then 5% of the forest district area are grouped by the dominant species regarding both current status and type of management objective. Figure 12.5 shows the resulting silvicultural units and their percentages of forest district area for forest district I.

12.5.2
Scenario Simulations Applying Different Silvicultural Treatments

Since the structure of the current status and the type of management objective are the main silvicultural factors influencing the conversion process, the DSS allows for the specification of specific treatments for each silvicultural unit. The effect of the decision variables target diameter, maximum harvest volume and thinned basal area is presented using the permanent sample plot data of stratum 50_25 (conversion of pure Norway spruce to dominant beech with Norway spruce) from forest district I (Fig. 12.5). A comparison is made using the default values and a second set of decision variables representing a more intensive alternative of thinning and a more moderate alternative of harvest (Table 12.2). Additional threshold values with respect to assortment calculation are a lower non-utilisable segment of 2 m length with root rot and an upper diameter of 13 cm

Table 12.2. Two alternatives of decision variables applied in scenario simulations for the silvicultural stratum 50_25 (conversion of pure Norway spruce to dominant beech with Norway spruce) from forest district I

Silvicultural treatment	Target diameter (cm)	Maximum harvest volume within 10 years (m^3/ha)	Maximum thinning volume within 10 years (m^3/ha)	Natural stocking degree for H_{dom} class 14–20 m	Natural stocking degree for H_{dom} class 20–26 m	Natural stocking degree for H_{dom} class >26 m
Default values (scenario I)	45	100	70	0.7	0.75	0.8
Alternative values (scenario II)	55	50	90	0.6	0.65	0.8

with bark simultaneously exceeding a minimum length of 5 m for round timber. These threshold values for assortments have been applied for both scenario simulations.

The overall standing volume is 387 m^3/ha in bark at the year 2000 and 480 m^3/ha in bark at the year 2020 for scenario II and 399 m^3/ha in bark for scenario I. The volume distribution by DBH classes for the scenario simulation using default values shows the increasing amount of harvested volume exceeding the DBH class of 44 cm as a result of choosing a target diameter of 45 cm (Fig. 12.6). In the decades following 2020, an increasing amount of timber will be harvested according to target diameter, again pointing out the problem of oversized timber if target diameter harvesting is not applied consequently. The associated volume distribution by assortments has its emphasis at classes L2b and L3a, which is the production target for Norway spruce in Lower Saxony.

The volume distribution in scenario II shows an increasing amount of target diameter harvest starting at DBH class 56 cm because the target diameter was raised to 55 cm. The overall amount of target diameter harvest is 82 m^3/ha in bark (54 m^3/ha merchantable sorted volume) compared to 176 m^3/ha in bark (116 m^3/ha merchantable sorted volume) in scenario I. For a comparison, the thinning volume of trees exceeding 45 cm DBH in scenario II was summed up with the target diameter harvest amount of trees exceeding 55 cm DBH. In scenario II a higher proportion of the assortment classes L1b and L2a is obtained so that the assortment structure is less favourable than in scenario I. All values are periodic calculations for 20 years taking into account all plots from the 50_25 stratum.

The overall thinning volume for trees less than 45 cm in DBH is 130 m^3/ha in bark for scenario II and 106 m^3/ha in bark for scenario I. While the thinning intensity is higher in scenario II, it cannot completely counteract the less intensive target diameter harvest, so that there is a higher accumulation of timber in DBH classes from 40 to 56 cm. This might cause a problem of oversized timber in the future if the huge amount of harvest by target diameter cannot be sold for some years because of sale problems or limited available labour. For Norway spruce, the enhanced values for target diameter cause an increasing risk of defect by root rot disease.

Figure 12.7 presents 40- and 60-year prognoses of the assortment structure assuming the decision variables defined for scenarios I and II. These scenarios give an impression of future marketing problems caused by oversized timber or irregular harvest amounts. Even in scenario II the proportion of assortment class L3b only slightly increases and no problem with oversized timber will occur if all timber can be sold. However, the harvest amounts are quite variable with 54 m^3/ha in the first, 126 m^3/ha in the second and 174 m^3/ha of sorted merchantable volume without bark in the third 20-year period. This is equivalent to 82, 188 and 255 m^3/ha in bark including all volumes up to a 7-cm upper diameter. The huge harvest amount in the second and especially the third 20-year period, which is necessary to avoid assortment classes exceeding L3b, might cause marketing problems, and unsold timber volume will result in oversized timber again. In scenario I only a little harvest volume will exceed class L3a owing to the smaller target diameter. The harvest amounts are more uniformly distributed with 116, 197 and 156 m^3/ha of sorted merchantable volume in the three 20-year periods. The equivalent

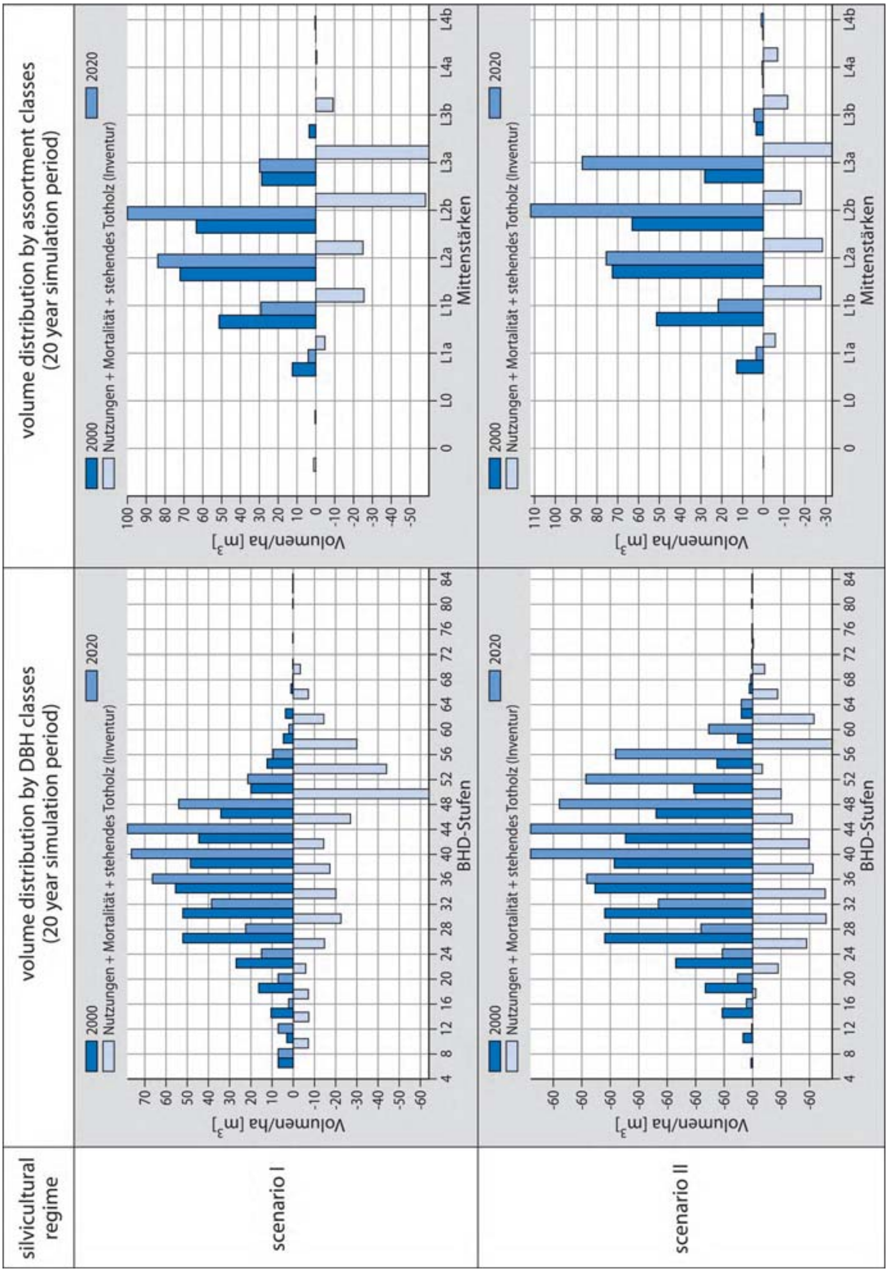


Fig. 12.6. Results of the two scenario simulations (20 years) for the silvicultural stratum 50_25 (conversion of pure Norway spruce to dominant beech with Norway spruce) from forest district I. *Left graph* presents volume distributions by DBH classes and *right graph* volume distribution by assortment classes. *Blue bars* represent the actual state (2000), *medium blue bars* the state

total volumes in bark are 176, 300 and 236 m^3/ha. Scenario I results in more uniform harvest amounts, but the total amount of merchantable timber is even higher so that marketing problems will occur as well. Another problem might be that the supply of timber after 2060 will decrease rapidly in scenario I. In this context we have to consider that an ingrowth rate is not yet estimated by the simulator. Nevertheless, the conversion from pure Norway spruce stands to stands with dominant beech with Norway spruce will decrease the ingrowth rate of Norway spruce.

Therefore, a combination of both scenarios probably would provide a better alternative using threshold values of scenario I for the first period and a slightly increased target diameter and decreased maximum harvest volume for the later periods.

The example given in this section illustrates a typical problem in strategic forest planning and the application of the DSS in providing information to support problem solving and decision making. The presented volume distributions by DBH and assortment classes are only one part of the results that can be calculated with the DSS. The program provides several distribution types to describe user-defined strata or the total forest enterprise:

- Distributions by DBH classes and assortment classes:
  - Frequency distribution;
  - Basal area distribution;
  - Volume distribution (total volume exceeding 7 cm);
  - Volume distribution (merchantable butt log volume);
  - Volume distribution (merchantable upper log volume);
  - Volume distribution (non-merchantable volume of stumps, volume violating assortment threshold values, non-merchantable volume of root rot segments, etc.).

12.5.3
Further Description for Silvicultural Units or Any User-Defined Stratification of the Forest District

The above section illustrates the kinds of information provided by the DSS to describe silvicultural units or the whole forest enterprise based on mean distributions of the current status, the future status and the amount of thinning and harvest. Additionally, percentages of the forest district area covered by stand types with certain properties can be calculated. Therefore, the proportions of stratified inventory plots that have been assessed in the field inventory phase have to be

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in 2020 and *pale blue bars* the amount of thinning and target diameter harvest within the planning period 2000–2020. Translations: *Nutzungen + Mortalität + stehendes Totholz* (*Inventur*) removal + mortality + standing dead wood (inventory); *Volumen* volume; *BHD-Stufen* diameter classes; *Mittenstärken* assortments by middle diameter

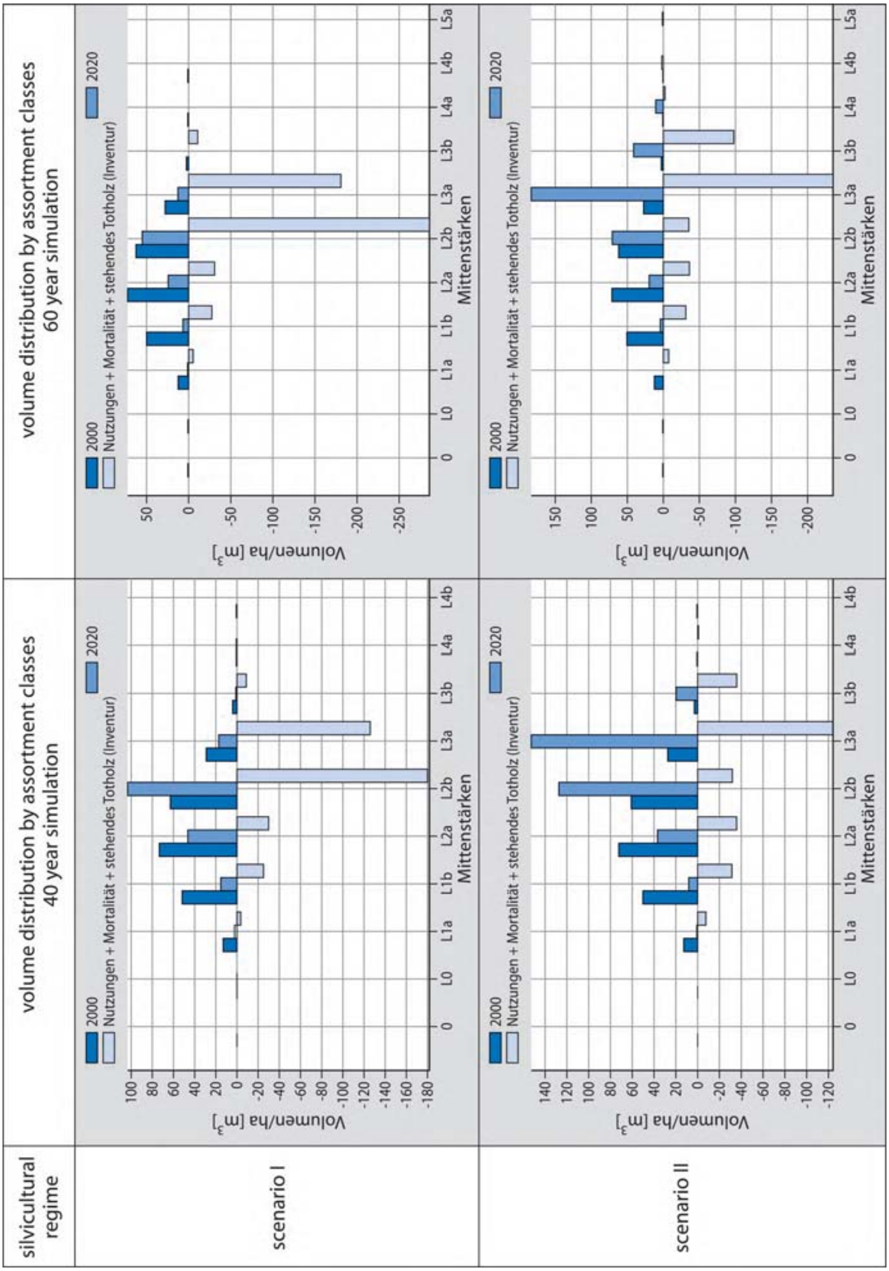

Fig. 12.7. Results of the scenario simulations (40 and 60 years) for the silvicultural stratum 50_25 (conversion of pure Norway spruce to dominant beech with Norway spruce) from forest district I. Volume distributions by assortment classes were calculated to provide information about changes in the assortment structure which could cause marketing problems.

converted by weighting because of the two-phase inventory design. The DSS allows for stratification by the stand variables listed below:

- Standing volume of living trees.
- Total basal area of living trees.
- Volume of standing deadwood (assessed by inventory).
- Volume of lying deadwood (assessed by inventory).
- Dominant height of the dominant tree species.
- Volume increment predicted by the growth simulator.
- Amount of thinning predicted by the growth simulator.
- Amount of harvest predicted by the growth simulator.
- Mortality predicted by the growth simulator.

State variables with changes due to tree growth, thinning, harvest and mortality, such as standing volume, are calculated for the current and future status. The distributions can be calculated for the whole forest district as well as for any combination of current status (BT), stand type of management objective (WET) and site. Figure 12.8 presents distributions of forest district percentages by selected stand variables for the silvicultural unit 50_25 from forest district I. For state variables the distributions describing the future status are displayed. Thinning and harvest activities in this example are controlled by applying the default values of scenario I (Table 12.2).

As mentioned in the introduction, the conversion to mixed species stands and the variety of possible treatments complicates the determination of multifunctional sustainability. Instead of theoretical optimal guidelines, as in the normal forest model, simulations can provide information about future forest development. Figure 12.9 presents distributions by increment and harvest amount classes for a 20-year prognosis applying control variables of scenario II, which can be compared with the associated distributions of scenario I (Fig. 12.8). In combination with calculations of mean distributions for silvicultural units as presented in Figs. 12.6 and 12.7 these distributions for describing forest area proportions are useful in determining adapted management regimes, ensuring sustainability of multiple forest functions.

12.5.4
Regeneration Status

Regeneration is assessed on each permanent sample plot as tree species-specific three-class height distribution with height classes 0–50, 50–130 and exceeding 130 cm and simultaneously falling below 7 cm DBH. This information is crucial for planning the necessary amount of artificial regeneration in the conver-

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Blue bars represent the actual state (2000), *medium blue bars* the state in 2040/2060 and *pale blue bars* the amount of thinnings and target diameter harvest within the planning periods. For translations, see Fig. 12.6

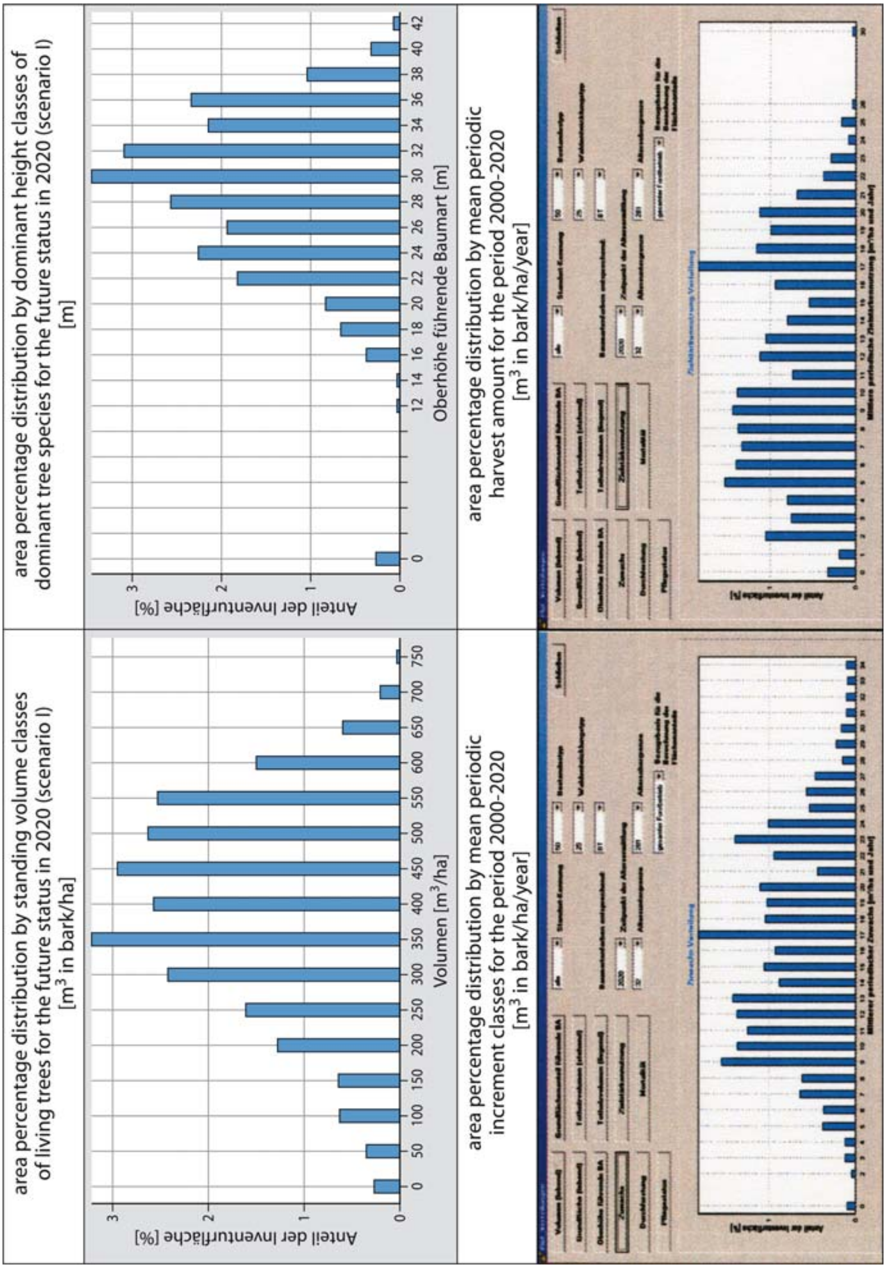

Fig. 12.8. Percentage distribution of selected stand variables for the silvicultural unit 50_25 (conversion of pure Norway spruce to dominant beech with Norway spruce) of forest district I applying the control variables of scenario I (default values)

sion process and for initialising models for prediction of regeneration development and ingrowth rates of trees exceeding a DBH of 7 cm during a growth period. As mentioned before, ingrowth cannot be predicted by the current version of the DSS. However, the program provides a comprehensive analysis of the current status, allowing for a calculation of tree-specific distributions of forest areas covered by different regeneration densities. Stratification can be conducted by current status (BT), stand type of management objective (WET) and site. Additionally, the program allows for a differentiation by height classes and varying damage states caused by browsing and bark peeling. The total forest district area and the area of the selected stratum can be defined optionally as reference for the calculation of area percentages. Figure 12.10 illustrates the analysis of regeneration status for the silvicultural unit 50_25 (conversion of pure Norway spruce to dominant beech with Norway spruce) from forest district I.

12.6
Summary

As forest management strategies change and as more forest land is converted to mixed-species stands, forest growth simulators have become more important for the development of silvicultural strategies and in conducting forest planning. However, in order to handle large amounts of forest inventory data, to set up forest management plans and to evaluate alternatives, forest growth simulators need to be extended to be a real help for decision making. By the funding of the ITM project the Forest Research Station of Lower Saxony has developed such a system in cooperation with the State Forest Planning Agency.

In the discussion with the cooperation partner we realised that the system needs to be simple and easy to use. At this point, automatic selection of the 'best' scenario is not desirable. Instead it is more important for the acceptance and comfort of our partner that the results are understandable and that the forestry professionals can use the program and the output to derive their own conclusions. The most important information for our partner is the current and future diameter (assortment) distribution by species and strata, as well as the distribution of thinning and harvest material. For analyses of different scenarios, the change in target diameter and the change of the thinning program by strata were of greatest interest. In the meantime we have developed a conceptional framework in the form of a computer program (see Fig. 12.3) which allows for mid- and long-term scenario simulations to support strategic planning. We have tested the program with real inventory data. The tests were satisfactory for our partner after minor adjustments.

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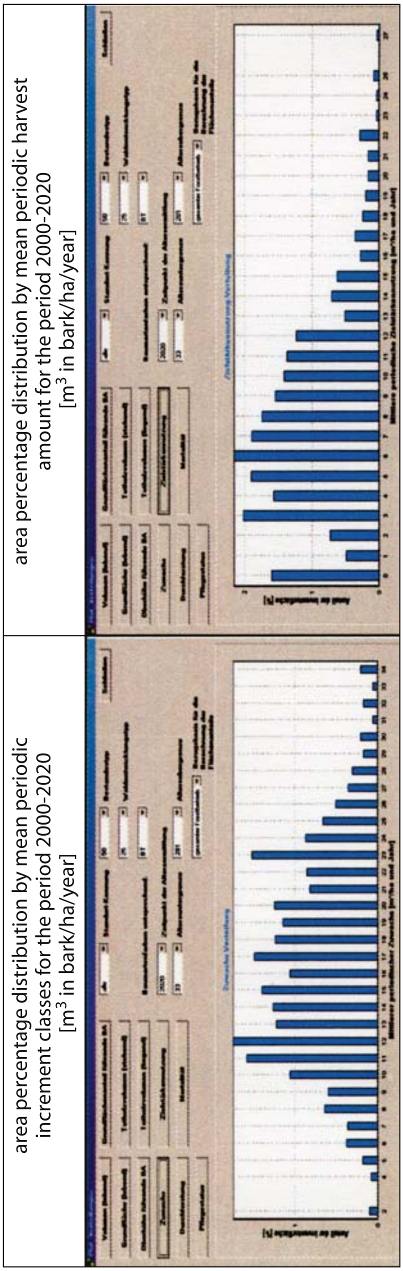

area percentage distribution by mean periodic increment classes for the period 2000-2020 [m^3 in bark/ha/year]

area percentage distribution by mean periodic harvest amount for the period 2000-2020 [m^3 in bark/ha/year]

Fig. 12.9. Percentage distribution of selected stand variables for silvicultural unit 50_25 (conversion of pure Norway spruce to dominant beech with Norway spruce) of forest district I applying the control variables of scenario II

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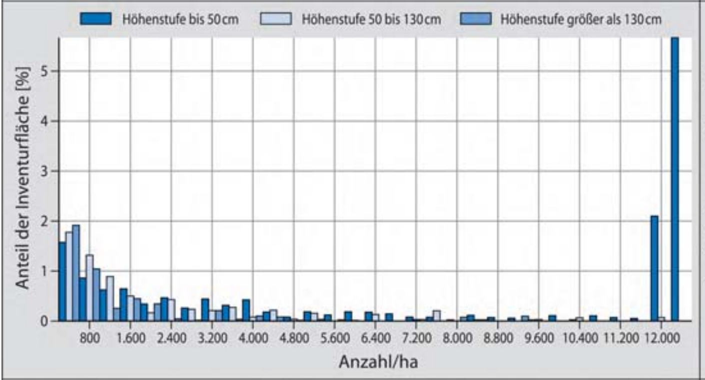
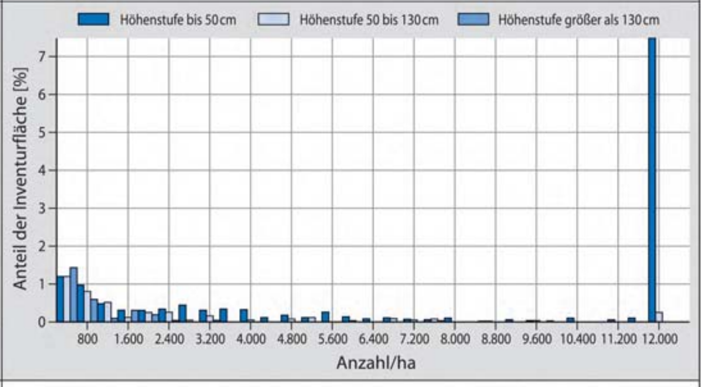
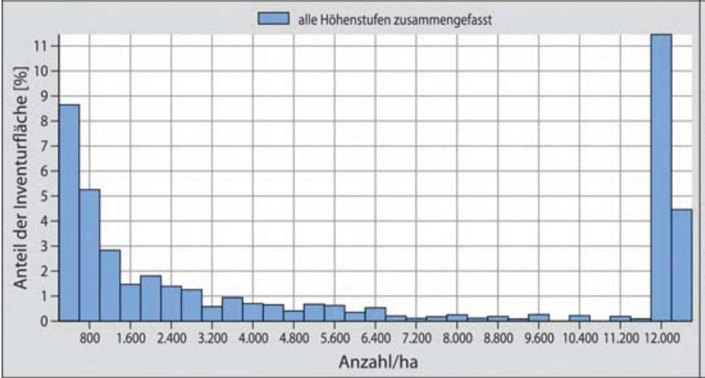
Fig. 12.10. Different area percentage distributions by density classes of regeneration. In the *upper graphs*, the color patterns of the bars represent the height class categories (*Blue bars* less than 50 cm in height, *medium blue bars* 50–130 cm in height and *pale blue bars greater than 1.3 m in height)*



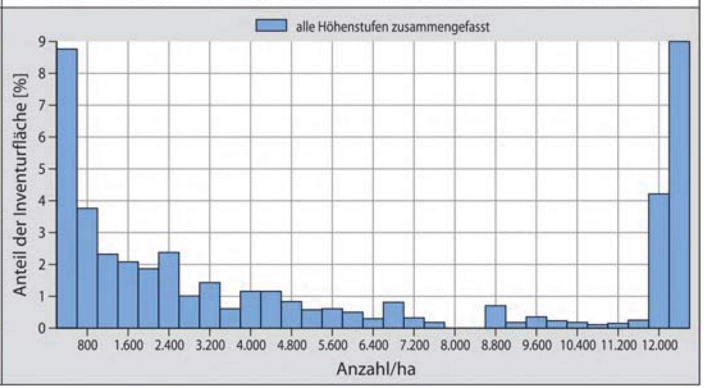
area percentage distribution by density classes of regeneration for silvicultural unit 50_25 differentiated by height classes



area percentage distribution by density classes of Norway spruce regeneration for silvicultural unit 50_25 differentiated by height classes



area percentage distribution by density classes of Norway spruce regeneration for total forest district area (height classes combined)



area percentage distribution by density classes of beech regeneration for total forest district area (height classes combined)

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The Use of Multi-Criteria Decision Analysis and Multi-Objective Optimisation in Forest Planning

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Abstract. This chapter explains several multi-criteria decision analysis methods that can be used to systematise the evaluation of alternative forest plans. The discussed methods include SMART (the Simple Multi-Attribute Rating Technique), AHP (the Analytic Hierarchy Process), outranking methods, and voting methods. The second part of the chapter summarises various methods of heuristic search, which can be used to find good combinations of management alternatives for forest stands. The following heuristics area are explained: random ascent, Hero, simulated annealing, threshold accepting, great deluge, tabu search, and genetic algorithms.

13.1
Introduction

Forest planning may be divided into strategic, tactical and operational planning (Pukkala 2002). Strategic planning aims at finding a direction of forestry that is best for the decision-makers or society in the long term. Often, only a few and clearly different strategy alternatives are considered in strategic planning.

Tactical forest planning tries to determine optimal management for every forest stand in the planning area, aiming at fulfilling those management objectives that were regarded as important in strategic planning. The result of tactical planning is a list of management actions that should be undertaken in different stands of the forest.

Operational planning determines the best way to implement the actions, or operations, prescribed in tactical planning. Some actions are related to timber harvesting and transporting and others to silvicultural tending of the stand. Operational planning is not usually considered to belong to the forest planning discipline, but to forest technology (harvesting operations) or silviculture (tending operations).

Today's forest planning situations typically concern several interest groups and stakeholders. In addition, a single stakeholder often has several conflicting goals. This kind of situation calls for developing and adopting multi-criteria decision analysis tools for strategic forest planning. These methods have been devel-

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oped in management science in order to ease and systematise the comparison of strategy alternatives.

The decision alternatives of tactical planning are all different combinations of stand management options. Since the number of combinations is huge, numerical optimisation tools are often used instead of multi-criteria comparison tools.

This chapter briefly summarises some of the methods that are available for comparing alternative forest plans in strategic and tactical planning. These methods were used at the University of Joensuu (Finland) in the EU-supported project *Implementing Tree Growth Models as Forest Management Tools*. To simplify the discussion, it is assumed that strategic planning has only a few distinctly different alternatives that may be compared using multi-criteria decision analysis methods. These alternatives are produced beforehand by foresters, and presented to the stakeholders in an informative way.

In tactical planning, only the decision space is produced before the comparison step. The decision space is a collection of management options for stands. All combinations of these options are decision alternatives, and tactical planning aims at finding the single best alternative from among a vast number of combinations. Since it is impossible to evaluate all alternatives in a reasonable time, not even with a computer, sophisticated comparison tools, namely numerical optimisation methods, must be used. These methods both produce decision alternatives by combining stand management options in different ways and evaluate the goodness of each new alternative. Only the selected combination, which is the solution of the optimisation problem, is displayed to the decision-maker for further evaluation. If the solution is not acceptable the problem formulation is changed (constraints added, objective weights altered) and the problem is resolved. As opposed to multi-criteria decision analysis tools, all objectives must be numerical.

13.2
Multi-Criteria Decision Analysis in Strategic Planning

13.2.1
The Basic Setup

Multi-criteria decision analysis assumes that several objective variables affect the goodness and ranking of decision alternatives (Fig. 13.1). These variables may be termed decision criteria or attributes, and they may be divided into sub-criteria (indicators) and sub-sub-criteria (verifiers of indicators). A decision alternative produces partial value (sub-priority, sub-utility) through different criteria. The ranking of an alternative is based on its total priority, or total utility, which is the sum of all sub-priorities of the alternative. Because different criteria may be unequally important, a sub-priority is often multiplied by the weight, or importance, of the criterion, before calculating the total priority.

The following formula summarises the principle that is used to rank decision alternatives in several multi-criteria comparison methods:

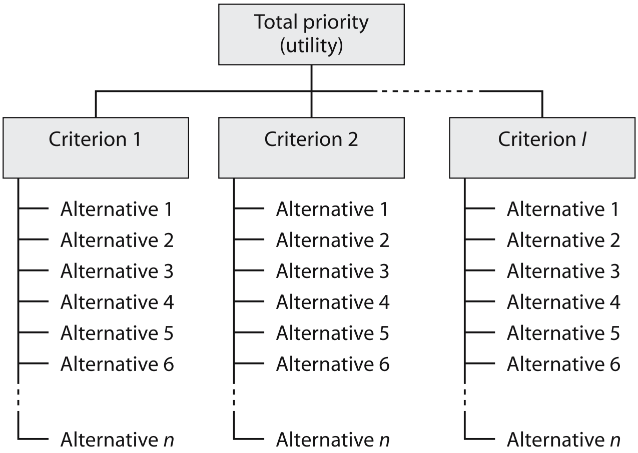

Fig. 13.1. Decision hierarchy of multi-criteria decision analysis. Decision criteria are evaluated for their importance (weight, priority), and decision alternatives are evaluated with respect to every criterion for their performance (sub-utility, priority)

$$U_j = \sum_{i=1}^{I} w_i u_{ij}$$

where U_j is the total priority (utility) of decision alternative j, I is the number of decision criteria, w_i is the weight of criterion i, and u_{ij} is the priority of alternative j with respect to criterion i. This basic setup can be modified in several ways. When the criteria are divided into sub-criteria, the formula may be written as

$$U_j = \sum_{i=1}^{I} \left[w_i \sum_{k}^{K_i} v_{ki} u_{kij} \right]$$

where K_i is the number of sub-criteria of criterion i and v_{ki} tells how much sub-criterion k contributes to criterion i. The weight v_{ki} may be termed the local priority of sub-criterion k, whereas product $w_i v_{ki}$ is its global priority.

If there are several decision-makers with their own preferences, the overall ranking can be computed from

$$U_j = \sum_{d=1}^{D} \left[v_d \sum_{i}^{I_d} w_{id} u_{idj} \right]$$

where D is the number of decision-makers, v_d the weight of decision-maker d, I_d the number of decision criteria of decision-maker d, w_{id} the importance of criterion i of decision-maker d, and u_{idj} the priority of alternative j with respect to criterion i when evaluated by decision-maker d.

If it is assumed that there is uncertainty or risk related, for instance, to future timber prices or growth rate of trees, the formula may be converted into

$$U_j = \sum_{s=1}^{S} \left[p_s \sum_{i}^{I} w_i u_{isj} \right]$$

where S is the number of different states of nature, p_s is the probability of state s, and u_{isj} is the priority of decision-alternative j with respect to criterion i when the future state of nature is s. Note that in this formula the weights of decision criteria do not depend on the state of nature but the outcome of a decision alternative depends on it.

Most multi-criteria evaluation methods have four basic steps:

1. Specify decision criteria.
2. Specify decision alternatives and provide information about every alternative (predict the consequences of alternatives).
3. Derive the weights of decision criteria (and, if required, the weights of decision-makers, states of nature, sub-criteria, etc.).
4. Conduct single-attribute evaluation (every decision alternative is evaluated in terms of every criterion).

There are several methods for both criteria weighting and single-attribute evaluation. Sometimes the same method is used in both steps, but in most cases the technique differs. Because strictly speaking all combinations of methods used in steps 3 and 4 are different techniques, the potential number of multi-attribute comparison techniques is high. The following briefly describes some methods or classes of methods that have been discussed in the literature. More detailed reviews with forestry applications can be found in Laukkanen et al. (2001) and Kangas and Kangas (2002). All reviewed methods haven been tested in forestry. Some common techniques such as those based on decision tables (e.g. Render and Stair 1992) and decision trees (French 1989) are not discussed because they are not particularly multi-criteria methods. Also some multi-criteria methods such as Even Swaps (Hammond et al. 1998) and Stochastic Multi-Attribute Acceptability Analysis (Lahdelma et al. 1998) are skipped because they have only rarely been used in forestry.

13.2.2
Simple Multi-Attribute Rating Technique

The Simple Multi-Attribute Rating Technique (SMART) is a class of rating techniques, the common feature of which is that rating is used in both criteria weighting and single-attribute evaluation of decision alternatives (Edwards 1971). Rating means that criteria are given weights that describe their importance and alternatives are given points that describe their quality in terms of a certain criterion.

Several methods are available to derive the weights of decision criteria. In one method the decision-maker first ranks the criteria and then gives a weight for the least important criterion. He or she then gives weights to the other criteria in relation to the least important one. The weights are finally scaled so that their sum equals one. Another possibility is to first distribute 100 points to the criteria and then scale the points so that their sum equals one. The third method is the simplest since it only requires that the decision-maker ranks the criteria according to importance, after which a formula (one of several) is used to calculate the weights from the ranks.

The fourth method, the so-called swing weighting, is the most complicated but it may be the most realistic as it takes into account the range of variation of the decision criteria in the current decision problem. The decision-maker imagines two hypothetical alternatives: in the first alternative every criterion is given the best possible value and in the second alternative the worst possible value, based on the ranges of the criteria in the problem at hand. The decision-maker then thinks of the poorer hypothetical alternative and decides which one of the criteria, when changed from the worst possible level to the best level, improves the alternative most. This criterion is given 100 points. The decision-maker then selects another criterion in which the change is second-most desirable, and gives points less than 100 for the desirability. Once all criteria are evaluated in this way, the points are scaled so that their sum is one.

There are also several ways to conduct single-attribute evaluation of decision alternatives. One way is to give 0 points to the worst alternative and 100 points to the best one. The other alternatives are then given points between 0 and 100, either subjectively or in relation to a numerical variable that describes the attainment of the criterion. Another method evaluates alternatives using a verbal scale, which is converted into a numerical scale using a predefined conversion table. The third possibility is to use a mathematical function (sub-utility function) which transforms the value of the criterion variable (such as net income) into a priority value.

After deriving the weights of the criteria and completing the evaluation of all decision alternatives with respect to every criterion, the alternatives are ordered with the following formula:

$$U_j = \sum_{i=1}^{I} w_i u_{ij}$$

where U_j is the total priority of alternative j, w_i is the weight of criterion i and u_{ij} is the sub-priority of alternative j with respect to criterion i.

13.2.3
The Analytic Hierarchy Process

The characteristic feature of the Analytic Hierarchy Process (AHP) is that paired comparisons are used to derive criterion weights and the sub-priorities of decision alternatives (Saaty 1980). Every criterion is compared with every other criterion in terms of the importance of the criteria to the decision-maker. Usually, a verbal scale is used. The verbal expressions are converted into numerical ratios using one of the scales shown in Table 13.1 (Saaty 1980; Ma and Zheng 1991; Lootsma 1993; Salo and Hämäläinen 1997). The numerical ratios are collected into a matrix (I×I matrix if there are I decision criteria), yielding the upper right corner of the matrix. The lower left corner is obtained by taking reciprocals of the upper corner elements. The diagonal elements are assumed to be equal to

Table 13.1. Alternative scales to convert verbal comparisons of decision criteria into numerical ratios in the pairwise comparisons of AHP. When alternatives are compared, the verbal scale is 'equally good', 'better', 'much better', etc. It is possible to give intermediate values between two verbal expressions (e.g., between 'more important' and 'much more important')

Verbal scale	Numerical scale			
	Saaty (1980)	Ma and Zheng (1991)	Salo and Hämäläinen (1997)	Lootsma (1993)
Equally important	1/1	9/9	1.00	1.00
	2/1	9/8	1.22	1.41
More important	3/1	9/7	1.50	2.00
	4/1	9/6	1.86	2.83
Much more important	5/1	9/5	2.33	4.00
	6/1	9/4	3.00	5.66
Very much more important	7/1	9/3	4.00	8.00
	8/1	9/2	5.67	11.31
Absolutely more important	9/1	9/1	9.00	16.00

one. The criteria weights can then be calculated from this matrix by solving the equation

$$\mathbf{Aw} = \lambda \mathbf{w}$$

where $\mathbf{A}$ is the matrix of ratios, λ is the maximal eigenvalue of the matrix and $\mathbf{w}$ is the eigenvector corresponding to λ. The elements of $\mathbf{w}$ are the weights of decision criteria.

After deriving the criteria weights, AHP proceeds to single-attribute evaluation. This is done by taking one criterion at a time, and comparing every pair of alternatives with respect to the criterion, using a similar verbal scale as was used when criteria were compared. Now the question is how good (preferable) alternative A is compared to alternative B in terms of criterion X. The comparisons of alternatives with respect to a single criterion are collected into a matrix, from which the sub-priorities are computed in the same way as criterion weights:

$$\mathbf{B}_i \mathbf{u}_i = \lambda_i \mathbf{u}_i$$

where $\boldsymbol{B}_i$ is the matrix of ratios for criterion i and $\boldsymbol{u}_i$ is the vector of sub-priorities. After completing the evaluations for all criteria, the total priorities of alternatives are obtained from

$$U_j = \sum_{i=1}^{I} w_i u_{ij}$$

The total priorities (or total utilities) are on the ratio scale, which means, for instance, that priorities 0.4 and 0.2 for alternatives A and B, respectively, can be interpreted so that A is twice as good as B.

13.2.4
Outranking Methods

The difference between outranking methods and SMART and AHP is that outranking does not use single-attribute evaluation. Criterion weights are required, and if the criteria are not regarded as equally important, the weights may be derived by one of the methods discussed above. Single-attribute evaluation is replaced by giving two or three thresholds per criterion (Fig. 13.2). In the PROMETHEE method (Brans and Vincke 1985) the indifference threshold (R in Fig. 13.2) gives the difference between alternatives in a criterion variable, below which the alternatives are regarded as equally good (the decision-maker is indifferent between alternatives that differ less than the indifference threshold). The preference threshold (P in Fig. 13.2) shows how much the difference should be to make an alternative clearly or strongly preferable to the other. Between the indifference and preference thresholds (if they are different), an alternative is weakly preferable to the other.

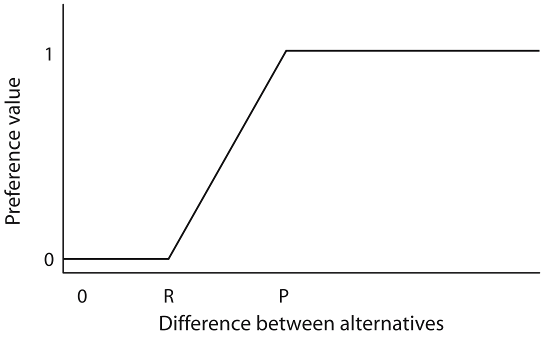

Fig. 13.2. An example of a preference function used in outranking to compare two alternatives with respect to a decision criterion. The *x-axis* gives the difference between two alternatives in the criterion variable, and the *y-axis* tells how much the alternative with a higher value is preferred to the other alternative. In this example, a high value of the criterion variable is preferable (the criterion variable is 'maximised'). Point *R* on the *x*-axis is the indifference threshold and point *P* is the preference threshold

Once the indifference and preference thresholds have been determined for every criterion, one numerical preference value per criterion is calculated for every pair of decision alternatives. The value is zero if the difference is less than the indifference threshold and one if alternatives differ more than the preference threshold. Differences between the two thresholds are given a preference value between zero and one (Fig. 13.2). The preference values are combined into outranking degree, which is a multi-criteria preference index for a pair of decision alternatives. The outranking degree of alternatives A and B [O(A, B)] is as follows:

$$O(A, B) = \sum_{i=1}^{I} w_i p_i (A, B)$$

where w_i is the weight of criterion i, I is the number of decision criteria, and p_i is the preference function for criterion i (Fig. 13.2). A simplified way to interpret outranking degree is to say that it tells in how many criteria *A* is better than *B* (when criterion weights are taken into account).

The outranking degrees related to an alternative can be combined into positive and negative flows (or leaving and entering flows). For alternative A they are:

$$F^{+} (A) = \sum_{A \neq B} O(A, B)$$

$$F^{-} (A) = \sum_{A \neq B} O(B, A)$$

The difference of the positive and negative flow of an alternative is its net flow. The alternatives may be ordered on the basis of positive flow, negative flow, or net flow.

Another version of outranking methods is ELECTRE (Roy 1991). An outranking degree is calculated in the same way as in PROMETHEE, but it is now called the concordance index. Then a third, so-called veto threshold is given for every criterion. It is such a difference in the criterion variable which makes one of the alternatives so much inferior to the other that the deficit cannot be compensated for with a good performance in the other criteria. The comparisons of two alternatives with respect to the veto thresholds of decision criteria are combined into a discordance index. This is used to modify the concordance index, resulting in the final outranking degree of a pair of alternatives. If none of the veto thresholds is exceeded, the concordance index is equal to the outranking degree .

In ELECTRE, the decision alternatives can be ordered based on their outranking degrees in several ways. If there are *n* alternatives, each alternative has *n*-1 outranking degrees. The 'min' procedure (or 'maximin') assumes that the alternative with the highest minimum outranking degree is the best.

13.2.5
Voting Methods

Voting methods are especially suitable if there are several decision-makers. One voting method is that of approval voting. Every decision-maker gives a vote to all alternatives that are acceptable to him/her. This means that a decision-maker can give one or several votes, or no votes at all. The alternative with the highest total number of votes wins.

An application of approval voting, suitable to multi-criteria situations, is multi-criteria approval. In this method the decision criteria are first ordered according to their importance. It is then determined whether an alternative is better (+) or worse (–) than the average in terms of a certain criterion. The results from all criteria and alternatives are collected into a table (two examples are given below), from which the overall ranking of the alternatives may be seen.

The drawback of multi-criteria voting is that sometimes it is impossible to rank the alternatives. In the following example the result is clear (1 > 2 > 3):

Alternatives	Criterion 2 (most important)	Criterion 3	Criterion 1 (least important)
1	+	–	+
2	–	+	+
3	–	+	–

However, in the following example it can be said that alternative 1 is worse than 2 and 3, but it is impossible to say which one of 2 and 3 is the best. Alternative 3 gets approval from two criteria and alternative 2 from one only. However, alternative 2 is the only one that is approved in terms of the most important criterion.

Alternatives	Criterion 2 (most important)	Criterion 3	Criterion 1 (least important)
1	–	-	+
2	+	–	–
3	–	+	+

Approval voting is a non-preferential voting method because the decision-maker does not order the alternatives according to preference. In preferential voting the decision-maker gives *n* points to the best of *n* alternatives, *n*-1 points to the second best, and so on (1 point to the worst alternative). After collecting the votes, the alternatives may be ranked in several ways. In the plurality method the alternative with the most first-place votes wins. In the method of plurality with elimination, the alternative that has the lowest number of first places is eliminated, and the results are recalculated for the remaining alternatives. This is repeated until only one alternative remains. In the Borda count method, all points that a decision alternative collects are summed, and the sums are used to rank the alternatives.

13.2.6
Summary

Of the comparison methods discussed above, AHP requires most work, and very much preference information is collected from the decision-maker. The number of pairwise comparisons becomes easily too large, making the method impractical. On the other hand, the method is versatile, gives the priorities on a ratio scale, and facilitates many types of sensitivity analyses.

The SMART is much easier for the decision-maker because direct rating is used instead of paired comparisons. However, the analysis may still be tedious, especially when there are many criteria and alternatives. In addition, it may be difficult to rate alternatives. Outranking methods do not require single-attribute evaluation of decision alternatives; only the thresholds for indifference and preference need to be given for the criteria (and the veto thresholds in the ELECTRE method). Except for eliciting the criterion weights and specifying the thresholds, all the analyses can be automated, making the method easy to the decision-maker if a good computerised interface is available.

The voting methods are the most suitable in cases that involve many decision-makers, such as participatory planning of public forests. The information required from the participants is little and simple: whether or not a decision alternative is acceptable, or what is the preference order of decision alternatives. In voting, the participants do not even specify the decision criteria. An exception is multi-criteria approval, in which an alternative is approved or rejected separately for every criterion. If the decision on approval is automated (assuming that alternatives better than average are approved), the preference information consists only of the weights of decision criteria. The drawback of multi-criteria approval is that the result may be blocked or undefined, which hinders an unambiguous choice of the best decision alternative.

The above discussion shows that there are many methods available for the comparison of decision alternatives. The properties of the methods vary greatly, as do the decision situations. Therefore, an overall ranking of the methods is impossible.

13.3
Multi-Objective Optimisation in Tactical Planning

13.3.1
The Basic Setup

As mentioned above, the decision alternatives of tactical planning are all combinations of stand management options. Since the number of combinations is enormous, numerical optimisation techniques are often used instead of multi-criteria comparison tools. Numerical optimisation has been used in forest planning already for several decades. However, the traditional methods such as linear programming and goal programming are no longer sufficient for solving current planning problems, which are often multi-objective, multi-party, non-linear, non-additive and spatial. Therefore, new techniques, namely heuristics, have been devised and adopted (Borges et al. 2002).

A tactical planning problem is typically solved in two steps: first, a situation-specific planning model is developed, which combines the information about management objectives and that of the consequences of management alternatives. Prediction of the consequences is based on the use of models of the regeneration, growth, and survival of trees. Second, the problem is solved using various optimisation methods. The outlook of the planning model depends to some degree on the technique that is used to solve the problem. Usually the problem formulation consists of an objective function and constraints. The objective function shows how the objective variable depends on the decision variables, and the constraining equations show how the consumption of a critical resource, or the production of a secondary objective, depends on the decision variables. With heuristics the decision variables are often binary (0, 1), indicating whether (1) or not (0) a certain management option of a certain stand is used.

One way to formulate a multi-objective planning problem is to combine all objective variables into a utility function, which means that the variable that is eventually maximised in optimisation is an abstract concept, utility. This is called utility-theoretic problem formulation. The problem may be formulated, for example, as follows (Pukkala 2004):

Maximise

$$U = \sum_{i=1}^{I} w_i u_i \,(q_i)$$

subject to

$$q_i = Q_i\,(\mathbf{x}) \qquad i = 1, \ldots, I$$

$$\sum_{k=1}^{N_n} x_{kn} = 1 \qquad n = 1, \ldots, N$$

$$x_{kn} = \{0,1\}$$

where U is the total utility, I is the number of management objectives, w_i is the importance (weight) of management objective i, u_i is a sub-utility function for objective i, and q_i is the value of objective variable i. Q_i is an operator that calculates the value of objective i, **x** is a vector of binary decision variables (x_{kn}) which indicate whether stand n is treated according to schedule k, N_n is the number of alternative treatment schedules in stand n, and N is the number of stands.

The objective variables (q_i) can be any functions of the decision variables (**x**). The values of objective variables are calculated with 'operators' or routines programmed into the calculation software. This means that optimisation is not restricted to objectives that are linear combinations of decision variables.

Another alternative is to have only one variable in the objective function and the other goals in the constraining equations. In this case, the optimisation seeks solutions that maximise (or minimise) the objective variable while satisfying the target levels of constraining variables (the right-hand sides of the constraints). Solutions that satisfy all constraints are called feasible solutions.

A kind of compromise between the two approaches is to include more than one variable in the objective function via a so-called penalty function. Variables that do not appear in the objective function may be taken care of by constraints. The objective function looks like as follows:

Maximise

$$z = q_1 - \sum_{i=2}^{I} w_i \mid q_i - T_i \mid^{\alpha}$$

where q_1 is the amount of objective variable, q_1 (i=2, ..., I) is the amount of penalty variable i, I is the total number of objective and penalty variables, wi is the weight of penalty variable i, and T_i is the target level of variable i. Parameter α tells how quickly the penalty increases as a function of deviation. It is possible to devise the penalty function so that only exceeding the target or falling short of it are avoided, but not both. One more possibility is that both exceeding and falling short of the target increase penalty, but with different rates.

The optimal solution of the planning problem, when heuristics are used, is the combination of stand management options (management schedules) that maximise the objective function and satisfy all the constraints. Any combination of management schedules may be called a candidate solution (or just solution), and those solutions that satisfy the constraints form the feasible set of solutions. When a heuristic algorithm is implemented in a computer program, a solution may be stored in one of the following ways:

	Stand 1			Stand 2					Stand 3	
1.	0	1	0	0	0	0	0	1	1	0
2.	2			5					1	

The first way uses a vector of as many elements as there are treatment schedules (treatment alternatives, management options) of stands. Those schedules that are in the current solution are indicated by 1 while all other elements are zeroes. There can be only one 1 per stand. The other way is to have as many elements in the solution vector as there are stands. Each element gives the number of a stand's management schedule that is currently in the solution.

Optimisation proceeds so that, once provided with a feasible initial solution, the heuristic algorithm makes changes in the combination of schedules in the current solution, and initiates a calculation routine that first calculates the values of variables that appear in the objective and constraining functions, using operators similar to $Qi(\mathbf{x})$. It then checks whether the new combination is feasible and evaluates the objective function value. The new objective function value is passed back to the optimisation algorithm, the functioning of which depends on how good the new combination (new solution) is compared to the previous one.

The heuristics most commonly used in forest planning problems include simulated annealing, tabu search, and genetic algorithms (Reeves 1993; Borges et al. 2002). In Finland, a method called Hero (Pukkala and Kangas 1993) has been used for more than a decade. A simple method called random ascent (or random descent in minimisation problems) may be added to the list of common heuristics (Reeves 1993). Heuristics called great deluge and threshold accepting, both of which resemble simulated annealing, have also been tested in forest planning (Bettinger et al. 2002).

Most of the common heuristics belong to the category of local improvement methods. Their idea is to improve the solution gradually by changing it locally, and usually only a little at a time. Such a small change is called a move. Typically, a move consists of changing the treatment schedule of one stand and doing nothing to the other stands. An exception to this principle is the genetic algorithm, which uses more drastic moves (Reeves 1993).

Solutions that can be obtained from the current solution with one move form its neighbourhood. If a move consists of a change in just one stand, the neighbourhood may be referred to as a one-stand neighbourhood (Heinonen and Pukkala 2004). If changes are made simultaneously in two stands, we may talk about a two-stand neighbourhood. It is also possible to talk about one- or two-optimal (or three-optimal, etc.) heuristics depending on how many stands will have a changed treatment schedule (Bettinger et al. 1999, 2002).

The following explains briefly how the heuristics mentioned above may be used in forest planning. The algorithms are described in the way they are used with a one-stand neighbourhood. A certain heuristic is not a fixed method but rather a principle or idea, or a set of ideas. Therefore, a heuristic method can be modified and implemented in different ways. The following descriptions should therefore be seen as examples of the ways to implement the heuristics.

13.3.2
Random Ascent

In random ascent (Fig. 13.3A), a set of (feasible) initial solutions is produced by selecting a random treatment schedule for each stand from all the schedules produced for it. The best random solution is the initial solution of random ascent, which first selects a random stand and then a random treatment schedule for the selected stand. If the selected schedule improves the objective function value it is included in the solution, otherwise it is not. The search procedure is stopped when the maximum number of trials, as specified by the user, is reached. In order to decrease problems arising from getting trapped in local optima, the whole process of generating an initial solution and applying random ascent can be repeated for a user-specified number of times.

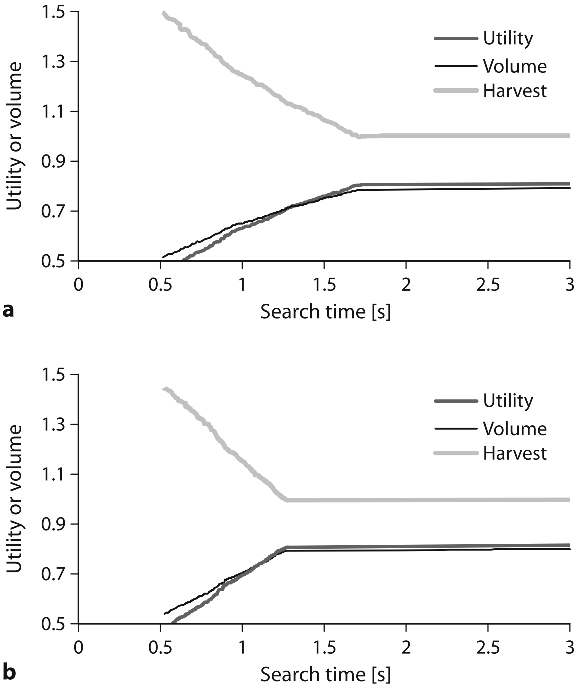

Fig. 13.3. Development of objective function value (utility) and objective variables (volume and harvest) during a random ascent (**a**) and Hero (**b**) optimisation. The remaining growing stock volume (volume) and harvested volume (harvest) are given as a proportion of the target value

13.3.3
Hero

In Hero (Fig. 13.3B) the initial solution is also the best of a user-defined number of random solutions. Starting from the initial solution, the stands and their treatment schedules are explored sequentially to see whether another treatment schedule would improve the objective function value. If an increase is detected, the treatment schedule that improves the solution replaces the previous one. When all the treatment schedules of all the stands are examined in this sequential way, the process is repeated until no schedules that would further improve the solution can be found. With a two-stand neighbourhood the first stand in which a change is made is selected in the same way as described above, i.e., sequentially, but the other stand is selected, for instance, randomly.

13.3.4
Simulated Annealing

As in the previous methods, in simulated annealing, the initial solution is formed by the best of a set of random combinations of stand treatment schedules. It differs from the previous techniques in that it may also accept inferior solutions to avoid premature convergence to a local optimum (Dowsland 1993). A candidate move consists of selecting first a random stand and then a random schedule that would replace the current schedule of the selected stand. Moves that improve the objective function value are always accepted. Non-improving moves are accepted with a probability of

$$p = exp\left((U_{New} - U_{Old})T_i^{-1}\right)$$

where T_i is the current 'temperature' and U is the objective function value. The 'temperature' is a parameter of the method and it defines the probability of accepting a candidate solution poorer than the current solution. During the optimisation process, the temperature is gradually decreased so that at the end of the search the likelihood of accepting inferior moves is close to zero (Fig. 13.4). The temperature cools according to a given cooling schedule, which is usually implemented so that the temperature is multiplied with a multiplier of less than one (0.8–0.999) to obtain the next temperature. A certain number of candidate moves are tested at each temperature. The number of moves may be the same at every temperature, or it may increase when temperature decreases, meaning that the search is intensified as the process continues ('cools'). The search stops, for example, when a user-specified stopping temperature is reached or a certain number of consecutive temperatures result in no change in the solution (Fig. 13.5).

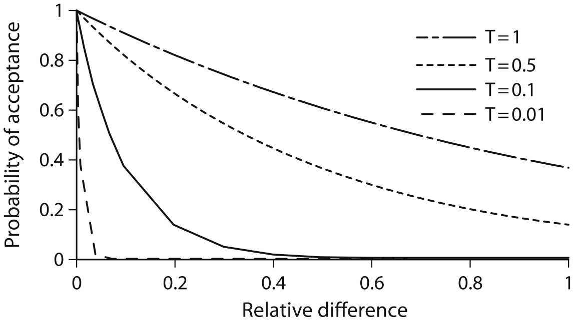

Fig. 13.4. Probability of accepting inferior solutions in simulated annealing as a function of temperature (*T*) and difference between the current solution and the new candidate. Both the temperature and the difference are expressed as a proportion of current objective function value

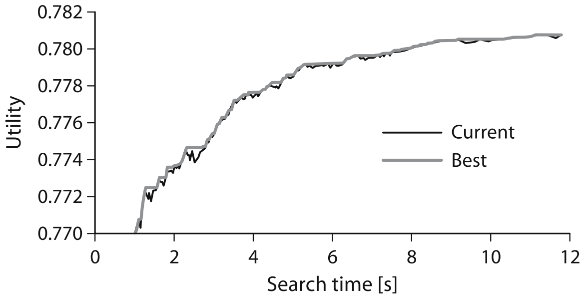

Fig. 13.5. An example of development of the best and current objective function value in simulated annealing. Simulated annealing accepts inferior solutions with a decreasing probability

13.3.5
Threshold Accepting

Threshold accepting is a simplified version of simulated annealing. In simulated annealing, the probability of accepting a move depends on its quality so that the probability is 1 if the candidate solution is at least equally good as the current solution, and 0.367879 if the candidate is equal to the current objective function value minus temperature (Fig. 13.4). Threshold accepting simplifies the decision of whether or not to accept a candidate solution: all moves that produce a candidate equally good as or better than the current objective function value minus a threshold are accepted (Fig. 13.6). The threshold has the same role as the temperature of simulated annealing. The threshold is gradually reduced during optimisation, and a certain number of moves is tested with every threshold. The process is terminated once the threshold becomes very small or the solution no longer improves.

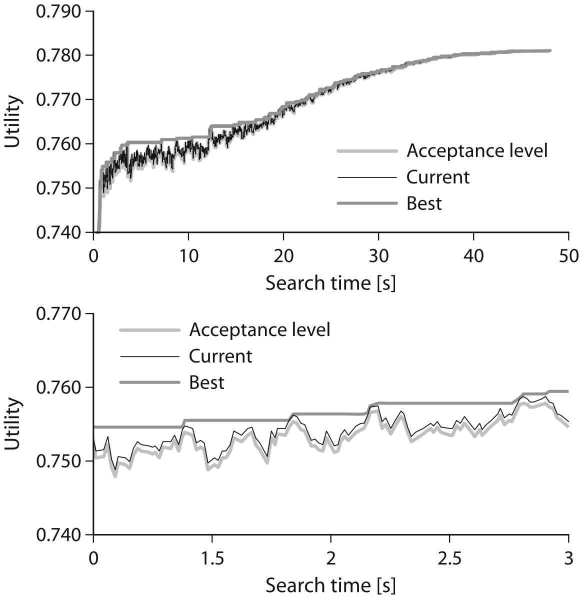

Fig. 13.6. An example of development of the best and current objective function value and the acceptance level (current value – threshold) in threshold accepting. The *lower sub-figure* is a detail of the *upper one*, showing the threshold more clearly (the difference between the two lowest lines). The threshold decreases during optimisation with the result that probability of accepting inferior moves decreases

13.3.6
Great Deluge

Another method similar to simulated annealing and threshold accepting is that of great deluge (Fig. 13.7). It uses an initial, user-specified objective function value (water level) above which all candidate moves are accepted. If the move improves the objective function value, the acceptance limit is increased by a user-defined amount (a rain event occurs and rises the water level). Gradually the acceptance limit approaches to the current and the best objective function value, which means that only improving moves become acceptable (downhill moves are no longer possible because the terrain is under water). When the acceptance level reaches the best objective function value recorded so far, this way of searching for better solutions is stopped. However, a certain number of random moves are usually tested to see if the solution can be further improved.

13.3.7
Tabu Search

Tabu search is based on searching the neighbouring solution space before accepting one change in the solution. The production of a set of candidate moves and accepting one of them is repeated for many iterations (Fig. 13.8). Typical of tabu search are tabu lists. The most commonly used tabu lists memorise recent moves, and can be used to prohibit them for some time. Schedules that partici-

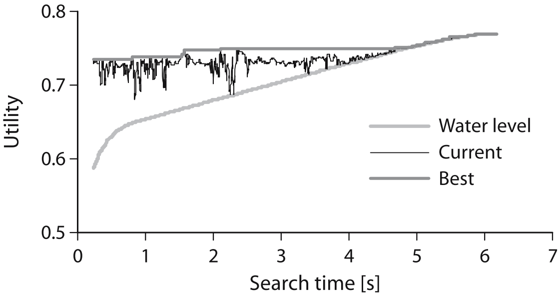

Fig. 13.7. An example of development of the best and current objective function value in great deluge. All solutions better than *Water level* (the *lowest line*) are accepted, but the water level rises during optimisation

pate in the move are kept in the tabu list for a certain number of iterations. This number is the initial tabu tenure of the schedules that participate in the move.

In the following example, after inspecting several candidate moves it is found that replacing management schedule 2 of stand 3 by management schedule 5 is the best candidate move. This move is therefore implemented with the consequence that schedules 2 and 5 of stand 3 are included in the tabu list with a full tabu tenure (for instance, 30 iterations).

Stand	1	2	3	4	5	6	7	8
Number of treatment schedules	4	4	6	8	8	8	3	5
Current solution	3	1	**2**	4	8	1	1	2
The best candidate solution	3	1	**5**	4	8	1	1	2
Schedules with full tabu tenure			**2, 5**					

An iteration reduces the tabu tenure of all moves (or schedules) by one. A schedule may again participate in a move once its tabu tenure has decreased to zero. The best non-tabu move of the inspected candidates is accepted. If all candidates are in the tabu list the one with the shortest tabu tenure is accepted. If a candidate move would yield a solution better than the best obtained so far, it is accepted even if the move is tabu. The initial tabu tenure of the entering schedule (schedule 5 of stand 3 in the above example) may be different from the tabu tenure of the leaving schedule (schedule 2). It is usually profitable to have a shorter tabu tenure for the entering schedule because the whole compartment in which a change was made is tabu for the same time as the entering schedule. Tabu search is stopped when a certain number of iterations has been completed or a certain number of iterations goes without an improvement in the solution.

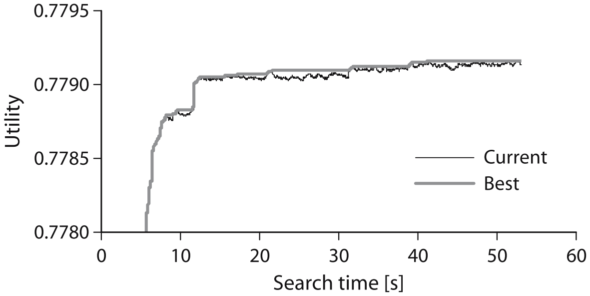

Fig. 13.8. An example of development of the best objective function value in tabu search (*upper line*). The *lower line* is the current objective function value

Tabu search can also have lists other than the one described above, which is an example of recency-based lists. Frequency-based lists memorise, for instance, how many times a schedule has participated in a move or how long it has belonged to the solution. These lists can be used in various ways to intensify or diversify the search.

13.3.8
Genetic Algorithms

Unlike the heuristic optimisation techniques described above, the search process of genetic algorithms is not based on neighbourhood search. Instead, genetic algorithms are based on an initial population of solution alternatives, their evaluation and their breeding (mixing, combination). The initial solutions are called parent chromosomes, which are processed by crossing over (combining parts of two chromosomes) and by mutation (random change in one or several genes, or stands). These operations result in a new chromosome (offspring). At least one of the two parents of a new chromosome is selected with the probability proportional to its ranking. The second parent may be chosen randomly with an equal probability for all chromosomes. In the incremental genetic algorithm technique, the new chromosome replaces one initial chromosome. The removed chromosome is selected based on its objective function value, the probability of removal being highest for chromosomes that have a low objective function value. The updated group of chromosomes is called generation.

The following example illustrates the crossing over between two parents (two solutions) to produce a new solution (offspring). The numbers in the cells indicate the management schedule that is in the solution. The crossing-over points are marked with thick vertical lines.

First parent	3	1	2	4	8	1	1	2
Second parent	4	1	5	7	5	2	3	1
Offspring	3	1	5	7	5	2	1	2

The offspring may be further modified by one or several mutations, which means that the management schedule of the compartment is replaced, with a small probability, by another schedule of the same compartment:

Before mutation	3	**1**	5	7	5	2	1	2
After mutation	3	**5**	5	7	5	2	1	2

The offspring obtained in this way is evaluated for its 'fitness,' which means that the objective function value of the new solution is calculated. The search is stopped when a user-specified number of generations (iterations) has been completed (Fig. 13.9). The best member of the population at the end of the search is used as the solution for the forest planning problem.

13.3.9
Summary

Hero and random ascent are the simplest heuristics. Their main difference is that random ascent evaluates moves in a random order while Hero inspects them systematically covering all candidate moves. The methods are simple, but suffer from the drawback that the algorithm may be trapped in a local optimum. All the other heuristics are better in this respect. They are slower, but can find better solutions, especially in difficult problems. The suitability of different methods to a particular problem is hard to determine beforehand. However, all methods seem to be at least satisfactory regarding most problems if the parameters of the methods are appropriately set. There is some evidence that tabu search and genetic algorithms are especially suitable to spatial problems. Simulated annealing is reasonably good in many types of problems. Threshold accepting seems to be as good as or even better than simulated annealing although it is simpler.

Different heuristics can be modified and they can also be combined in several ways. For example, it is possible to combine simulated annealing and Hero so that cooling and accepting moves are applied in the same way as in simulated annealing, but the neighbourhood is inspected in the same way as in Hero, i.e., sys-

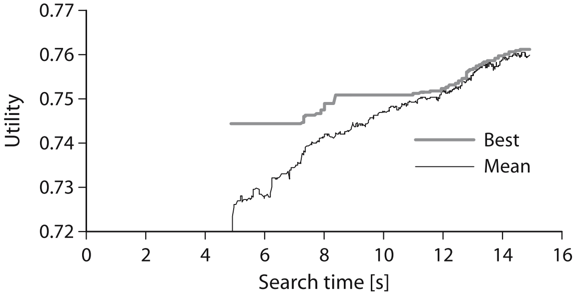

Fig. 13.9. An example of development of the best objective function value in genetic algorithm *(upper line)*. The *lower line* is the mean objective function value of the current population (30 solutions in this example)

tematically (Kurttila and Pukkala 2003). The solutions found by random ascent, tabu search, simulated annealing, and genetic algorithms can be used as a starting solution for a Hero search, with the result that some improvement can often be made. One possibility is to produce some of the initial chromosomes of genetic algorithm with another heuristic.

Another option is to use two-stand instead of one-stand neighbourhood in the local improvement methods (i.e., in all the above methods except genetic algorithms). This means that a move consists of changing the treatment schedule simultaneously in two stands instead of one stand as done in one-stand neighbourhood search. It appears that the use of two-stand neighbourhood improves the result especially in spatial problems (Heinonen and Pukkala 2004).

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Modeling Cork Oak Production in Portugal

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Abstract. Cork oak (*Quercus suber* L.) stands are managed in agro-silvo-pasture systems and their sustainability depends on balanced relations amongst their components. Actual changes in management, mainly due to increasing mechanization and the installation of new stands, have required the development of tools to generate scenarios for management options. The maintenance of a balanced sustainable land use that may cope with the variability of the Mediterranean climate is the main ecological output. The economical output is mainly related to cork production which feeds the stoppers and related industries. An integrated multilevel monitoring procedure was created in order to understand the dynamics of the cork oak system. In the frame of this monitoring system a single tree spatial growth simulation model (CORKFITS) was developed to be used as a decision management tool. This chapter describes the development of CORKFITS. The individual tree model was developed and tested in several areas of southern Portugal. The model showed successful performance in estimating the cork quantity values, when evaluating the calibration data set plots. The quality estimation required a recalibration of the cork growth model constructed on the first data set. New values of cork growth model coefficients are presented. A method for alternative data collection by means of remotely sensed imagery was developed. An algorithm for near infrared (NIR) aerial imagery was developed in order to obtain data on stand structure and individual tree characteristics necessary for simulation.

14.1
Introduction

Cork oak stands occupy about 22% (750,000 ha) (DGF 2001) of the Portuguese forest area and are economically and ecologically important. Portugal produces about 50% of the world's cork and processes 80% of it.

The maintenance of a balanced sustainable land use that copes with the variability of the Mediterranean climate is the main ecological output. The economi-

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Growth Models for Europe

cal output is mostly related to cork production that feeds the stoppers and related industries.

Cork oak stands are managed in agro-silvo-pasture systems ("montados") whose sustainability depends on balanced relations between components. Moreover, their sustainability can be doubly threatened: (1) by the intensification of the undercover activities related to grazing (soil dishing and undercover cultivation), which results in a lack of regeneration and the consequent disappearance of the crown cover, leading to a growing risk of soil erosion, and (2) by the extensification that leads to stand invasion by shrubby species and other oaks, increasing competition and the risk of forest fire.

The site quality in cork oak stands is essentially related to soil depth, structure and nutrient status, erosion thus having a hard impact on it. The loss of crown cover will increase the soil exposure, leading to a decrease in site quality and an escalating process of stand degradation (Rosenberry et al. 1980; Langdale and Schrader 1982).

Actual changes in management, fundamentally owing to increasing mechanization and installation of new stands, have created the need to develop tools to generate scenarios involving different management options (Ribeiro et al. 2001a).

There are three kinds of cork – "virgem", "segundeira" and "amadia" – corresponding to the first, second and subsequent debarks. The first cork is used only for agglomerates; the second can be used to extract stoppers but with high production of disposals due to the irregularity of the tissue; the third and subsequent extractions produce regular cork tissue which is optimal for stopper fabrication. Cork quality is connected with radial thickness or calliper (determined by the cork growth) and porosity. The production of stoppers demands a minimum calliper of 2.7 cm; therefore cork growth is one of the most important variables in the cork oak production system.

The spatial tree growth simulators are tools that not only enable the generation of tree growth scenarios dependent on site and competition status, but also allow the simulation of management actions (Daniels 1976; Holmes and Reed 1991; Biging and Dobbertin 1992; Kimmins 1993; Jones and Carberry 1994; Pukkala et al. 1994; Vanclay 1994; Pretzsch 1997; Bartelink 1998; Grote and Erhard 1999).

The growth simulator CORKFITS was developed as an application of the SILVA model (Pretzsch et al. 2002) to cork oak stands. It uses the potential modifier principle and it shares several components such as the structure generator, parameterized for cork oak stands, and the visualization module, adapted to the crown model of cork oak (Ribeiro et al. 2001b, 2003a). The single cork oak trees are subjected to natural (genetics and competition) and artificial (debark, crown pruning, root pruning) factors that affect their growth. Therefore, there is a large amount of unexplained variability that is added to the models in the form of random error components.

This chapter is concerned with: (1) model evaluation outside the parameterization area, (2) recalibrated functions to adjust the simulator to the study region, (3) the new functions of crown growth and mortality, (4) the new models for individual tree identification using aerial photography, and (5) the software implementation of the new models in CORKFITS.

14.2
Data

For model validation and construction two different sources of data were used: (1) temporary inventory plots and (2) permanent research plots (Table 14.1).

The monitoring system is a data acquisition system, which collects and uses information obtained in the field and laboratory. For a list of symbols used in the system, see Table 14.2. In fieldwork, all trees in the plots are measured every 5 years for the following parameters: perimeter at 1.3 m (pob), total debark height (dh), stem height (sh), total tree height (h), crown height (ch) and crown radius. At debarking time (which occurs every 9 or 10 years) total fresh cork weight (cwf) and cork thickness (e) are evaluated. Additionally, cork samples are collected at tree level: (1) a 10×15 cm plank is taken to assess water content (in isolated containers), and (2) a 20×40 cm plank is used for image analysis. In all permanent plots, the soil profile was described and samples were collected from each horizon. Data were collected in order to characterize the climate rainfall, air temperature, soil temperature at two depths, local radiation, and air and soil moisture. In the laboratory several procedures were developed: (1) the soil samples were processed for physical and chemical analyses; (2) cork moisture was evaluated in the 10×15 cm planks; (3) cork porosity (size, number and shape of pores), defects and growth rings were measured with an image analysis tool using the scanned 20×40 planks in order to evaluate cork and stopper quality; (4) single tree spatial structure modelling used digital orthophotos of colour infrared aerial photographs, scale 1:40,000, with a ground resolution of 1 m (Ribeiro et al. 2003a).

Table 14.1. Type, name, area, number of measurements and functions of the installed plots

Name	Number of plots	Area per plot (ha)	Number of measurements	Function
Permanent plots				
Machoqueira	67	0.5	2	Parameterization
Quinta Grande	1	3	1	Evaluation/calibration
Ruivos	1	3	1	Evaluation/calibration
Fidalgos	1	1	1	Evaluation/calibration
Temporary inventory plots				
Carreta	15	0.25	1	Evaluation

The data came from the region of Coruche and the plots (temporary and permanent) were placed so as to sample the cork oak stands according to the main watershed areas of the region (Fig. 14.1).

The collected data set was divided into two groups: (1) new model parameterization data and (2) evaluation calibration data. The new model parameterization data set corresponds to a repeated measurement made on the 67 permanent plots that formed the basis of the CORKFITS parameterization and were used to construct new crown growth models and mortality models. The evaluation/calibration data were used to evaluate and calibrate the model in the entire Coruche region.

The descriptive statistics of the set of measured plots are presented in Tables 14.3 and 14.4.

14.3
Model Structure

The cork oak single-tree spatial growth simulator CORKFITS 2.1 was constructed with data generated by the monitoring system (Ribeiro et al. 2001b, 2003b). The simulator was built assuming the potential increment modifier prin-

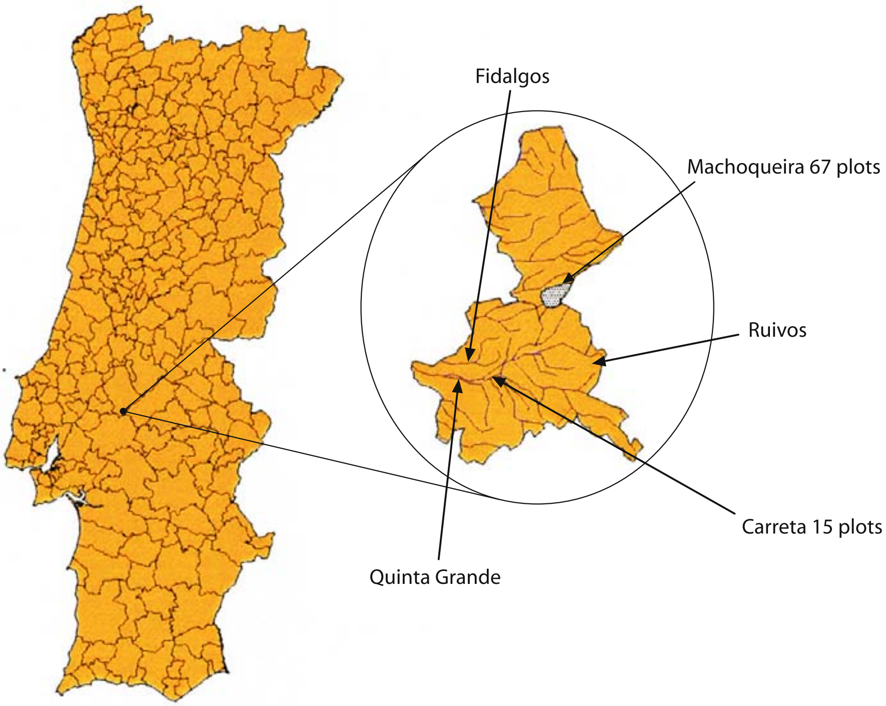


Fig. 14.1. Location of the temporary and permanent plots

Table 14.2. Symbols used in this model

Symbols	Variables	Symbols	Variables
d_{os}	Diameter measured at 1.3 m over stem (cm)	ich	Total tree height increment over 5-year period (m)
d_{ob}	Diameter measured at 1.3 m over bark (cm)	sh	Stem height (m)
p_{os}	Perimeter measured at 1.3 m over stem (cm)	ch	Crown height (m)
p_{ob}	Perimeter measured at 1.3 m over bark (cm)	dh	Debark height (m)
g_{os}	Sectional area at 1.3 m over stem (m^2)	ds	Debark surface (m^2)
g_{ob}	Sectional area at 1.3 m over bark (m^2)	cw_d	Cork dry weight (kg)
ca	Crown horizontal projection area (m^2)	id	Intensity of debark
ica	Crown horizontal projection area increment over 5-year period (m^2)	e	Cork thickness (cm)
ica_{pot}	Potential crown horizontal projection area increment over 5-year period (m^2)	cg_9	Cumulative sectional area of cork growth in 9 years (m^2)
h	Total tree height (m)	$cg_{9_{pot}}$	Potential cumulative sectional area of cork growth in 9 years (m^2)

ciple (Pretzsch 1997; Ribeiro et al. 2001b): $z=zpot \times modifier + \varepsilon$, where zpot is the potential growth as a function of site; modifier is the reduction factor as a function of the spatial competition index and the intensity of debark; and ε is a random error.

CORKFITS 2.1 is composed of sub-growth models (cork, stem, tree height and crown), cork production models and mortality models (Ribeiro et al. 2001b, 2003a). In all the models, except potential functions, a random error component is added. A structure generator STRUGEN was used, based on a filtered Poisson process (Pretzsch 1992, 1997), whose filters were parameterized for cork oak stands' natural spatial structure (Ribeiro et al. 2001b). This structure generator

Table 14.3. Descriptive statistics of the increment data of the Machoqueira plot at tree level. *SEM* Standard error of the mean; *SD* standard deviation

$n = 980$	p_{ob}	ich	icca
Mean	90.54	0.80	6.85
SEM	1.036	0.158	0.143
SD	32.444	0.494	4.470
Minimum	35	0	0.238
Maximum	258	2.10	19.58

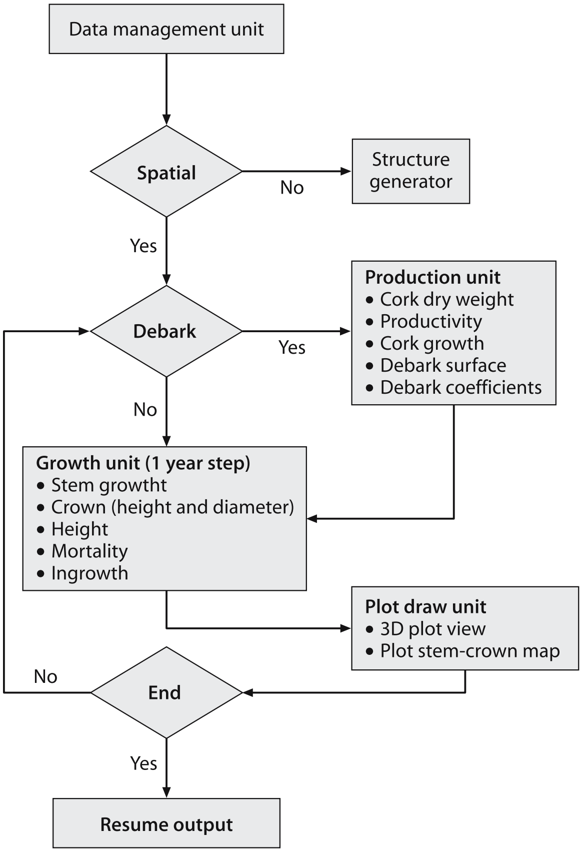


Fig. 14.2. CORKFITS 2.1 flowchart

simulates virtual stands as well as regeneration (Ribeiro et al. 2003a).

Figure 14.2 presents the CORKFITS 2.1 flowchart.

14.4
Methods

In this section the methods and procedures are presented as follows: (1) model evaluation outside the parameterization area; (2) modelling procedures; (3) creation of an individual tree model for identification and delineation of cork oak crowns; and (4) software development and implementation of the new models.

14.4.1
Model Evaluation Outside the Parameterization Area

The study region is composed of three main watersheds (Fig. 14.1) defined by the River Sorraia in the south, the River Erra in the middle and the River Muge in the north. The entire region is on sand deposits of the Ribatejo province, of Miocenic formation, a mesa-type landscape with U-shaped gullies, valleys and occasional sandstone outcrops. Slopes range between 0 and more than 35%, between 0 and 5% being the most representative slopes. The average annual rainfall is about 600 mm. The main soil families are Eutric fluvisols, Dystric leptosols, Cambric podzols and Eutric leptosols.

The placement of the plots aimed the evaluation of the CORKFITS model outside the parameterization area (Machoqueira, Fig. 14.1), situated in the northern part of the River Muge watershed. Selection of the locations of the evaluation/parameterization plots was made in three steps: (1) identification of the watershed areas and classification of the cork oak pure stands within each of them at GIS level, using digital topographic maps and digital aerial photographs; (2) identification of the most representative stands in each watershed using topographic, soil and crown cover variables; (3) selection of the plot location in the field according to stand structure, moment of debark and agreement of the owner to allow the installation and measurement of the plots.

The evaluation procedure of the production module of CORKFITS 2.1 (Fig. 14.2) was aimed at: (1) cork growth models and (2) cork dry weight models (Table 14.5).

These models were used to estimate quantity (cork dry weight models) and quality (cork growth models) which are the economic parameters used to build the cork production index (cpi) which thus combines production and quality (defined by cork thickness): cpi=dcw×Q, where dcw is dry cork weight per hectare and Q is a quality index

$$Q=\sum_{k=1}^{n} ip_k p_k$$

Table 14.4. Descriptive statistics of the evaluation calibration plots at tree level

Quinta Grande $n = 118$	p_{ob}	p_{os}	h	sh	ch	dh	e	cw
Mean	137.00	128.96	9.13	2.26	4.63	4.64	2.56	34.25
SEM	2.76	2.71	0.14	0.07	0.10	0.22	0.05	1.78
SD	29.92	29.41	1.55	0.72	1.06	2.37	0.49	19.35
Minimum	62.00	55.71	5.00	120	2.40	1.40	1.36	6.42
Maximum	234.00	223.98	14.4	4.60	9.8	11.85	3.98	111.69
Ruivos $n = 99$								
Mean	131.94	115.22	8.65	2.90	4.69	2.69	2.66	35.52
SEM	2.95	2.87	0.15	0.09	0.10	0.09	0.06	1.71
SD	29.39	28.50	1.45	0.93	0.98	0.92	0.59	17.02
Minimum	73.00	59.00	5.90	1.50	2.40	1.16	1.59	7.00
Maximum	226.00	206.00	12.30	5.90	7.20	5.30	4.62	96.10
Fidalgos $n = 65$								
Mean	122.22	102.52	8.38	2.11	3.85	1.72	3.14	21.45
SEM	3.63	3.64	0.19	0.08	0.10	0.06	0.11	1.25
SD	29.30	29.35	1.52	0.65	0.77	0.45	0.88	10.05
Minimum	68.00	49.00	4.90	1.30	2.50	1.00	0.40	5.00
Maximum	212.00	187.00	12.10	4.60	6.10	3.08	4.85	45.00
Carreta $n = 209$								
Mean	114.64	96.51	--	2.70	--	3.36	2.89	26.78

Table 14.4. Continue

Carreta $n = 209$	p_{ob}	p_{os}	h	sh	ch	dh	e	cw
SEM	2.16	2.07	--	0.07	--	0.15	0.06	1.41
SD	31.20	29.96	--	1.07	--	2.17	0.92	20.33
Minimum	523.00	40.00	--	1.30	--	0.92	0.64	3.20
Maximum	212.00	205.00	--	7.50	--	10.10	6.68	108.00

Table 14.5. Function, equation, parameters and period of the evaluated models of the production unit of CORKFITS 2.1 (Ribeiro et al. 2001a)

Function	Equation	Parameters	Period (years)
Cork dry weight	$cw_d = a^* (p_{os} * dh)^b$	a, b	9 or 10
Cork cumulative potential growth (Yoshida I function, Zeide 1993)	$cg_9 = \dfrac{a * b * d * g_{os}^d}{g_{os} * \left(b + g_{os}^d\right)^2}$	$a, b, d=f(site)$	9 or 10
Cork growth modifier	$m = e^{-a * ci^b * id}$ *		9 or 10

$$^* \; ci_i = \sum_{j=1}^{n} \frac{d_j}{d_i} * \frac{1}{dist_{ij}}$$

Hegyi competition index; competitor selection criteria $dist_{ij} = 0.33 \times d_j$; d_i and d_j diameter at 1.3 m of target tree i and competitor j. Intensity of debark id = $^{ds}/_{g_{os}}$

with ip_k the index price for cork quality k, p_k the proportion of cork weight in cork quality class k, and n the number of cork quality classes). The index prices are indexed to the price of the most valuable cork quality class for industry (Ribeiro et al. 2003a). This index is used in the decision making process combined with other stand variables in simulation studies (Ribeiro et al. 2003a, 2004).

The evaluation was performed for each plot using the following procedure: (1) activation of the data management module to compute the necessary initial variables to start the simulator; (2) run 100 repetitions for each plot to construct $\hat{\bar{x}} \pm 95\%ci$ where $\hat{\bar{x}}$ is the estimated mean for 100 repetitions of a 1-year simulation and 95%ci is the 95% confidence interval for each mean. The evaluation was done at p_{os} class level comparing the real value of the mean $\bar{x} \pm 95\%ci$, measured in the field) with $\hat{\bar{x}} \pm 95\%ci$.

The error structure $(\bar{x} - \hat{\bar{x}})$ was evaluated with linear regression in order to find trends that could be used to correct bias.

14.4.2
Modelling Procedures

14.4.2.1
Recalibration

In the recalibration process, the evaluation/calibration plot data set is used. The new parameters and model statistics are calculated with the nonlinear regression module of SPSS, version 12.0.

14.4.2.2
Mortality

The causes of mortality of cork oak trees can be related to several factors (age, pressure of debark, pressure of soil dishing, pressure of crown pruning, presence of diseases and plagues, site quality, etc.) which act alone or in combination to cause a large noise on the data.

A logistic function was used, which is widely employed in mortality modelling (Vanclay 1995; Dursky 1997; Pretzsch et al. 2002). Repeated measurements were taken from 67 permanent plots of 0.5 ha over a period of 5 years in order to model mortality. The trees were classified as:

$$y = \begin{cases} 1, \text{dead tree} \\ 0, \text{alive tree} \end{cases}$$

A vector of independent variables $x' = (x_1, x_2, \ldots, x_p)$ was considered, composed of dendrometric and growth parameters.

Considering the conditional probability $E(Y/\mathbf{x}) = \pi\ (\mathbf{x}) = P(Y = 1/\mathbf{x})$, the model of logistic regression is:

$$\pi\ (x) = \frac{e^{g(x)}}{1 + e^{g(x)}}$$

The logistic model was fitted with the maximum likelihood method using SPSS version 12.0. The variables were selected by the forward Wald method.

14.4.3
Creation of an Individual Tree Model for Identification and Delineation of Cork Oak Crowns

The model used near infrared (NIR) remotely sensed photography, for several reasons: (1) infrared photography does not provide a way of seeing through fog, which consists of water droplets, but it can improve visibility through certain kind of haze where the light scattering is produced by much smaller particles. Thus, infrared photography does not always result in an increase in the range of vision, but it generally increases the contrast of the distant subjects and thus the amount of detail that can be seen; (2) NIR reflectance decreases as a result of a change in leaf orientation, from predominantly horizontal to predominantly vertical, at a certain stage in the growth cycle. NIR reflectance also decreases with loss of leaf chlorophyll due to various reasons such as tree illness and damage. Thus, NIR reflectance is species specific due to its dependence on these factors (Gitelson 2001)

The photos taken in September 1995 were used in this work. The focus length was 154, camera type Zeiss RMK Top 15/23 and scale of the photos 1:40,000. The photos were scanned with a pixel resolution of approximately 40×40 cm.

A new sub-module for CORKFITS was developed allowing the use of aerial imagery as an alternative source of input data for the simulation. This method permits the appliance of digitalized NIR aerial photos and produces information about individual trees (crown size, stem position, etc.) necessary to initialize the simulation. The algorithm consists of several steps: (1) image segmentation, (2) individual crown delineation and (3) computation of input data for CORKFITS.

14.4.3.1
Image Segmentation

A new index for colour transformation of Mediterranean forests was proposed. It showed equal accuracy performance with that of other indices proposed for similar purposes in different areas, but involved the smallest overestimation error and avoided the largest grey levels on the scale for subsequent shape analysis. Performance was evaluated by comparing with manually processed images. Four different sets of aerial photographs (different year, flight height and scale) were used. Fifteen scans were taken from different parts of the photo, generally not further than 60% of the width from the centre. One pixel corresponded to 30, 40 and 80 cm. The indices in Table 14.6 are as follows:

Index 1 (2×R–G–B)/2 (Ohta et al. 1980)
Index 2 256×[R/(R+G+B)] (Andreasen et al. 1997)
Index 3 $i1i2i3_{new}$ (Phillip and Rath 2002); colour space defined with the following matrix:

$$\begin{bmatrix} i1_{new} \\ i2_{new} \\ i3_{new} \end{bmatrix} = \begin{bmatrix} 0.33 & 0.34 & 0.33 \\ 0.39 & 0.07 & -0.54 \\ -0.51 & 0.35 & -0.14 \end{bmatrix} * \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Index 4 New index – B-square (Surový et al. 2004a)
Index 5 Normalized difference index (NDI) (Woebbecke et al. 1992):

$$\mathrm{NDI} = \frac{\text{red - green}}{\text{red + green}}$$

Table 14.6. Accuracy of individual indices in different photo sets

Accuracy	Photo 1		Photo 2		Photo 3		Photo 4	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Index 1	91.52	4.89	92.14	2.82	89.56	2.84	88.00	1.83
Index 2	81.94	15.24	89.12	8.20	86.24	4.21	86.47	2.84
Index 3	92.82	4.69	92.51	2.30	89.97	2.73	88.54	1.99
Index 4	93.19	3.61	93.04	2.48	89.46	3.62	88.57	1.64
Index 5	87.68	5.80	89.37	2.75	88.11	1.95	88.11	1.95

14.4.3.2
Individual Crown Delineation

An algorithm based on tree top identification and crown edge detection was developed and tested. The system begins by looking for the darkest (in the case of the B-square index) pixel in the whole image. This pixel is considered as an initial point for the following steps, where in all possible directions there is a search for a valley or a contour of the crown. A contour is found when the next pixel being observed in that direction is marked as background. A valley is found when the next pixel grey level is significantly higher (the difference is larger than one) than the present pixel. This should mean that the reflected lightness is increasing because of another crown segment. The information about crown segment is stored and analyzed. Each angle length (crown axis) measured is compared with lengths measured for two units backward and forward. If the processed length is significantly different – if it is an outlier among the other four lengths – its size is set to the average of these four. This is done because some outliers can appear due to the rounding and also sometimes there is no valley in certain directions, or the system can go through the same grey level of the other tree. After this process of "edge smoothing" all pixels belonging to the crown segment, including the edge pixels, are marked and they are excluded from subsequent analysis.

14.4.3.3
Computation of Input Data for CORKFITS

The automated system is able to find only information about the tree stored in the image. This is represented by the tree position and the tree crown dimension and shape. These two variables are an outcome of the image analysis process. However, for simulation run and study, some other tree characteristics must necessarily be generated. As an input to the software it is important that each tree has its identifying number. X and Y positions have to be recalculated to be oriented to the centre with coordinates (0, 0). The dependency of crown area to stem area at breast height (1.3 m) is known. In order to estimate stem diameter from crown area measured on the photograph a back-calculation equation is used. Similar processes are used to estimate the tree and crown heights. The last variable needed – stem height – is defined randomly. All variables are stored in the text file, which can be processed with the growth simulator model CORKFITS 2.1.

Prediction based on both data sets, field and photos, were compared (Surový 2004b). The results appear to be usable for short-term prediction of cork production. For a longer-term prediction the missing regeneration which is causing the difference can be eliminated by regular remote sensing or partial field measurement.

14.4.4
Software Development and Implementation

The model was incorporated into the software environment by the graphic user interface (GUI) common for Windows systems. The source code was written in Object Pascal compiled with a Borland Delphi compiler. The sub-modules for handling the GIS data, reading and displaying the shape files were partially written in assembler instructions.

Data from simulations are stored in databases Paradox 7 and DBASE IV. The latter is necessary for compatibility with GIS shape files. Input data are introduced in text files, but it is also possible to introduce data interactively. Graphical output uses a Microsoft Direct X engine.

Important coefficients of the model and variables, which are planned to be calibrated in future for new regions, are removed from the source code and are accessible for interactive changes in the software menu.

14.5
Analyses, Results and Software Implementations

This section presents: (1) the evaluation results of the simulator outside the parameterization area; (2) the recalibrated model parameters and statistics; (3) the individual cork oak model for crown identification and delineation in NIR; (4) software developments; and (5) a simulation study example.

14.5.1
Evaluation Results of the Simulator Outside the Parameterization Area

The evaluation of the model, performed with new data, aimed to test the model at regional level in order to decide the necessity of recalibration of the growth models.

In the evaluation, the simulated outputs for cork production (cork dry weight, cwd, kg) and cork growth (cork thickness, e, cm) are compared with the real data. The simulation was made with 100 1-year simulations and the results are presented for each plot Pos class with the statistics: $\hat{\bar{x}}$ ± *95%ci_g* (estimated values, g) and $\bar{x}$ ± *95%ci_m* (measured data, m).

From Fig. 14.3 it can be seen that the simulator had a different behaviour in each plot concerning the estimation precision in Pos classes. In all plots there were no significant differences between the estimated and measured data except in Pos class 100–130 in Quinta Grande and in Pos class 160–190 in Carreta plots. In Quinta Grande a systematic underestimation of cork thickness in lower Pos classes was observed, this result being in opposition to the one observed in Carreta. In the Ruivos plot the model behaved more erratically, underestimating the thickness in Pos class 100–130 and overestimating it in Pos class >190. These results can be explained thus: (1) the measured data set presents large variability, which makes the mean estimation less precise and simulation evaluation less accurate; and (2) the site condition differed between the parameterization plots and the evaluation/calibration plots. The parameterization plots of Machoqueira are placed in the northern watershed (Fig. 14.1) where the stands are situated in areas with greater slopes with no access to the water table, sharing these site conditions with the Carreta and Ruivos plots. The Quinta Grande plot is situated in a flat zone with access to the water table. The observed results in Carreta show good behaviour of the simulator except in 9% of the large-dimension trees of Pos classes 160–190 and >190, which are in a flat area with undercover weed crops indicating that these trees are benefiting from some nutrient supply from the crops. In the Ruivos plot, once again, the density of the large trees was underestimated, indicating that this lack of information concerning large trees in the parameterization data set may be responsible for the observed performance. In Quinta Grande the accessible water table allows the young trees to grow better, even in the observed high competition status.

Observing the values of $e_g–e_m$ in Table 14.7 and considering that commercial cork classes are defined by one variable – the line (0.225 cm)– it can be seen that the estimation errors are, in the majority, inferior to the line in all plot Pos classes, indicating that the commercial classification would not be affected by them. In terms of overall mean thickness, only the Quinta Grande plot is above the 1 line, indicating that in this stand the simulator is not performing satisfactorily.

Figure 14.4 shows the error (eg–e_m) structure of the simulation. All regressions express the over- and underestimation referred to above, but none of them is significant at $\alpha=0.05$, indicating no significant trend in estimation.

These results led to the decision to recalibrate the cork growth models thus: (1) the results observed from large trees in the Carreta and Ruivos plots indicate a lack of information at this level in the parameterization data; and (2) the Quinta Grande data will be useful to recalibrate potential×modifier cork growth functions in order to adapt the simulator to these site conditions.

Figure 14.5 and Table 14.8 show the good performance of the cork dry weight models in estimating cork production. Only the Carreta results indicate a systematic overestimation of weight, which could be the result of the methods used in water moisture evaluation applied to this data set in 1990.

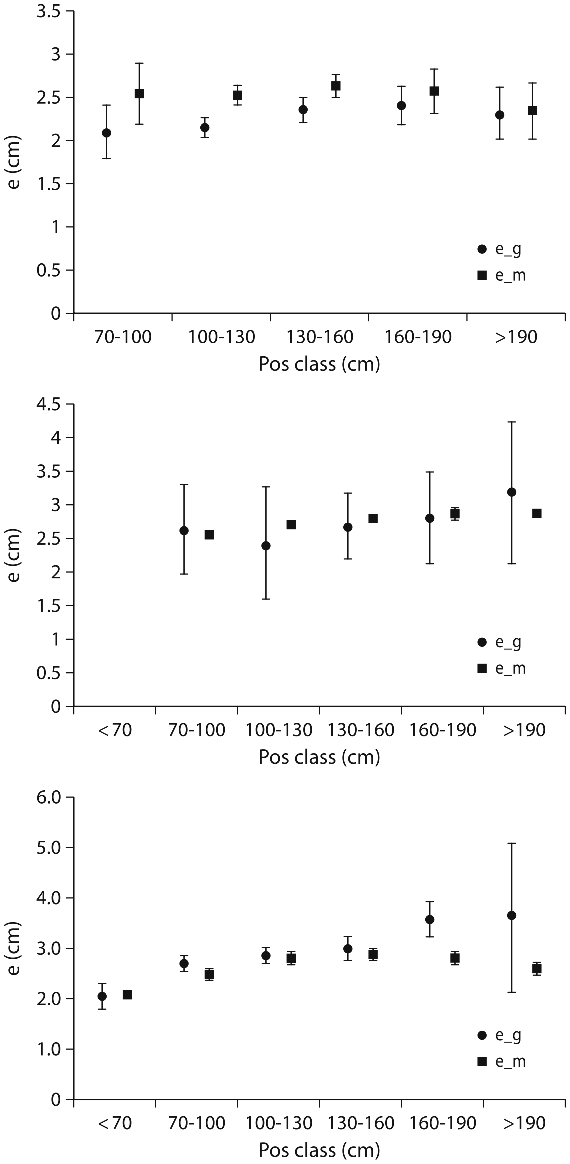


Fig. 14.3. Mean measured thickness (e_m, cm) and mean estimated thickness (e_g, cm) and the 95% confidence interval (95% ci)for each mean for each p_{os} class (in cm). *Above* Quinta Grande plot; *middle* Ruivos plot; *below* Carreta plot

The Quinta Grande results in Table 14.8 illustrate the very good behaviour of the simulator in contradicting the performance of the cork growth model, which can be explained by the smaller density of the cork due to the higher growth. The results for the Ruivos plot are evidence of the poorer behaviour of the model especially in the Pos class 70–100.

Table 14.7. Mean measured thickness and confidence interval (*ci*) for measured (e_m, 95% ci_m, cm) and estimated (e_g, 95% ci_g, cm) thicknesses per p_{os} class

p_{os} class	e_m	e_g	95% ci_m	95% ci_g	$e_g–e_m$
Quinta Grande					
70–100	2.55	2.10	0.35	0.31	–0.45
100–130	2.53	2.16	0.11	0.10	–0.37
130–160	2.64	2.36	0.13	0.13	–0.29
160–190	2.57	2.41	0.24	0.22	–0.16
>190	2.35	2.32	0.33	0.30	–0.02
Overall average	–0.26				
Ruivos					
70–100	2.66	2.47	0.65	0.07	0.18
100–130	2.53	2.77	0.82	0.02	–0.24
130–160	2.72	2.86	0.49	0.04	–0.15
160–190	2.75	2.90	0.67	0.08	–0.14
>190	3.40	2.93	1.06	0.07	0.47
Overall average	–0.13				
Carreta					
70–100	2.71	2.51	0.15	0.10	0.20
100–130	2.87	2.81	0.14	0.12	0.06
130–160	3.01	2.89	0.24	0.11	0.12
160–190	3.60	2.81	0.34	0.12	0.79
>190	3.63	2.61	1.46	0.11	1.01
Overall average	0.17				

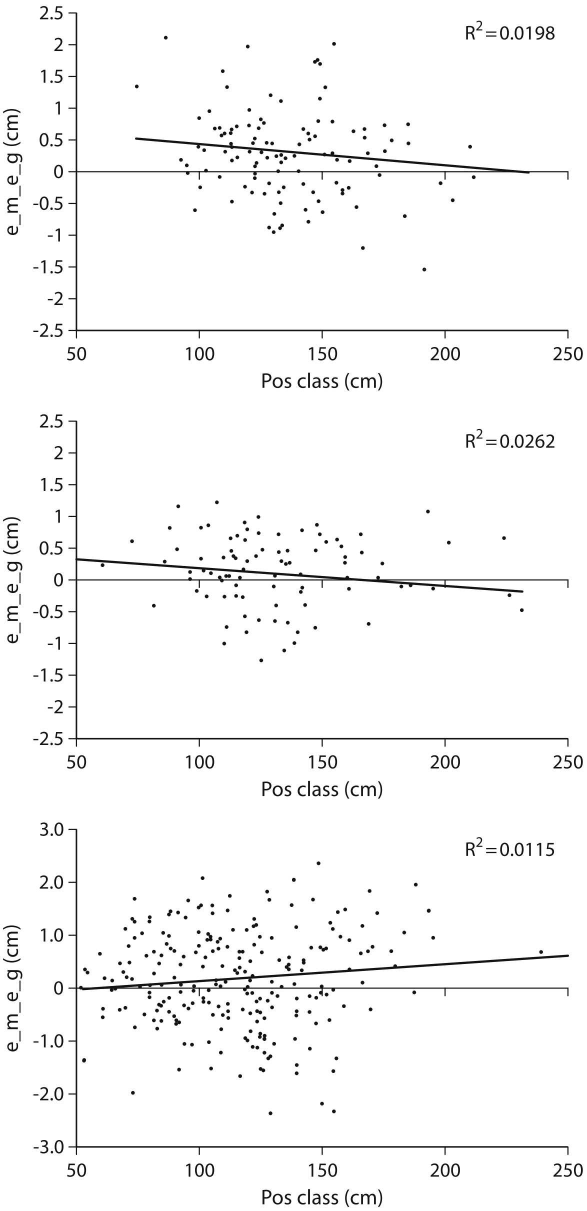


Fig. 14.4. Individual error distribution of measured and estimated thicknesses

The results led to the decision of no recalibration of the cork dry weight models due to its good performance in the evaluation/calibration plots.

14.5.2
Recalibrated Model Parameters and Statistics

It was decided to recalibrate the cork growth models in CORKFITS using all the data from all permanent plots in the data set. New cork growth models and mortality model statistics are presented below.

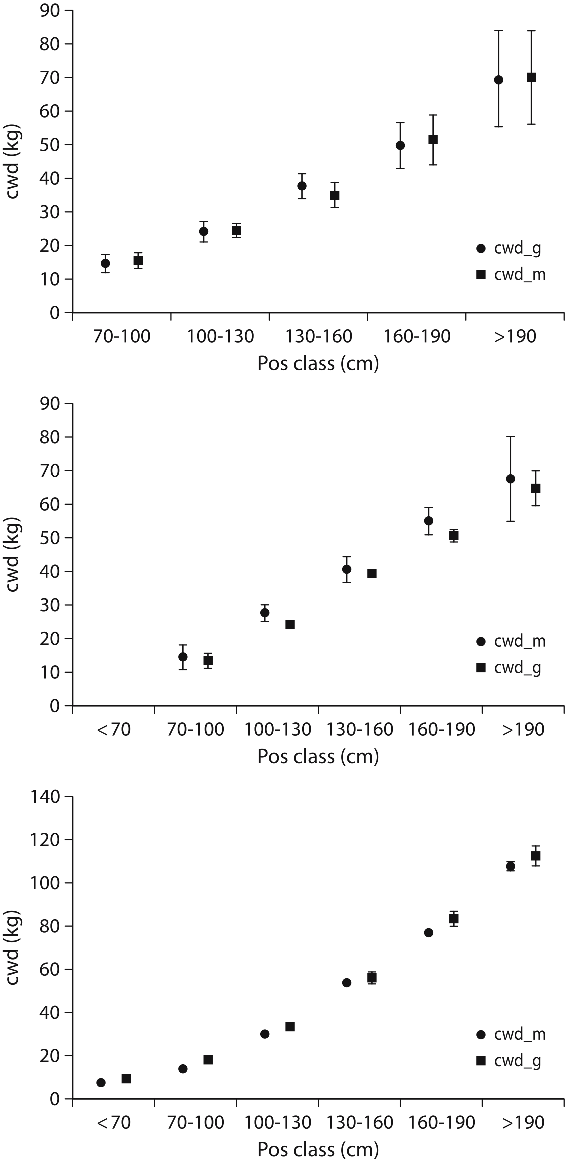


Fig. 14.5. Mean measured cork dry weight (cwd_m, kg) and mean estimated cork dry weight (cwd_g, cm) and the 95% ci for each mean for each p_{os} class (cm). *Above* Quinta Grande plot; *middle* Ruivos plot; *below* Carreta plot

14.5.2.1

Potential Cork Growth for the 9-Year Period ($cg_{9_{pot}}$, m^2)

For potential cork growth modelling, it was used the 95th percentile values in each of the 20 classes of cg_9 were used. The parameter estimates are dependent on the soil growth limitations for cork oak. The new model statistics are: model 1, soil with no growth limitations for cork oak; and model 2, soil with no growth limitations for cork oak:

Model 1:

$$cg_{9_{pot}} = \frac{0.12491 * 0.949400 * 1.61830 * g_{os}^{1.61830}}{g_{os} *(0.949400 + g_{os}^{1.61830})^2}, R^2_{adj}\ 0.95611, \text{RMS } 0.00001288$$

Model 2:

$$cg_{9_{pot}} = \frac{0.06931 * 0.61346 * 1.56281 * g_{os}^{1.56281}}{g_{os} *(0.61346 + g_{os}^{1.56281})^2}, R^2_{adj}\ 0.93214, \text{RMS } 0.00002048$$

Modifier (m)

The new model statistics are: model 3, soil with no growth limitations for cork oak; and model 4, soil with no growth limitations for cork oak:

Model 3: $m = e^{-0.30759 * ci\ 0.11546 * id}$, R^2_{adj} 0.71442, RMS 0.00004518

Model 4: $m = e^{-0.40032 * ci\ 0.06626 * id}$, R^2_{adj} 0.62511, RMS 0.00005134

14.5.2.2

Potential Crown Horizontal Projection Area Increment for the 5-Year Period ($ica_{5_{pot}}$, m^2)

For potential crown horizontal projection area increment modelling for the 5-year period, the 95th percentile values in each of the 20 classes of ica were used. The parameter estimates, as before, depend on the soil growth limitations for cork oak. The new model statistics are: model 5, soil with no growth limitations for cork oak; and model 6, soil with no growth limitations for cork oak:

Model 5:

$$ica_{5_{pot}} = \frac{15.98954 * 0.18055 * 1.86331 * g_{os}^{1.86331}}{g_{os} *(0.18055 + g_{os}^{1.86331})^2}, R^2_{adj}\ 0.84939, \text{RMS } 13.42684$$

Model 6:

$$ica_{9_{pot}} = \frac{9.41971 * 0.08469 * 1.79138 * g_{os}^{1.79138}}{g_{os} *(0.08469 + g_{os}^{1.79138})^2}, R^2_{adj}\ 0.71641, \text{RMS } 15.39542$$

Table 14.8. Mean measured cork dry weight and confidence interval for measured (cwd_m, 95% ci_m, kg) and estimated (cwd_m, 95% ci_g, kg) per pos class

pos class	cwd_m	cwd_g	95% ci_m	95% ci_g	cwd_g–cwd_m
Quinta Grande					
70–100	15.55	14.81	2.37	2.47	–0.74
100–130	24.56	24.29	2.07	2.83	–0.28
130–160	35.20	38.15	3.63	3.85	2.96
160–190	51.58	49.97	7.10	6.71	–1.61
>190	70.37	69.76	13.86	14.32	–0.62
Overall average	–0.01				
Ruivos					
70–100	15.38	21.56	3.46	1.93	–6.18
100–130	31.34	33.77	2.13	0.86	–2.43
130–160	55.95	53.58	3.62	1.12	2.37
160–190	79.73	77.17	3.85	1.65	2.56
>190	108.28	96.54	12.45	5.00	11.74
Overall average	–0.13				
Carreta					
70–100	13.42	18.09	0.64	0.62	–4.67
100–130	30.10	33.85	0.47	1.25	–3.75
130–160	54.44	55.93	0.58	2.17	–1.48
160–190	77.00	83.41	0.75	3.36	–6.41
>190	107.74	112.60	1.72	4.76	–4.86
Overall average	–3.53				

Modifier (m)

The new model statistics are: model 7, soil with no growth limitations for cork oak; and model 8, soil with no growth limitations for cork oak:

$$\begin{cases} \text{Model 7: } m = e^{-0.41086 * ci},\ R^2_{adj}\ 0.45867, \text{RMS } 19.10922 \\ \text{Model 8: } m = e^{-0.32574 * ci},\ R^2_{adj}\ 0.40540, \text{RMS } 20.64030 \end{cases}$$

14.5.2.3
Mortality Model

The logistic mortality model was fitted with the maximum likelihood method using SPSS version 12.0. The variables were selected with the forward Wald method. The analysis of maximum likelihood estimates is presented in Table 14.9.

The results presented in the table indicate that mortality is independent of tree dimension (g_{os}) and that is dependent on intensity of debark (id) and cork cumulative growth (cg_9). This fact indicates that the trees are affected by the debark pressure and that before dying they experience a reduction in cork growth which indicates the decay status.

The probability of survival of a tree in a 5-year period is given by model 9:

$$\text{Model 9: } \pi\ (\mathbf{x}) = \frac{e^{-126.871 cg_9 + 0.045 id + 24.460 g_{os}}}{1 + e^{-126.871 cg_9 + 0.045 id + 24.460 g_{os}}}$$

with a cut-off point of 0.75.

Table 14.9. Analysis of maximum likelihood estimates for the selected tree survival probability model

Model		χ^2	P (>χ^2)
−2LogL (likelihood)	118.160	35.719	0.000
Analysis of maximum likelihood estimates			
Variable	Parameter estimate	Wald statistic	P (>χ^2)
cg_9	−126.871	79.469	0.000
id	0.045	8.832	0.003
gos	24.460	10.915	0.001

14.5.3
Individual Cork Oak Model for Crown Identification and Delineation in NIR

A new sub-module was developed allowing the use of aerial imagery as an alternative source of input data for simulation purposes. This method allows the use of digitalized NIR aerial photos and produces information about individual trees (crown size, stem position, etc.) necessary for simulation start. The algorithm consists of several steps.

First, a set of filters working with spectra information on individual pixels is applied, where vegetation is defined and distinguished from the background. Second, the vegetation part is smoothed with a Gaussian filter of appropriated kernel, and an algorithm looking for the tree tops combined with a valley following approach is applied to delineate the individual tree crowns. A set of functions for calculation of tree dimensions derived from crown size was evaluated, so that the rest of the initial data for the simulation can be obtained.

As Fig. 14.6 shows, the initial image spectra is simplified in order to obtain a grey level image. Due to the constitution of the filters, the grades of grey colour correspond to the probability of a pixel being vegetation or not. In other words, the greyer the pixel, the greater the probability of the existence of vegetation. There are several options regarding how this image can be divided into two groups (vegetation and background). The most common and easy to use is thresholding with the histogram of the picture. The method developed in this work uses the grey level histogram of the picture and classification of the vegetation/background is made with the location of the valley point that divides the grey levels corresponding to the referred groups. The algorithm can operate: (1) in full automatic mode, where the thresholding is performed without human intervention, and (2) in semi-automatic mode, where the user has to visually locate the valley point in the displayed grey level picture histogram (Surový et al. 2004b).

After image division into vegetation/background groups, delineation of the individual tree crowns involves two steps (Fig. 14.7): (1) location of the darkest pixel (the tree top, the most illuminated point in the crown) and stem placement set with its coordinates; and (2) looking for crown edges, which are represented as

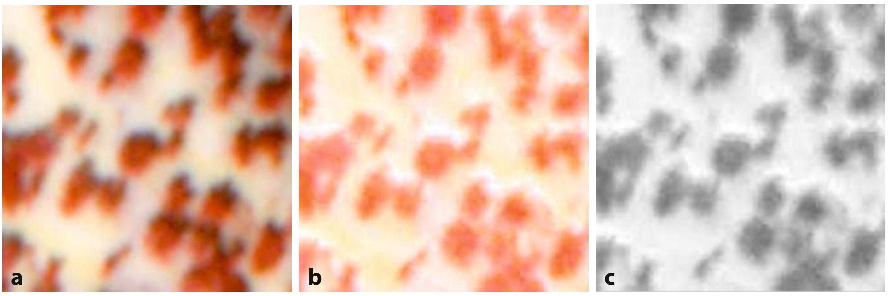


Fig. 14.6. From *left* to *right* Application of simplification filters to provide a frequency map

pixels in the direction of the crown centre, the following neighbour pixel or background, or pixels with increasing grey level (another crown).

Due to too detailed scanning, this simple algorithm approach may not be very accurate. Therefore, smoothing by sophisticated Gaussian kernel filter produces a better input image (Fig. 14.7). This procedure is generally replacing the human eye simplification of too detailed a scan into “blobs” corresponding to the tree crown.

After the primary sketches are defined, several filtering algorithms have to be applied to eliminate the crowns inside other crowns, which appear because of the photo noise (Fig. 14.8). The following variables are obtained directly by this algorithm: stem position, crown size and crown shape. The rest of the variables are generated by reversing formulas which describe the correlation between the stem and crown, etc.

Two varieties of system were developed: fully and semi-automatic ones. The number of trees measured with the fully automatic system had an average error of 37.6±22.5%, while the semi-automatic system had an average error of 19.1±20.8%. Simulations based on photo data differ (negatively) from the simulations based on real data especially in later years (40–100), mostly because of the regeneration trees not being visible in the photos (Surový et al. 2004b).

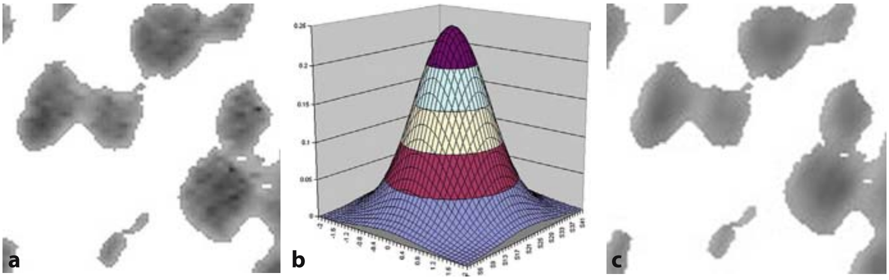


Fig. 14.7. Use of Gaussian kernel filter to eliminate the noise of too detailed a scan

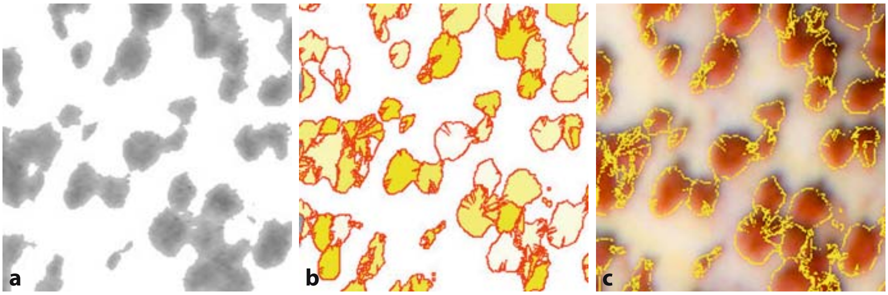


Fig. 14.8. Cutting algorithm, starting in the darkest crown parts and looking for vegetation edges or “valleys”

14.5.4
Software Developments and a Simulation Study Example

In order to make the models usable at the enterprise level by the end users, it was decided to develop a software interface (www.corkfits.net). The software allows users to: (1) input data describing their stands in different precision levels, (2) process them (run the simulation), (3) view prognoses, and (4) test different management scenarios and different economic evolutions.

The developments were made: (1) in the data management unit in the data input algorithms, (2) in the simulation options, and (3) in the output units.

14.5.4.1
Developments in the Data Management Unit

Three basic levels of input data are possible in CORKFITS 2.1: (1) basic information about the stand, where the user is asked to introduce only basic information (tree number per hectare and percentage distribution in width classes); (2) medium precision information, where the user can both digitalize data and open a text file containing tree list data without individual coordinates (e.g. National Inventory plots); and (3) high precision input data, where the user can both digitalize data and open a text file containing tree list data with individual coordinates (e.g. permanent research plots). The tree dimensions generator algorithm and STRUGEN are activated at levels (1) and (2) to generate missing data, thus creating the file with the initial necessary information to start the simulator. Combination of these three levels can be used in the GIS interface where it is possible to work with larger area information structured in information system.

14.5.4.2
Development of Simulation Options

Simulation can be processed in several ways: (1) two-site quality selection (soils with or without growth limitations for cork oak according to the Portuguese soil chart types); (2) selection by the user of the number of repetitions of one simulation to generate confidence intervals for the estimates (for all growth models a random error component is added); (3) possibility, after the simulation, to "walk" back in individual years and display the stand status or try different management options (e.g. natural or artificial regeneration); and (4) selection of the management options at any moment of the simulation, with the possibility to save previous management results.

Other simulation options can be set before or during the simulation, for example: (1) cattle (subsidy income for one unit, area used by unit, income per hectare); (2) cork (income per harvest unit of arroba, time–price development of income per unit, labour productivity in terms of stems, of trees with branches of first and second level, cost of labour, cost development per unit of labour); (3) soil mobilization (type of soil mobilization used during the simulation, costs per hour and type, productivity per hour, intensity of intervention in the 9- to 10-year period); and (4) plantation costs (type of plantation: new, additional; cost of labour, productivity, price of the plants).

14.5.4.3
Development of Output Options

Outputs are saved in database format, and all values can be accessed through the software environment. A special query tool is built-in and can be used to extract only desired characteristics. A list of data can then be exported to other formats (.txt, .xls) for further studies. Chart and graphic outputs were developed for management tests, as follows: (1) crown cover chart, (2) cork amount chart, (3) cork thickness chart, (4) stem thickness classes distribution chart, (5) cork quality chart, (6) econo-chart, income-chart, and (7) cost-chart and profit-chart (www.corkfits.net). All the above outputs display corresponding characteristics produced during the simulation. All the economics results regarding profits and costs are discounted with a discount rate (which can be modified after the simulation run).

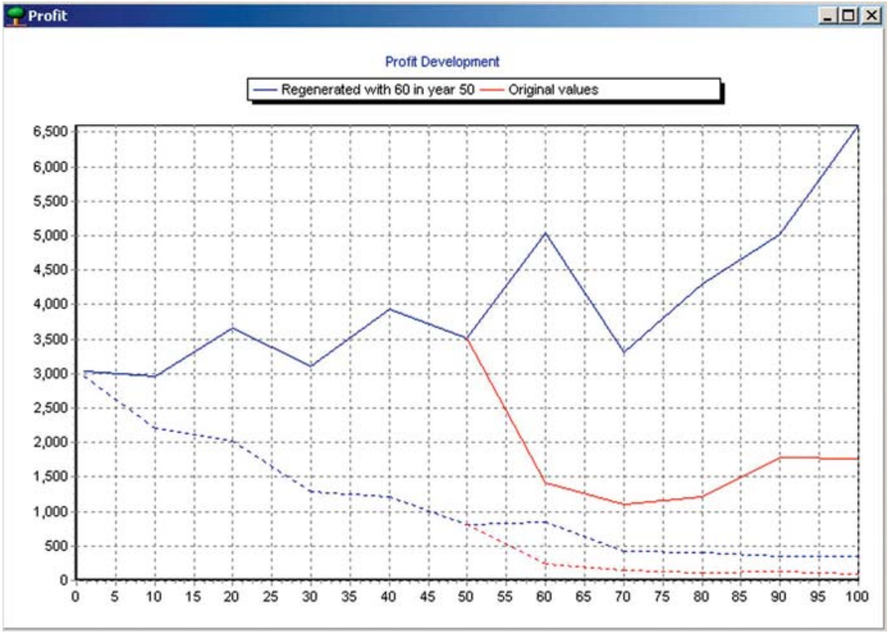
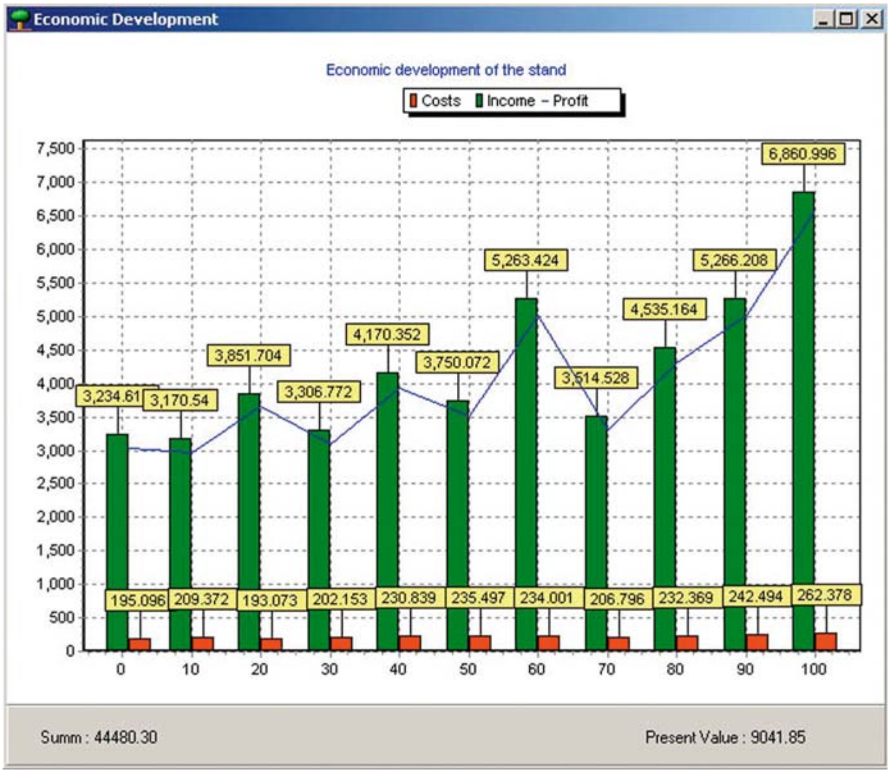


Fig. 14.9. Profit development chart (EUR). *Solid lines* Profit evolution without discount rate; *dashed lines* actual value of profit with discount rate of 3%; *red line* no regeneration; *blue line* regeneration with 60 plants ha^{-1}



Summ : 44480.30

Present Value : 9041.85

Fig. 14.10. Economic development of the stand (EUR)

A simulation example of the profit development (difference between income and costs) is shown in Fig. 14.9 and serves as a guide for economical sustainability management due to the demonstration of the good effects of regeneration (60 plants ha–1 at simulation year 50) on the profit lines (compare red with blue lines). Figure 14.10 shows the income and cost structure in 10-year intervals as well as the profit line without the discount rate applied for the same simulation example, demonstrating the benefits of regeneration compared to the costs of its implementation, with no discount rate.

The possibility of using the CORKFITS 2.1 system at a regional level has been developed (www.corkfits.net). The data structured in a GIS can be processed with an in-built module, which allows the user to introduce GIS data for larger areas; for example, a GIS map for a forest enterprise where these data can be processed. The outputs of this calculation are thematic maps including: a density map, crown cover map, production map, cork quality map, etc. (Fig. 14.11).

The simulation run can be executed without any management interruption, or there is a possibility for interactive regeneration management. The output data can also be saved and exported to other data formats (text, Excel).

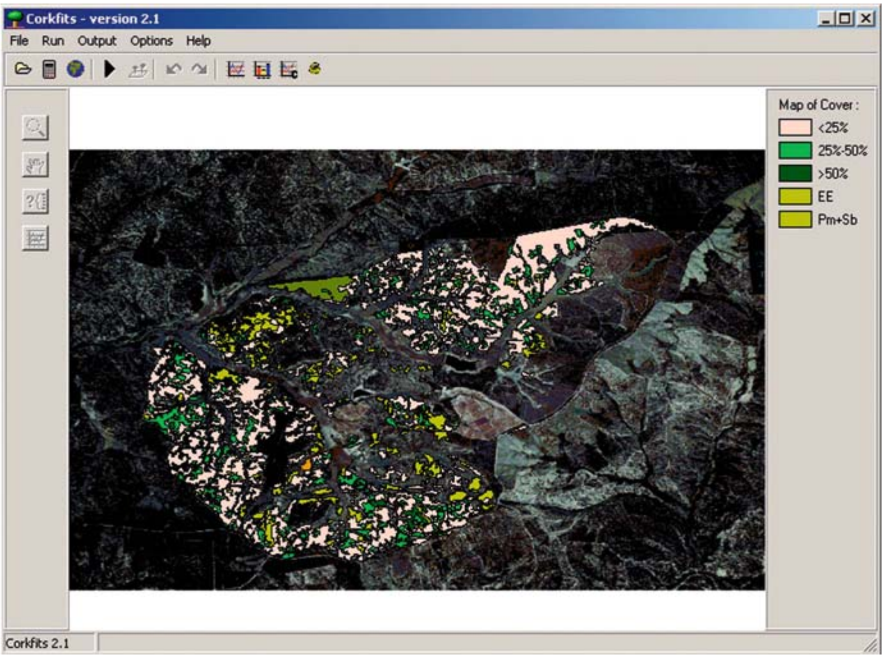


Fig. 14.11. GIS interface

14.6 Conclusion

The evaluation process of the CORKFITS growth simulator shows that the cork dry weight model was behaving well outside the range of calibration data for cork weight estimation. The cork growth model presented some deviations in large pos tree classes in Carreta and Ruivos. In Quinta Grande the characteristics of this site are responsible for the observed deviation mainly due to the presence of a water table combined with a deep soil which compensates the effects of the observed competition. The results led to the recalibration of the cork growth functions in order to be able to simulate growth at regional level.

As an alternative source of data, aerial imagery was proposed and tested. Simulation based on aerial imagery should be used only for shorter time prediction because of the lack of small trees and regeneration, usually invisible in photos. This drawback could be eliminated by additional field measurement or by regular remote sensing (every 10 years).

The CORKFITS growth simulator was considered by company representatives as useful and a practical tool which enables the acquisition of reliable results for planning and decision making processes.

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Implementing Tree Growth Models in Slovakia

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Abstract. Significant effort in converting even-aged, single species stands into mixed, uneven-aged stands and in conserving natural forests has been expended in recent decades by policy makers in Slovakia. These efforts necessitate the use of models for the prognosis of forest development. This chapter describes the approach taken by the Slovakian scientific group (the Technical University in Zvolen) in the field of calibration and construction of Slovakian localized tree growth models. We used two different approaches for development of the models. The first model is a calibrated version of SILVA 2.2 (from the Technical University in Munich) and is called SILVA SK. Its calibration process is described. SILVA SK has already been integrated into geographic information system (GIS)-based forestry information systems (LesHIS, GOLEM) and is ready for use in the field of forestry. First test runs in selected forest districts have been applied. The second model is that of SIBYLA. We began the process of its development because it satisfies all Slovakian specific requirements: an economic environment, forest management, and forest biometry standards. This model will replace SILVA SK and will be prepared for field implementation within a short time. The construction of the SIBYLA model is summarized. The model is implemented as the computer program SIBYLA Suite.

15.1
Introduction

In recent decades, Slovakian forestry policy makers have expended significant effort in converting even-aged, single species stands into mixed, uneven-aged stands and in conserving natural forests. This effort has been complicated by global and local climatic changes that are transforming the economic environment. These factors have led to an increased need for capable managerial tools, including growth models.

In the past, yield tables were an important tool for forest growth modeling in Slovakia (Halaj et al. 1987). However, these tables are losing their relevance as

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Sustainable Forest Management
Growth Models for Europe

mixed uneven-aged stands become more important. Tables do not allow for ecological site classification of these stands, because site classification is based only on dominant height and age. A single age is not a meaningful variable in uneven-aged stands. Another disadvantage of yield tables is their poor ability to predict the reaction to different treatments; yield tables are constructed for one treatment of one tree species. Besides these disadvantages, the current tables do not contain other important outputs, such as stand structures, costs, and revenues. All these factors have led to the need for a new growth model.

In addition to the development of a growth model, there is also the need to connect the model to sophisticated geographically oriented information systems and to develop a methodology for application of decision support systems in forest management. These tasks were completed within a scientific project of the fifth framework program of the EU. The main goals were:

- to choose a tree growth model from one of the project partners (Austria, Germany, Finland) and calibrate it to Slovakian biological and economic conditions;
- to make a connection between the growth model and data from the national inventory and geographic information systems (GIS);
- to develop a methodology for decision support, planning, and forest management; and
- to begin work on the development of our own model, which would be fully adapted to Slovakian forest conditions and which could potentially be implemented in the field of forestry in the coming years.

15.2
Experimental Material and Data Background

Long-lasting cooperation between the Technical University of Zvolen and the Technical University of Munich led to SILVA 2.2 (Pretzsch 2001) being chosen as the basic growth model for calibration. The reasons for using this model were the similarities of the natural conditions in Bavaria and Slovakia and the fact that Slovakian researchers took part in the development of some parts of the model and its software components during stays at the Chair for Forest Yield Science in Freising. Moreover, the structure of the growth model meets the conditions for putting it into practice in Slovakian forestry. In addition to being the basis for the calibrated version of the model (SILVA SK), the modeling principles of SILVA 2.2 became the basis for the new growth model SIBYLA. Experimental materials and background data used for calibration and development were heterogeneous and consisted of the following resources:

1. Yield tables (Halaj et al. 1987), mainly height and diameter growth curves at the best and worst quality sites, were used to derive ecological site classifications. These were incorporated in the SIBYLA model according to the methodology of Kahn (1994) and were an important source for deriving height and diameter increments. The yield tables are based on a wide range of measurements and supplement experimental data. The yield tables are based on material from experimental plots that were established in 1964 – 1973 (Halaj

and Ŕehák 1979). Additional data came from permanent plots established in the past for various scientific purposes (Pařez 1965; Vyskot 1966, 1969; Korenek 1967; Korpel' 1968, 1970; Šebík 1968; Vazúr 1968; Réh 1972; Sabol 1975). Most of the plots were in the third or fourth cycle of measurement. The total number of measurements was 2,199 for spruce, 436 for fir, 724 for pine, 1,239 for beech, and 746 for oak. Detailed descriptions of the plots are in referenced publications.

2. The next important source for the development of the SIBYLA model was inventory data on the diameter and height structures of Slovakian forests (Halaj 1957, 1978). These data were used to determine relationships between maximum stand height (or maximum diameter) and dominant stand height (or mean diameter) in order to construct a model of ecological site classification as well as a generator of diameter frequency. The diameter inventory was carried out on 740 stands of spruce, 370 stands of fir, 380 stands of pine, 420 stands of beech, and 370 stands of oak. The height structure was based on 85 permanent plots of spruce, 57 plots of fir, 55 plots of oak, and 75 plots of beech. The broad range of experimental material is sufficient for modeling diameter and height structures and was a very valuable source of data for constructing partial algorithms for the SIBYLA model.
3. Height curves within the structure generator of the SIBYLA model were constructed using models in the form of equations of uniform height curves that were published by Šmelko et al. (1987). These equations were derived as unified height curves, described by Halaj (1955), based on rich empirical material consisting of graphical charts of chosen forest stands from all forest eco-regions in Slovakia from all age, height, and site levels; 1,382 spruce stands, 692 fir stands, 514 pine stands, 1,472 beech stands, and 879 oak stands were used.
4. In order to estimate the volume of trees with SILVA SK and SIBYLA, volume equations were used. These were constructed and published by Petráš and Pajtík (1991). Empirical material on the form of cut trees was used for constructing volume relationships which were based on 2,111 spruce trees, 1,477 fir trees, 1,659 pine trees, 1,886 beech trees, and 1,893 oak trees.
5. To calculate the harvested volume, the SILVA SK and SIBYLA models use tree assortment tables (Petráš and Nociar 1990, 1991). These are based on 11,947 cut trees from 167 experimental plots in important tree species regions. Included in this material were 4,203 beech trees, 3,042 oak trees, 1,836 pine trees, 1,705 spruce trees, and 1,161 fir trees.
6. In addition to the above mentioned sources, data from a 4×4 km network of permanent monitoring plots installed by Lesoprojekt Zvolen in 1994 according to methodology by Švec et al. (1993) were used. These data were used to derive equations for diameter and height increments for the SILVA SK model and a residual element of diameter and height increments in order to model the biological variability of growth processes in the SIBYLA model. The total number of permanent monitoring plots was 1,189, with sizes of 200, 500, or 1,000 m2, depending on stand density. The plots represent all Slovakian forest areas (Fig. 15.1.). Repeated measurements of diameter and height of trees were performed from 1996 – 2002, with 1/10 of the Slovakian area being measured every year. Hence, the measurement periods were from 2 – 8 years. In to-

Fig. 15.1. Localization of permanent monitoring plots in Slovakia in 4×4 km networks

tal, 7,358 spruce trees, 1,137 fir trees, 1,181 pine trees, 9,213 beech trees, and 3,444 oak trees were measured.

15.3
Methods and Principles of Model Calibration and Development

15.3.1
Calibration of Diameter and Height Increment in the Model SILVA SK

As mentioned in the previous section, data from permanent monitoring plots were used to calibrate models of height and diameter increment.

For each plot, simulated stands (50×50 m) were generated by expanding circular plots. A tree list was constructed for each simulated stand, with missing trees being generated. Unknown characteristics (tree co-ordinates, crown parameters) were calculated with the structure generator STRUGEN (Pretzsch 1993, 2001). Growth simulation was carried out. In the simulation, dead trees were considered to have been harvested. Instead of using a thinning generator, selection of harvested trees was based on lists of trees that had actually been removed. Growth was simulated for 5- and 10-year periods. The predicted annual diameter and height increments were calculated and synchronized with real annual increments from permanent monitoring plots. Linear interpolation was used for synchronization. Modelled increments (SILVA) and real increments (measurements) were compared. Differences between SILVA increments and real increments ($i_{SILVA} - i_{REAL}$) were tested for significance. In general, bias was detected for diameters and heights; therefore, regression functions between differences (BIAS) and SILVA increments were derived as follows:

$$B_d = a_0 + a_1 \cdot i_d\ (SILVA)$$

$$B_h = a_0 + a_1 \cdot i_h\ (SILVA)$$

The coefficients of the functions (a_0, a_1) for spruce, fir, pine, beech, and oak are given in Table 15.1. A sample derivation of coefficients for beech is shown in Fig. 15.2.

Additionally, an estimate of the range of random errors was developed. The method used is as follows:

1. Creation of SILVA increment classes and calculation of mean bias [$B(j)$] and standard deviation of biases [$s_B(j)$] for differences in each class.
2. Derivation of the regression model for standard deviations of biases, using the middle of SILVA increment classes [$s_B(j)=f(i_{SILVA}(j))$].
3. Calculation of random error [E] on the basis of a Gaussian distribution defined by bias and standard deviation of bias as follows:

$$E_d = (GAUSS\ (B_d, S_B)$$

$$E_h = (GAUSS\ (B_h, S_{B_h})$$

Final calibrated Slovakian increments are calculated by:

$$i_d\ (SK) = i_d\ (SILVA) - B_d + E_d$$

{ih_{d} (SK) = i_{d} (SILVA) – B_{d} + E_{d}}

$$i_h\ (SK) = i_h\ (SILVA) - B_h + E_h$$

{i_{h} (SK) = i_{h} (SILVA) – B_{h} + E_{h}}

Table 15.1. Coefficients of regression for calculation of biases in dependence of tree species

Species	Diameter		Height	
	a_0	a_1	a_0	a_1
Spruce	–0.2199	0.6962	+0.1993	0.0238
Fir	–0.3206	0.9734	–0.0748	0.8112
Pine	–0.1804	0.5601	–0.1325	0.9758
Beech	–0.2033	0.6148	–0.122	0.5626
Oak	–0.259	0.9979	–0.1196	0.7333

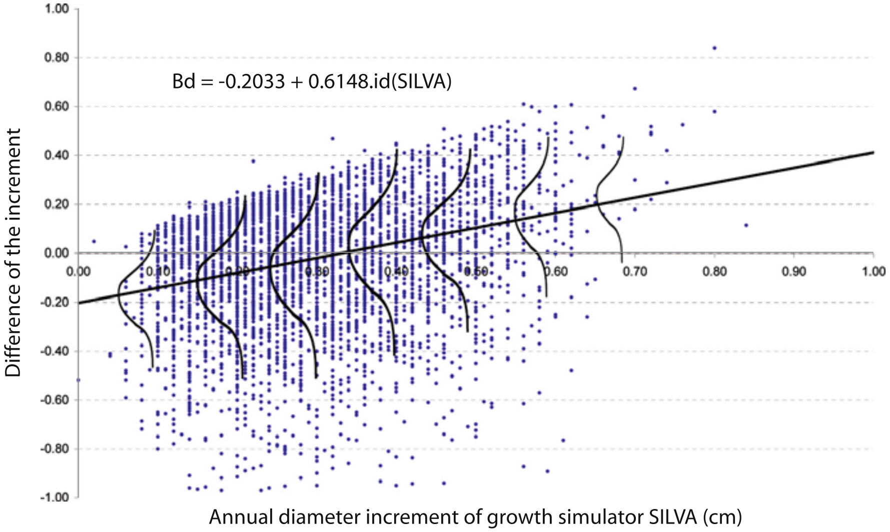


Fig. 15.2. Derivation of corrections (bias) for purposes of the calibrated model SILVA SK. Example of diameter increment of beech. The *x-axis* describes annual diameter from SILVA 2.2 and the *y-axis* describes observed differences between the SILVA modelled increment and real increment from permanent monitoring plots (SILVA-REAL)

15.3.2
Development of the SIBYLA Growth Model

During calibration of the SILVA SK model a systematic error in modeling diameter and height growth was discovered. Also, the calibrated version did not allow implementation of biometrics standards (tree volume calculation equations) or economic models (i.e., cost and revenue calculations). These had to be solved with external software modules, which was not good in terms of software processing consistency. The same problem occurred when defining site conditions, which were linked to German growth regions. This problem had to be solved using the software module SILVA Manager. There were also difficulties with implementing Slovakian algorithms of stand structure generation directly into the SILVA SK software application. There was an additional problem with defining the quality of trees, which was not included in the German model but was necessary for using local assortment models. These and other reasons led to the need for a new, fully localized, and parameterized growth model as well as a new software implementation of this model, which was named SIBYLA. The basic conditions for development of the first version of this model were low cost, a short development period, open architecture regarding future parameters, and compatibility with information systems being used in forestry. The result was "a skeleton of modified algorithms wrapped into a body of a new software application".

15.3.2.1
Basic Concepts of the SIBYLA Model

The growth model consists of several basic components: (A) a stand structure generator, (B) a 3-D forest structure model, (C) a calculating model which calculates production and ecological and economic forest stand parameters, (D) a mortality model, (E) a thinning model, (F) a competition model, and (G) an increment model. Algorithms of the major portions of the model (D, E, F, G) are based on the principles of the growth simulator SILVA 2.2 (Pretzsch and Kahn 1998). These algorithms were calibrated by means of modification of indices or parameters. Model A was partly revised: generation of the diameters and heights of individual trees in the stand, tree quality generation, and generation of GIS altitude coordinates of the tree base. Partial algorithms of the STRUGEN generator of the growth simulator SILVA 2.2 were used; this included generation of the horizontal coordinates (Pretzsch 1993) of the tree position and generation of crown parameters (Pretzsch and Kahn 1998). Model C was completely revised in conformity with algorithms derived for Slovakian conditions: calculations of forest stand production characteristics, forest density characteristics, biodiversity indices, and costs and returns from basic harvest and transport activities. Model B was also newly developed; it generates visual forest structure based on virtual reality. The flowchart of the SIBYLA model is shown in Fig. 15.3.

Data on individual trees (diameters, heights, horizontal and high-altitude positions, heights to the base of the crowns, crown diameters, and tree quality) are the initial input data to the growth simulator. In the case of missing data, this information is generated through the stand structure generator (model A). Missing data often occur with Slovakian forest inventory data, where only stand characteristics (mean diameters, mean heights, and volume per hectare for individual tree species) are available. Real or generated forest stands are displayed in the form of a 3-D model (B), while production characteristics, forest structure characteristics, and economic characteristics are calculated by means of the calculating model (C). Models function in a certain order: the mortality model is first (D), and is followed by the thinning model (E), the competition model (F), and the increment model (G), which are activated when simulation for the next period is required. Boolean values indicating the status of survival of individual trees in the current period (1=tree survived, 0=tree died) are the results of the mortality model. Boolean values also result from the thinning model (E) (1=keep tree, 0=remove tree). A growth reduction factor based on the competition model (F) is calculated afterwards, depending mainly on the competitive pressure of the surrounding trees. Finally, the increment model (G) is applied to each tree that passes to the following period (both Boolean values equal 1). Diameter and height increments of each tree, depending on climate and soil site characteristics, result from the increment model. These factors are reduced by the reduction factor from the previous model (F). New tree diameters and heights are calculated using this information. Remaining tree characteristics, such as crown parameters, are obtained from equations related to tree diameter and height. The new stand situation is again visualized by model (B) and output stand data are derived from the calculating model (C). The model sequence repeats until the end of the simulation.

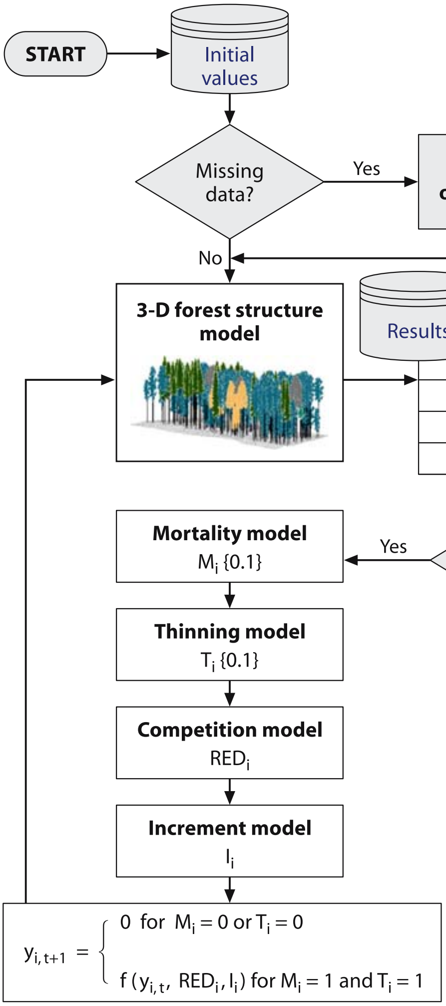


Fig. 15.3. Flowchart of the model SIBYLA

15.3.2.2
Stand Structure Generator

The model generates missing data for individual trees (diameter, height, crown parameters, spatial coordinates, quality). Diameter distributions and height curves are the basic components of the model. Curves of diameter distributions are derived from the Weibull function for each tree species (an example is shown in Fig. 15.4). Quadratic mean diameters (d_g), their coefficients of variation (s_d%), and number of trees per hectare (N) define the curves:

$$f(d_{1.3}) = \frac{c}{b} \cdot \left(\frac{d_{1.3}}{b}\right)^{c-1} \cdot e^{-\left(\frac{d_{1.3}}{b}\right)^{c}} \cdot N$$

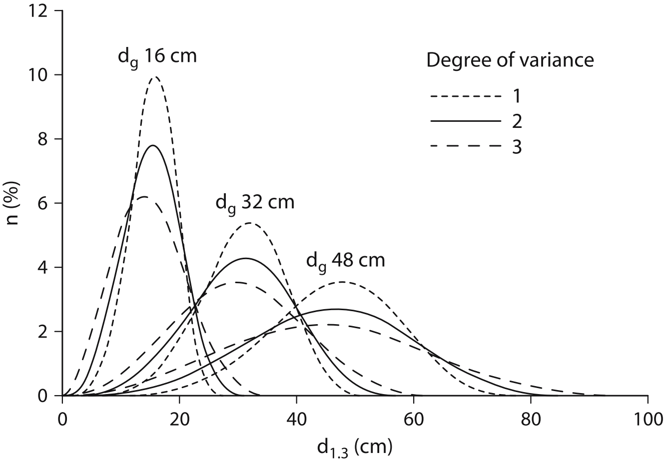


Fig. 15.4. Frequency diameter distribution depending on mean diameter (d_g) and degree of variance (*1* small; *2* medium; *3* large). Example for spruce. The *x-axis* describes diameter at breast height of tree and the *y-axis* describes frequency

Weibull coefficients (c, b) depend on the quadratic mean diameter and coefficient of variation.

Tree heights are calculated from uniform height curves (Šmelko et al. 1987) that are derived for each tree species. In addition to tree diameter ($d_{1.3}$), the quadratic mean diameter (dg) and mean height (hg) are the inputs into curves:

$$h = 1{,}3 + (h_g - 1{,}3) \cdot exp\left[(a_0 + a_1 \cdot h_g + a_2 \cdot d_g) \cdot \left(\frac{1}{d_{1.3}} - \frac{1}{d_g}\right)\right]$$

Crown parameters consist of height to the base of the crown (ch) and maximal crown diameter (cd) which are estimated from tree diameter ($d_{1.3}$) and height (h). The regression formulas from the SILVA 2.2 model are utilized (Pretzsch and Kahn 1998):

$$\mathrm{cd} = \mathrm{e}^{\left(a_0 + a_1 \cdot ln\,(d_{1.3}) + a_2 \cdot h + a_3 \cdot ln\,\frac{h}{d_{1.3}}\right)}$$

$$\mathrm{ch} = \mathrm{h} \cdot \left(1 - \mathrm{e}^{\left(a_0 + a_1 \cdot \frac{h}{d_{1.3}} + a_2 \cdot d_{1.3}\right)}\right)$$

Horizontal tree coordinates are next generated using the Poisson process (Pretzsch 1993). An algorithm allows one or more tree species to be distributed in clusters (or strips) within the random distribution of another tree species. The coordinate generation process is conducted by means of filters. Positions of grouped tree species (clusters or strips) are generated first. Second, the stand is filled with other tree species. The filter of the first step creates the stand macrostructure, i.e., clusters or strips; the second filter regulates the stand microstructure (preserving minimal distances between trees). The model is fully stochastic. Vertical coordinates are generated and attached to horizontal tree coordinates. A 3-D network (lattices) was developed using a digital terrain model and the principle of the bilinear interpolation was utilized (Fabrika 2003a). Qualitative tree characteristics (quality class and damage) are derived last. Data are derived using a stochastic generation procedure, which is based on the percentage of quality classes and composition of damaged trees. All the input data for generating the stand structure are adopted or derived from generally available forest inventory data. The described model is very flexible and allows the generation of a broad range of stand structures, from even-aged homogenous stands to uneven-aged mixed stands.

15.3.2.3
The Three-Dimensional Forest Structure Model

The model allows for visualization of the stand structure. Two approaches are used for this purpose. The first approach deals with generalized stand information. It uses projection techniques to display the stand in a 3-D perspective. The model allows the viewer to change the viewing angle by shifting and rotating the stand and the position of the viewer. The second approach exports stand characteristics to a virtual reality (virtual reality model language, VRML) system. It enables the creation of a consistent 3-D stand model with the unlimited ability to virtually walk and fly through the stand. Algorithms for technical execution of the virtual reality visualization are described by Fabrika (2003a). Examples of both approaches of the visualization used by the SIBYLA model are shown in Fig. 15.5.

15.3.2.4
The Calculating Model

The calculating model calculates production, biodiversity, cost, and returns. Data on the mean stem (average age, mean diameter, mean height, diameter variability, dominant height, mean stem volume) per hectare variables (number of trees, basal area, growing stock, crown projection area) and density characteristics (canopy cover, stand density index, and stand density) are calculated from production characteristics. The algorithms used for standard Slovakian biometry, for example, tree volume equations (Petráš and Pajtík 1991), and other algorithms adopted from abroad, for example, stand canopy cover (Crookston and Stage 1999), and the stand density index (Reineke 1933) are utilized for calculations.

Diversity and variability of forest stands is assessed by means of species diversity and structural diversity indices. Species diversity is made up of indices of species richness, species heterogeneity, and species balance. Structural diversity is made up of horizontal structure, vertical structure, and structural differentiation. Most of the indices are standardized on scales from 0 to 1, to make interpretation easier. A value of 0 indicates the lowest degree of the diversity and a value of 1 the highest. Classic biodiversity indices by different authors have been used

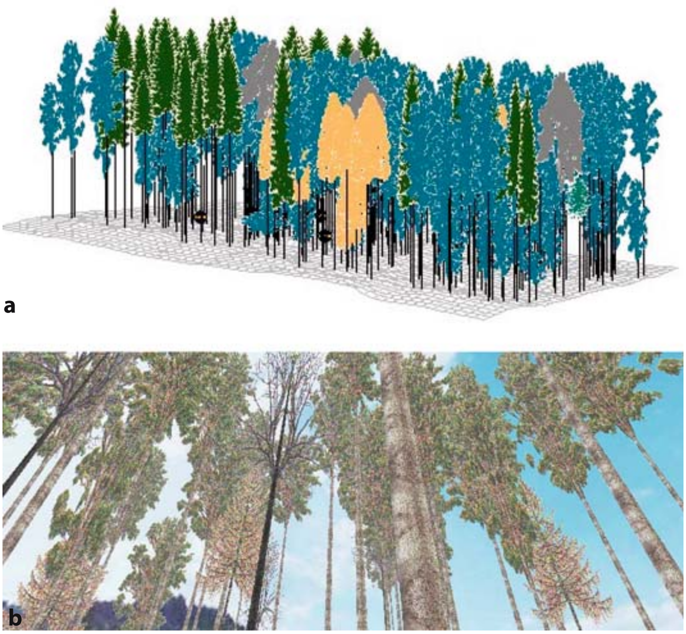


Fig. 15.5. Examples of visualization in the model SIBYLA (**a** 3-D projection; **b** virtual stand)

for calculations (Shannon 1948; Simpson 1949; Clark and Evans 1954; Margalef 1958; Menhinick 1964; Hill 1973; Pielou 1975; Pretzsch 1992; Füldner 1995; Jaehne and Dohrenbusch 1997).

Calculation of forest revenues is based on standard assortment models, where the total volume for each tree is divided into different timber classes (Petráš and Nociar 1990, 1991). The tree diameter, quality class, damage assessment, forest eco-region, and age are input into the model. Final returns from the forest are then obtained by multiplying the total volume in each class by its price in SKK (Slovak Crown) and then summing the results.

At the same time, the model calculates costs for basic activities: cutting, yarding, and conversion. Total direct costs are calculated for staff, fuel, and social costs. Staff costs (C_1) are derived from local efficiency standards for cutting, yarding, and conversion. Standard productivity time rates (ST) for each tree species are the basis for cost calculations. These rates are modified with deductions and overcharges according to operation conditions. Staff costs are calculated using the volume of the relevant tree species (V) measured in cubic meters and the staff salary (T) in SKK per hour:

$$C_1 = ST \cdot V \cdot T$$

Fuel costs ($C_{2.1}$) for activities using a chainsaw (cutting and conversion) are calculated as follows:

$$C_{2.1} = ST \cdot k \cdot F \cdot V$$

i.e., the standard time of relevant activities (*ST*) is reduced by the reimbursements reduction coefficient for the chainsaw (*k*) and recalculated according to fuel costs per reduced standard hour (*F*) and the exploited volume (*V*). Fuel costs ($C_{2.2}$) for yarding are directly derived from the actual yarded volume (*V*) and fuel costs per cubic meter (*F*):

$$C_{2.2} = V \cdot F$$

Social costs (C_3) are calculated on the basis of staff costs (C_1) and by the share of mandatory social delivery (*S*):

$$C_3 = C_1 \cdot S$$

Total direct costs (*C*) are calculated as a sum of the staff, fuel, and social costs.

15.3.2.5
The Mortality Model

This model is adopted from the SILVA 2.2 growth simulator (Ďurský et al. 1996; Ďurský 1997; Pretzsch and Kahn 1998). The output of the model is a survival indicator of each tree (0=tree will die, 1=tree will live). The probability that the tree will die is expressed as a percentage:

$$Mrt\% = \frac{a}{e^{(b \cdot F\text{–}logit)^c}}$$

The *F_logit* value is derived for each tree on the basis of its dimension, site characteristics, and competitive pressure. Values *a, b,* and *c* are coefficients that depend on tree species. Derivation of the tree survival indicator comes from the comparison of a randomly generated number from the uniform distribution (0...100) and probability *Mrt(%).* If the generated number is smaller than the calculated survival probability, the tree is considered as dead (resulting value is 0); otherwise, the tree is regarded as living (resulting value is 1).

15.3.2.6
The Thinning Model

The thinning model produces a cutting indicator for each tree (0=remove tree, 1=tree remains). The model allows different thinning methods: thinning from below, thinning from above, quality crown thinning, crop trees method, and target dimensions method. Algorithms are based on a combination of deterministic models, stochastic models, and fuzzy rules-based models (Kahn 1995). The mentioned thinning methods work without any assistance of the system user. A tree selection method for cutting is based on direct specification by the user and allowed as an alternative. The virtual forest stand, which is generated by VRML language, is used for these purposes. The user can directly enter into the virtual forest and specify thinning by an interactive selection of the target (crop) and extracted trees (Fabrika 2003a).

15.3.2.7
The Competition Model

The calculation of the growth reduction factor (competition index) is determined by the CCL index (Bachmann 1998), which quantifies the competitive pressure under the influence of adjacent trees:

$$CCL = \sum \beta_{ij} \cdot \frac{cA_i}{cA_j} \cdot k_i$$

The trees coming into the competition cone (αj) are regarded as competitors (i). The competition cone is an inverted cone with side walls at 30° from the central axis (see Fig. 15.6). The tip of the cone is positioned at 60% of the tree height. β_{ij} is the angle between the side wall of the cone, the tip of the cone, and the top of the competing tree. cA values express the crown basal areas of the central tree (j) and competitors (i). The value k_i represents the light transmission coefficient of individual competitors and depends on tree species. Along with light competition due to shading, the competition symmetry assessment and tree species mix-

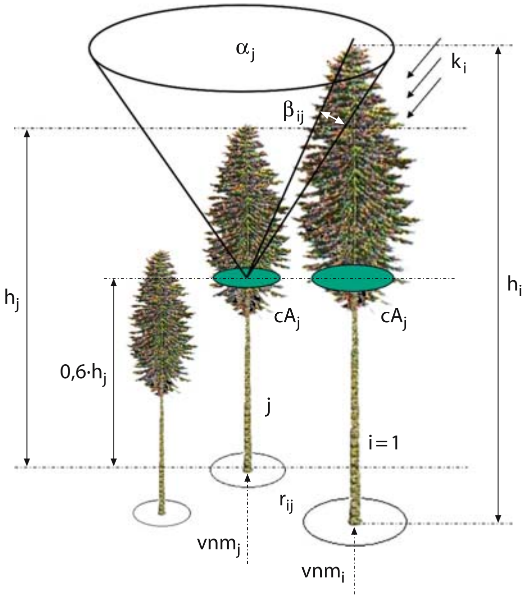


Fig. 15.6. Principle of the competition index CCL. Cone of light competition space (α_j) and competition angle (β_{ij}) between central tree (*j*) and its competitor (*i*).

ture enter into the calculation. These factors and the calculated *CCL* together affect the total competition index.

15.3.2.8
The Increment Model

The increment model was adapted from the model SILVA 2.2 (Pretzsch 1992). The model is based on an ecological site classification, which directly draws from the following climate and soil site characteristics (Kahn 1994): length of vegetation season (number of days with the mean day temperature higher than 10 °C), yearly temperature amplitude, mean temperature during the vegetation season, total precipitation during the vegetation season, CO_2 and N_2O content in the air, soil moisture, soil nutrient supply, and arid index in the vegetation season. These factors enter the fuzzy set membership, which was constructed through tree species-sensitive studies of environmental factors. The results of these operations are nutrient, thermal, and humid indices. These indices reduce the height growth potential of individual tree species from which the height increment is derived. Indices also reduce the potential diameter increment of tree species. This principle of modelling by changing growth parameters is based on Slovakian yield tables data, diameter and height frequency data, and measured data from permanent monitoring plots. The model is composed of two important parts:

1. a sub-model of relative increment sensitivity on ecological amplitude of climate and soil values; and
2. a sub-model of potential height and diameter ranges as a curve for optimal site conditions (maximum increment) and worst conditions (minimum increment).

Construction of SILVA 2.2 under German conditions was based on a wide scale of expensive empirical data. Because of the unavailability of this data for Slovakian conditions, we have constructed the first sub-model using all parameters of the SILVA 2.2 model. Our assumption is that relative sensitivity of the growth values on ecological amplitude for tree species (spruce, fir, pine, beech, and oak) is similar to Slovakian growth properties. Construction of the models is based on growth curves for diameter and height development at different site classes. These data are available in Slovakia (yield tables and experimental data). Thus, for the second sub-model, we have derived new ranges for diameter and height growth potential using the methodology of Pretzsch (1992) and Kahn (1994). The results of this model are upper and lower height curves, which are modelled using ranges of minimal and maximal asymptote and minimal and maximal ages of increment culmination. We utilized the following growth function by Korf:

$$h_{max} = c \cdot A \cdot e^{\frac{k}{(1-p)\, t^{p-1}}}$$

The function describes development of height potential (h_{max}) in relation to age (t). Coefficients of the model (A, k, p) are derived from Slovakian yield tables (Halaj et al. 1987). The coefficient c, which is a relationship between maximum and dominant height, is derived from Slovakian height frequency curves (Halaj 1978). A comparison between SILVA 2.2 and SIBYLA is depicted in Fig. 15.7. The next result of the model is diameter increment growth potential (i_{dmax}), which is dependent on tree diameter ($d_{1.3}$). The function is:

$$i_{dmax} = d_{1.3} \cdot \frac{k}{\left(\dfrac{-k}{In\left(\dfrac{d_{1.3}}{c \cdot A} \right) \cdot (p-1)} \right)^{\frac{p}{p-1}}}$$

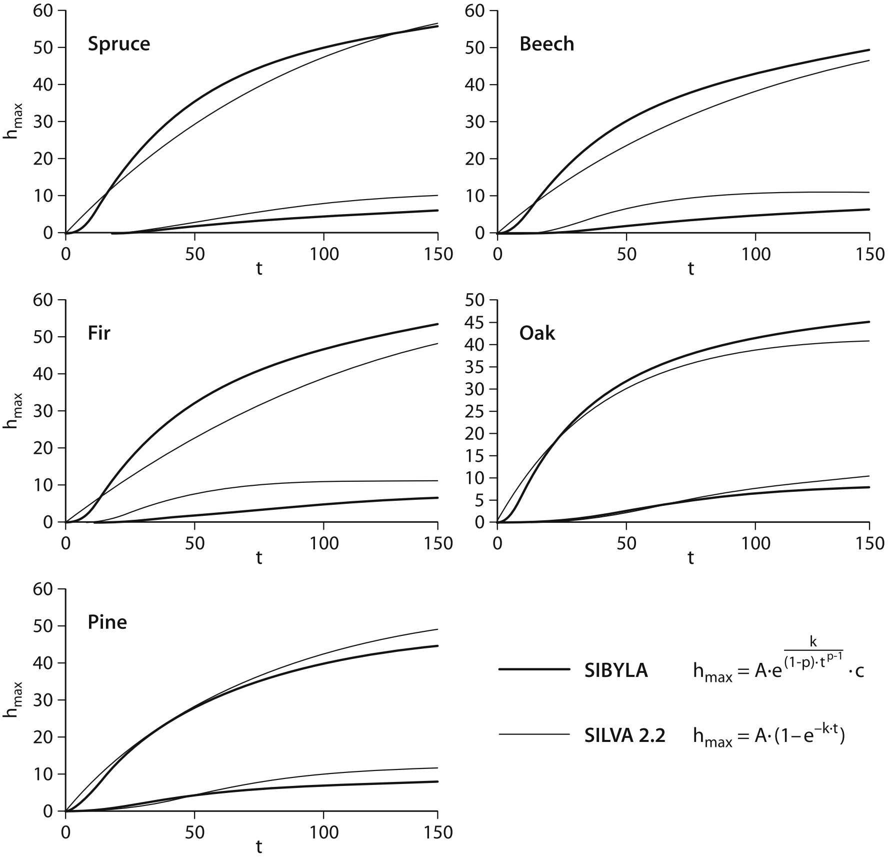
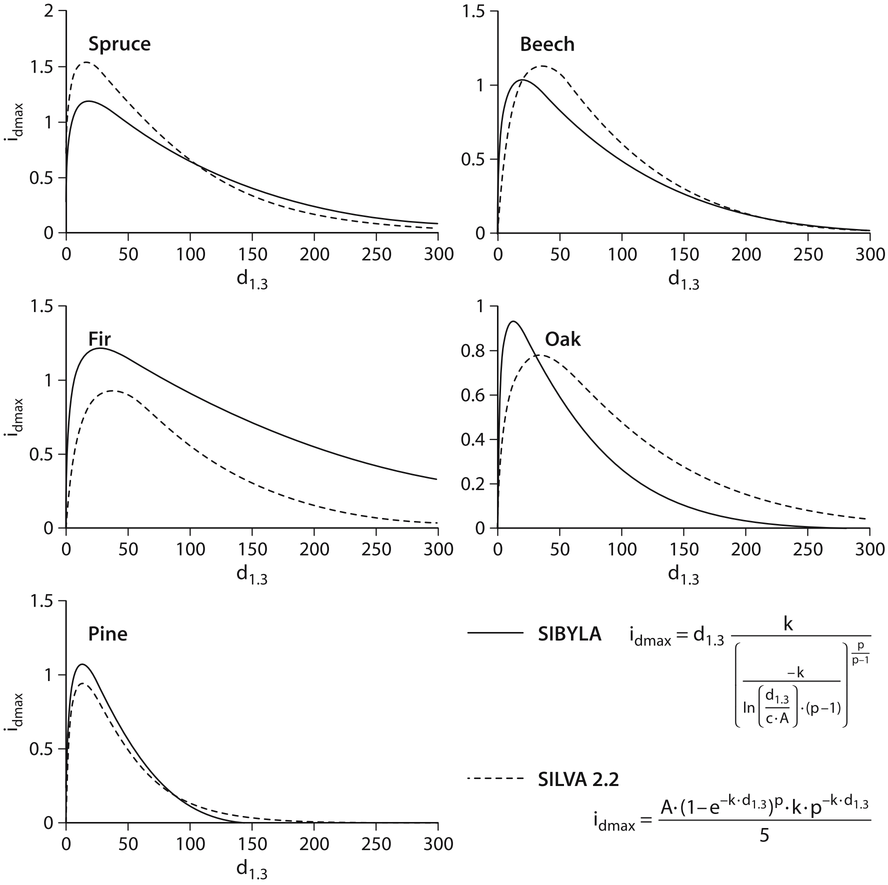


Fig. 15.7. Comparison of tree height potential in the models SIBYLA and SILVA 2.2. Figure describes upper and lower height potentials of a tree depending on its age, for spruce, fir, pine, beech, and oak. The *upper* height potential is derived for the best site conditions and *lower* height potential is derived for the worst site conditions. The function by Korf was utilized for the SIBYLA model and the function by Chapmann and Richards was utilized for SILVA 2.2

Coefficients of the model (*A*, *k*, *p*) are derived from Slovakian yield tables data (Halaj et al. 1987) and the coefficient *c*, which is a relationship between maximum and mean diameter, is derived from Slovakian diameter frequency curves (Halaj 1957). Comparison between the SILVA 2.2 and SIBYLA models is shown in Fig. 15.8.

In practice, detailed climate and soil parameters are often unknown. For this reason, we decided to create a new, generalized model based on current forest inventory data (forest eco-region, absolute altitude, stand aspect, stand slope, calendar year, and forest type). The model of climate characteristics was derived from weather bureau data, which were transformed into the necessary variables



$$i_{dmax} = d_{1.3}\frac{k}{\left(\dfrac{-k}{\ln\left(\dfrac{d_{1.3}}{c\cdot A}\right)\cdot(p-1)}\right)^{\frac{p}{p-1}}}$$

$$i_{dmax} = \frac{A\cdot(1-e^{-k\cdot d_{1.3}})^{p}\cdot k\cdot p^{-k\cdot d_{1.3}}}{5}$$

Fig. 15.8. Comparison of potential diameter increment in the models SIBYLA and SILVA 2.2. Figure describes maximal diameter increment for a tree depending on its diameter observed for the best site conditions for spruce, fir, pine, beech, and oak. The function by Korf was utilized for the SIBYLA model and the function by Chapmann and Richards was utilized for SILVA 2.2

(length of vegetation season, mean temperature in vegetation season, yearly temperature amplitude, and total precipitation in vegetation season) and were regionalized throughout Slovakia in the GIS environment. Geographic information tools were used by the regionalization procedure (Fig. 15.9). Forest eco-region geographic layer information was overlaid with climate images. Images were exposed to cross-classification through absolute altitude. The results are tables on climate characteristics for maximum and minimum absolute altitude within the individual eco-regions. The final climate characteristics were then interpolated on the basis of altitude from the forest eco-region reference table. Characteristics are consequently modified by aspect and stand slope modification functions. Soil characteristics are derived on the basis of the forest type. CO2 and N2O concentrations in the air are derived through regression, using the calendar year of the start of the simulation.

15.4
Software Implementation of the Models

15.4.1
Software Solutions for the SILVA SK Model

The calibrated diameter and height growth model SILVA SK described in Section 15.3.1 was implemented with the software application SILVA Manager. The application is fully localized to the Slovakian language and connected with the data of Slovakian forest inventory. Models of production characteristics of forests, biodiversity indices, costs, and revenues were included in the model following Slovakian biometrical and economic standards. The software application was built through external modules in order to avoid vulnerability which could arise through changing the source code of SILVA 2.2. Also, the software application was integrated into the forestry information systems GOLEM (Fabrika 2002a; Fig. 15.10) and LesHIS (Fabrika 2002b; Fig. 15.11). The systems allow the user to do the following:

1. Select forest stands for growth simulation with standard tools in the GIS.
2. Visualize stand structures through the stand visualization system (SVS) (McGaugey 1997).
3. Generate virtual stands with TreeView (Seifert 1998).
4. Specify climate, soil, and air pollution data for selected stands.
5. Specify thinning concepts (type, interval, and amount) for selected stands.
6. Execute growth simulations for selected stands.
7. View results of performed growth simulations.
8. Connect result databases from simulations into new GIS layers.
9. Create thematic maps from growth simulations.

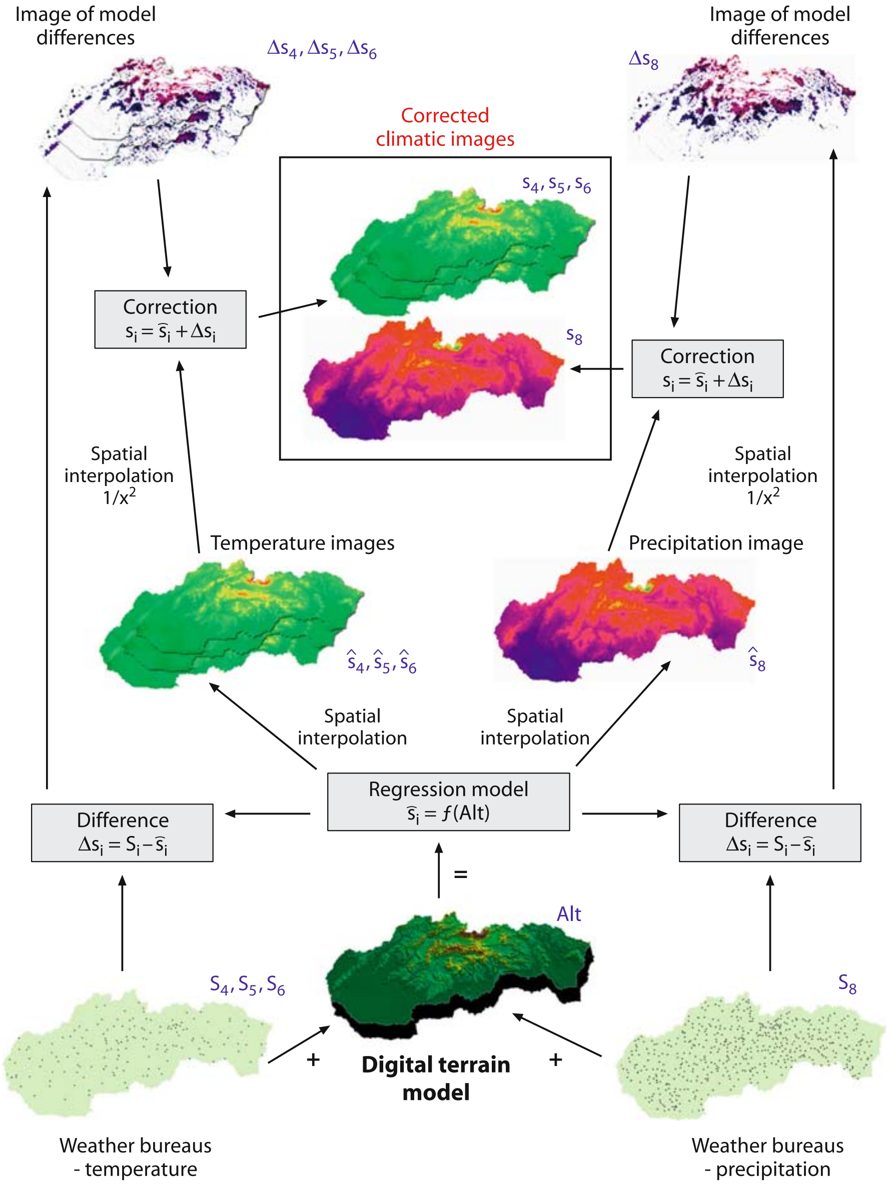


Fig. 15.9. Regionalization of climatic characteristics in the GIS environment. Figure presents techniques used for regionalization in the form of their sequence

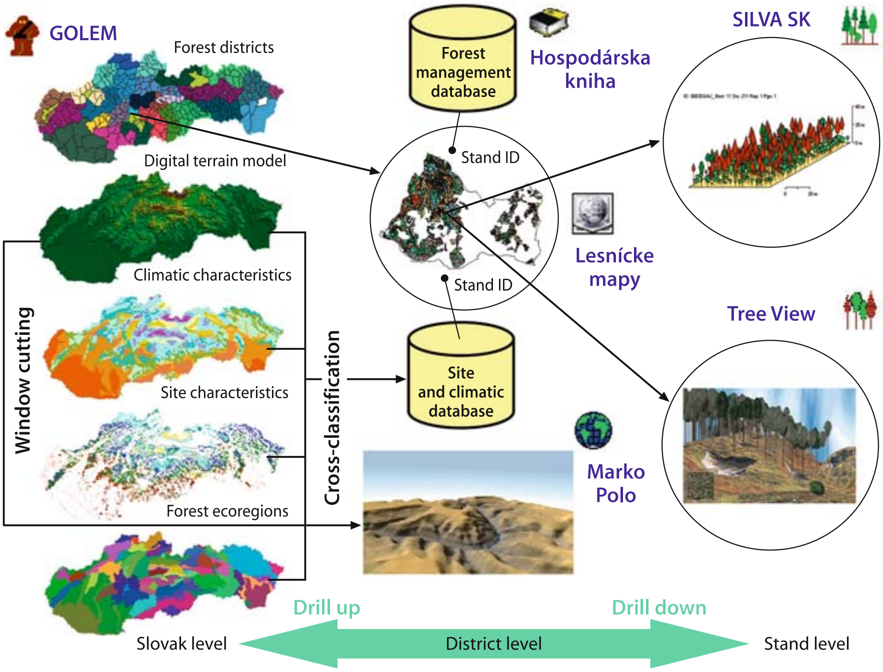
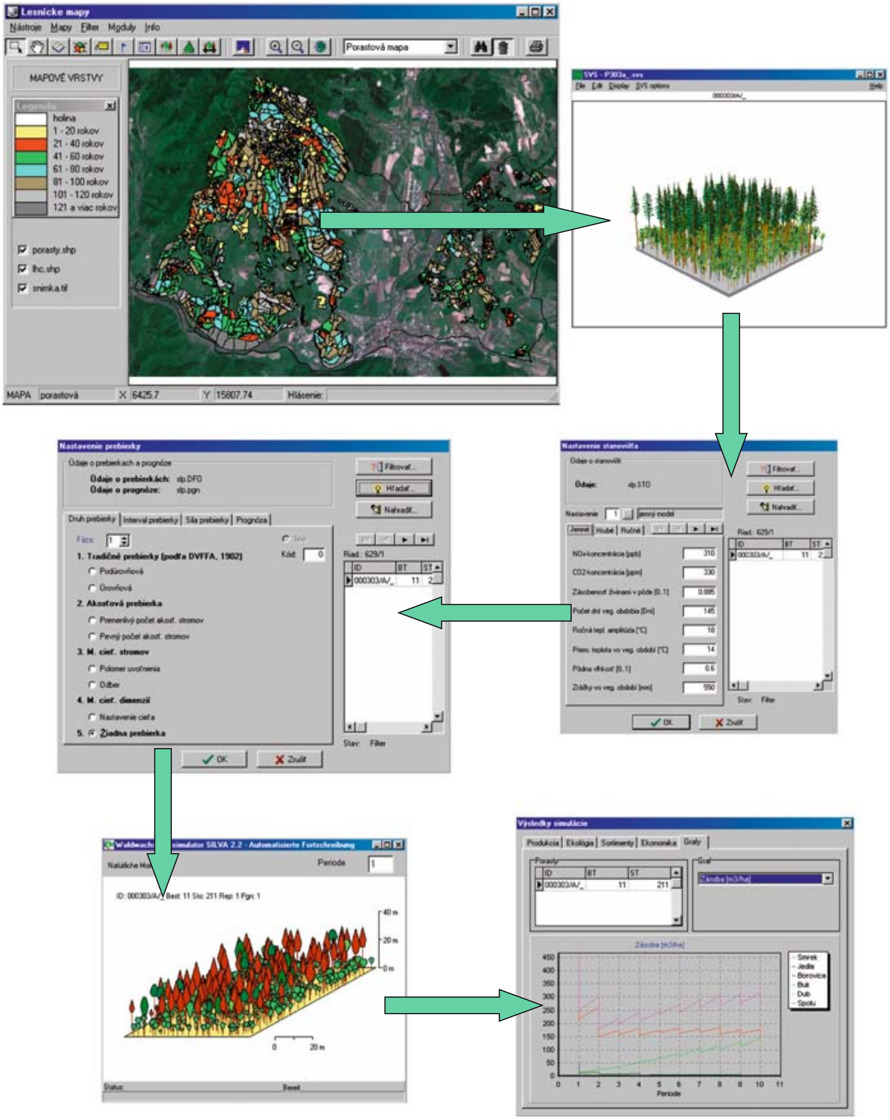


Fig. 15.10. GOLEM-based information system. Figure presents scheme of information system and its components

15.4.2 Software Solutions for the SIBYLA Model

The models described in Section 15.3.2 have been transformed into the version of the computer program named SIBYLA. It is a complex program package with component architecture. The program package is connected to a relational database which has the Microsoft Access format. Modules are solved through independent program units. These units can run sequentially and require user input only at the beginning. The principle of the command line mode and configuration files is utilized. It is possible to build the modules into other systems, for example, as a part of the macro-language interpreter, or into other information systems (e.g. GIS). Input – output communication is ensured by fixed relation database structure. It is also possible to use an interactive version of the program, which has a simple and general menu. While using this feature, the main control module SIBYLA Suite manages this menu. The following is a brief description of the individual modules (Fig. 15.12):

SIBYLA Medium	The module serves for data acquisition from forest inventory entries, permanent research plots, or field GIS.
SIBYLA Generator	The module serves for generation of unknown or missing data on individual trees.



Nastavenie prebierky

Údaje o prebierkach a prognóze

Údaje o prebierkách: slp.DFO

Údaje o prognóze: slp.pgn

Druh prebierky | Interval prebierky | Sila prebierky | Prognóza

Fáza: 1

Kód: 0

1. Tradičné prebierky (podľa DVFFA, 1902)
- ○ Podúrovňová
- ○ Úrovňová

2. Akosťová prebierka
- ○ Premenlivý počet akost. stromov
- ○ Pevný počet akost. stromov

3. M. cieľ. stromov
- ○ Polomer uvoľnenia
- ○ Odber

4. M. cieľ. dimenzií
- ○ Nastavenie cieľa

5. ● **Žiadna prebierka**

Riad: 629/1

ID	BT	ST
000303/A/_	11	2

Stav: Filter

Nastavenie stanovišťa

Údaje o stanovišti

Údaje: slp.STO

Nastavenie 1 jemný model

Jemné | Hrubé | Ročné

NOx-koncentrácia [ppb] 310

CO2-koncentrácia [ppm] 330

Zásobenosť živinami v pôde [0..1] 0.885

Počet dní veg. obdobia [Dni] 145

Ročná tepl. amplitúda [°C] 18

Priem. teplota vo veg. období [°C] 14

Pôdna vlhkosť [0..1] 0.6

Zrážky vo veg. období [mm] 550

Riad: 629/1

ID	BT	ST
000303/A/_	11	2

Stav: Filter

Výsledky simulácie – Porasty

ID	BT	ST
000303/A/_	11	211

Fig. 15.11. Presentation of some software forms of the information system LesHIS. Figure presents a thematic forest map, stand visualization, specification of site characteristics (climate and soil), selection of thinning concept, process of simulation, and results from simulation

SIBYLA Localizer The module serves for adjusting the climate and soil characteristics of forest stands. It is possible to directly specify the characteristics (if they are known) or indirectly with the generalized model. The generalized model

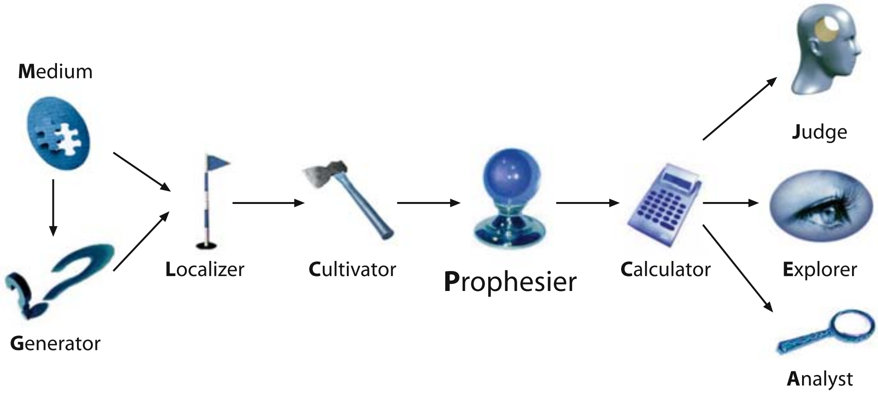


Fig. 15.12. Modules of the software SIBYLA Suite and their relations

	is based on stand localization on a forest eco-region map and the absolute altitude setting, aspect, slope, the calendar year, and the forest type.
SIBYLA Cultivator	The module serves for management of thinning methods and simulation parameters. It is possible to specify different thinning methods (thinning from below, thinning from above, quality crown thinning, crop trees method, or target dimensions method), the simulation length, interval, intensity of thinning measures, and so on. At the same time the program allows the user to specify the thinning through interactive tree selection (target and removal) in the virtual reality environment.
SIBYLA Prophesier	The main module, which executes the growth simulations and calculation of individual tree data in the periods of the growth simulation. Options from previous modules (initial stand status, site, thinning methods) are used in the simulation.
SIBYLA Calculator	The module serves for the calculation of stand production data, forest biodiversity, returns from the forest, and costs of cutting – transport activities. It is possible to specify the prices of types of wood, methods, technologies, cutting activities and conditions, wood yarding, and conversion. Moreover, it is possible to determine the staff tariffs, unit fuel costs for single activities, and other economic parameters.
SIBYLA Explorer	The module serves for exploring the outputs calculated by the “Calculator” module in individual periods of the growth simulation. Besides the general output dialogues, the module provides the possibility of forest visualization on 3-D perspective bases and the export of the stand

	to virtual reality and its survey by means of the "MARKO POLO – 3D Explorer" module.
SIBYLA Analyst	The module produces the resulting analysis from the growth simulation in the time series.
SIBYLA Judge	The module searches for optimal forest management strategies using decision support technology.

15.5
Discussion and Conclusions

Implementation of tree growth models in the field of forestry is very useful and has several advantages. The main advantage of the models is that they enable very flexible forecasting of forest development. At the same time, prognosis responds to different growth conditions (climatic, soil), different stand structures (even-aged, uneven-aged, pure, mixed), and different management treatments (type, power, and interval of thinning, cutting – transport technologies) and includes a wide range of output data (production, ecological, and economical characteristics). However, there are also disadvantages. For example, the process of implementation is very complicated and slow. Many foresters are uncomfortable using complicated models and software. Integration of the models into information systems with simple user environments and with connection to GIS appears to be one of the possibilities for a solution. If we offer such a tool to current foresters, they are able to become more familiar with the use of growth models and begin to sense the advantages of using them. It is necessary to start the process as soon as possible. Slovakia is a land without a long tradition in developing and implementing tree growth models, which has influenced the choice of two different approaches.

The *first approach* is modification of the SILVA 2.2 growth simulator for Slovakian conditions by calibration of tree diameter and height increment, followed by integration into forestry information systems. The calibrated model SILVA SK is the result. Calibration was performed using data from permanent monitoring plots located all over Slovakia. Repeated measurements have been utilized. The model was connected to forest inventory data with SILVA Manager software and integrated into the information systems GOLEM and LesHIS. Advantages of the solution are:

- very fast implementation of the model, which has made it possible to overcome the handicap of a short tradition in tree growth modelling;
- the possibility of immediate utilization in field forestry. We have already begun test runs in selected forest districts and established a demo version on the Internet;
- the possibility of testing the models for optimization of forest management. We have already prepared methodology for multicriterial spatial decision support (Fabrika 2003b; Sodtke et al. 2004).

Disadvantages are:

- the existence of biases in tree diameter and height growth. We have had to remove them indirectly by calibration equations (Eqs. 15.5 and 15.6);
- a lack of direct implementation of local biometrics algorithms (volume equations, uniform height curves) and economics models (quality assortment, calculation of costs and returns). We have had to improvise by using external program units. Consequently we have broken data processing consistency and processing time has been cumulated;
- problems of input data and dialogs for definition of climatic and soil factors. Dialogs are fixed to German forest eco-regions;
- input data and dialogs for definition of tree quality do not exist. However, tree quality is necessary for Slovakian assortment models;
- complicated and almost impossible direct software implementation of Slovakian algorithms for the stand structure generator (diameter frequency functions, uniform height curves).

In spite of these disadvantages, there is the undisputed advantage that current foresters are now able to utilize a growth simulator that is connected to forest inventory and a GIS. This feature allows us to begin systematic edification and institutional advertising to the forestry community. Because the model does not have all the necessary inputs and outputs for Slovakian needs (mainly in the areas of cutting – transport technologies, an economical environment, and models for calculation of cost and returns), the model is mainly only applicable in the prediction of forest production with regard to different thinning concepts and site conditions. Eventually, we can use the model for assessment of some ecological aspects by using structural indices offered by the SILVA SK model.

We initiated the *second approach* parallel with the first one. The second approach aims to develop a tree growth model that is fully adapted to Slovakian conditions and needs. We formulated the basic concept, developed algorithms, and created software solutions. Because one of the most important demands was that initial expenses were as low as possible, we mainly utilized existing algorithms that were generally valid for Slovakian conditions (volume equations, frequency diameter functions, uniform height curves, assortment models, performance standards, yield tables) and existing data material (permanent research plots, permanent monitoring plots). The software solution SIBYLA Suite is the result of this approach. The program solution is modular and is adapted to simple future implementation into information systems and the field of forestry. Advantages of the solution are:

- direct implementation of Slovakian biometrics models and economics models;
- inclusion of Slovakian models for regionalization of climatic and soil values and connection to Slovakian forest eco-regions;
- direct support of all required input data from forest inventory and processing by Slovakian models (assortment models and models for calculation of costs and returns);
- implementation of biodiversity indices preferred in Slovakian ecology assessment;

- sophisticated support for visualization of simulation results and possibilities for export to virtual forest stands by virtual reality model language (VRML) and their distribution to Internet environment,
- the opportunity for immediate usage, mainly for the purposes of growth simulation with outputs fully localized for Slovakia and Slovakian needs. We have already initiated the implementation process by using the program as an e-learning tool at the Technical University in Zvolen and by offering a demo version on the Internet.

Disadvantages are:

- utilization of a competition model, mortality model, and model of sensitivity to climatic and soil environmental factors, which have not been parameterized by Slovakian experimental data;
- for the time being, integration into GIS does not exist.

Because the first version of the SIBYLA model was partially implemented by models parameterized outside of Slovakia, we have initiated intensive negotiation with the Ministry of Agriculture of the Slovak Republic concerning financial support for new data collection. The result of the negotiations is a methodology for a new national forest inventory, where inventory plots are located on a 4×4 km network. The continuous inventory commenced on 1 April 2005. The methodology is prepared with the intention of including all necessary data for parameterization, including crown parameters and tree coordinates. Comprehensive data material will be available after the first repeated measurements. We will be able to derive new parameters and algorithms mainly for the increment model, the competition model, and the mortality model. Updating the models will be simple, because we will only replace some coefficients and equations in our source code which does not influence the user environment of the software. At the same time, the SILVA SK growth simulator will be replaced by SIBYLA Suite software in the information systems GOLEM and LesHIS.

The development of tree growth models is a difficult and ongoing process. The next step in the process is parameterization of the model using new coefficients, which will be derived from the new national forest inventory. Then, the model must be tested for accuracy and precision by comparing real growth data with simulated values. New modelling possibilities (natural regeneration models, models of spatial distribution and development of tree quality, and models of tree damage) arise and can be developed in the future. Nevertheless, we can say that we have already successfully initiated the process of implementation of tree growth models into forest management and forest education in Slovakia.

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Conversion of Norway Spruce: A Case Study in Denmark Based on Silvicultural Scenario Modelling

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Abstract. The aim of this study was to evaluate silvicultural alternatives for conversion of secondary plantations of Norway spruce [*Picea abies* (L.) Karst.] in Denmark. To enable simulations that could possibly aid decision making for policy as well as for forestry practice, the German growth simulator SILVA was calibrated for Norway spruce and beech in Denmark. Calibration comprised changes to the main driving functions of SILVA, such as the height and the diameter growth potentials of individual trees. The calibrated model was evaluated against observed growth for a number of sample plots. Scenarios for different methods for conversion of Norway spruce on former heathland were calculated and analysed, including uniform shelterwood, irregular shelterwood, and target diameter harvest. The predictions of growth and regeneration did not show any limitations to a successful conversion, but resulted in different growth patterns and species compositions.

16.1
Introduction

The aim of this study was to evaluate silvicultural alternatives for conversion of secondary plantations of Norway spruce [*Picea abies* (L.) Karst.] in Denmark. Norway spruce is currently the main commercial timber species. On moraine soils in eastern parts of the country, there are several immediate alternatives to even-aged Norway spruce and regeneration rarely poses major problems. On sandy soils in the west, Norway spruce is used extensively in plantations of first and second generation forest on former heathland. Here, tree growth is hampered by harsh site conditions (infertile sand, lack of humus, strong winds, late frost, and severe browsing) and it is difficult to establish alternative forest types. In this study we focus mainly on these latter areas.

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Conversion of spruce on a larger scale has been a recent undertaking in Denmark, and only few field experiments have been carried out to study tree growth and stand dynamics in relation to silvicultural practices (Skovsgaard et al. 2000; Brunner et al. 2003). To enable simulations that could possibly aid decision making for policy as well as for forestry practice, the German growth simulator SILVA (Pretzsch and Kahn 1998; Pretzsch 2001; Pretzsch et al. 2002) was calibrated to match local forest growth conditions. To properly include the young trees of the regeneration, SILVA received input from the regeneration simulator *Regenerator* (Brunner 2003), which was also calibrated for local conditions.

This study reports the calibration of SILVA for Denmark, a model evaluation, and scenario analyses for conversion of Norway spruce on former heathland.

16.2
The SILVA Model

The forest growth simulator SILVA (Pretzsch and Kahn 1998; Pretzsch 2001; Pretzsch et al. 2002), developed at the Chair of Forest Yield Science of the Technical University of Munich, is a comprehensive example of a spatially explicit individual-tree growth model, which covers forest types that also occur in Denmark. SILVA is based on a so-called potential-modifier concept, under which potential growth is modelled and subsequently modified according to, for example, competition. Potential growth is here defined as the maximum observed in our experiments. Consequently, our indicator of potential growth may be influenced by thinning and may not always be free of competition.

Basically, SILVA is calibrated on traditional forest biometrics data reflecting tree sizes and stand structure, and on the correlation between forest growth and site variables reflecting environmental conditions. For practical use and in the absence of long-term observations on local forest growth, SILVA is driven by site variables. If long-term observations of growth are available locally, these may be used directly to improve model predictions.

As a desirable feature, SILVA incorporates a three-dimensional competition index, which in the current version 2.2 has been simplified to combine two two-dimensional elements: the relation between crown intersection areas of competing trees, and the relationship between the heights of competitors. A three-dimensional search algorithm is used to identify potential competitors.

16.3
Calibration of SILVA for Denmark

16.3.1
Calibration Strategy

For the purpose of this study we calibrated SILVA for Norway spruce and beech in Denmark. Due to limitations in available experimental data, the calibration comprised only even-aged monospecific stands and only some of the main driving functions of SILVA, such as the height and the diameter growth potentials of individual trees. The competition model, involving crown length and crown width, was not calibrated specifically, and due to the commonly practised heavy thinning, mortality was not considered.

Throughout model calibration we tried not to modify the structure of basic relationships within the model, including tree and stand growth, inter-tree competition, and the relation between biometrical characteristics and site variables. We thus rely on the assumption that the effects of silviculture and effects of between-tree interactions, considered in relation to site conditions and stand structure, are similar for Denmark and the region for which these model components were originally calibrated.

Although in this study SILVA will be used only for scenario modelling of spruce conversion on former heathland, we decided to calibrate the model for the whole of Denmark. This was done to fully utilise the data potential, for example in terms of silvicultural effects on stand growth, and to ensure that SILVA would capture the range of and the gradients in site conditions within Denmark.

Our calibration includes equations for the site-specific height growth potential and the diameter growth potential.

16.3.1.1
Height Growth Potential

SILVA models the height growth potential using the Chapman-Richards function:

$$H_{100} = A \cdot \left(1 - exp\ (-k \cdot T)\right)^p \qquad \text{(Eq. 16.1)}$$

where H_{100} is the average height of the 100 thickest trees per hectare, T is stand age (in years), A is the asymptote (in metres), and k and p are shape parameters.

Calibration of site – growth relationships in SILVA requires information on nine site variables relating to nutrients, temperature, and water availability (Pretzsch et al. 2002). Based on the values of these variables, SILVA estimates the species- and site-specific potential height at any time using a non-linear, multiplicative dose-response model. There is a dose-response relationship for each of the nine site variables. For each of the three groups of site variables (nutrients, temperature, and water availability), the dose-responses combine into a complex effect factor which, in turn, is used to derive final, site-specific estimates of A, k, and p of the potential height growth model.

The first system of equations to calibrate includes the dose-response function for each of the nine site variables, modelling the species-specific growth response $r(x)$:

$$r(x) = \begin{cases} 2 \cdot [(x - c_1) / (c_2 - c_1)]^2, \; c_1 \leq x < c_1 + (c_2 - c_1)/2 \\ 1 - 2 \cdot [(x - c_2) / (c_2 - c_1)]^2, \; c_1 + (c_2 - c_1)/2 \leq x < c_2 \\ 1, \; c_2 \leq x < c_3 \\ 1-2 \cdot [(x - c_3) / (c_4 - c_3)]^2, \; c_3 \leq x < c_3 + (c_4 - c_3)/2 \\ 2 \cdot [(x - c_4) / (c_4 - c_3)]^2, \; c_3 + (c_4 - c_3)/2 \leq x < c_4 \\ 0, \; otherwise \end{cases} \qquad \text{(Eq. 16.2)}$$

where $r(x)$ is the response transformed onto [0;1], x is the value of a site variable (for example, 14 °C or 330 mm), and c_1, c_2, c_3, and c_4 are dose-threshold values for the response function. Generally, with increasing dose of nutrients, temperature, or precipitation, the growth response increases until an optimum level and possibly decreases thereafter.

The next system of equations to calibrate models involves the combined effect of site conditions on height growth, based on the so-called complex effect factors. The system includes three simultaneous equations:

$$KF_j = \left(\prod_{i=1+3(j-1)}^{3j} r_i \right)^{1-\gamma_{j+2}} \cdot \left(1- \prod_{i=1+3(j-1)}^{3j} (1-r_i) \right)^{\gamma_{j+2}} \qquad \text{(Eq. 16.3)}$$

$$A = A_0 + A_1 \cdot \left(\prod_{j=1}^{3} KF_j \right)^{1-\gamma_1} \cdot \left(1- \prod_{j=1}^{3} (1-KF_j) \right)^{\gamma_1} \qquad \text{(Eq. 16.4)}$$

$$T_{kulm} = T_0 - T_1 \cdot \left(\prod_{j=1}^{3} KF_j \right)^{1-\gamma_2} \cdot \big(1- (1-KF_1) \cdot (1- KF_2 \cdot KF_3)\big)^{\gamma_2} \qquad \text{(Eq. 16.5)}$$

where KF is the complex effect factor combining the effect of three site variables, r is the transformed response to a site variable (Eq. 16.2), A is the asymptote for stand height (to be used in Eq. 16.1), T_{kulm} is the age of height growth culmination, γ_j, A_0, A_1, T_0, and T_1 are parameters to be estimated, i=1, ..., 9 refers to the nine site variables, and j=1, 2, 3 refers to water availability, temperature and nutrients, respectively.

Due to a high degree of correlation between k and p, fluctuation in estimates of these parameters may lead to unlikely models of height development, viz. unlikely location of the inflection point. This is mainly a problem in the case of short observation periods or lack of observations at early stages of stand development. To alleviate this problem, SILVA has been constructed to ensure a 'realistic' and somehow 'standardised' development of stand height by tying together k and p. Height at the time of height growth culmination, H_{Tkulm}, is modelled as a function of the time of culmination, T_{kulm}, using the Mitscherlich function

$$H_{Tkulm} = b \cdot \big(1- exp(c \cdot T_{kulm})\big) \qquad \text{(Eq. 16.6)}$$

where $T_{kulm} = -\ln(1/p)/k$, $H_{Tkulm} = A(1 - 1/p)^{P}$, and b and c are parameters to be estimated.

Based on site-specific estimates of A (Eq. 16.4), T_{kulm} (Eq. 16.5), and H_{Tkulm} (Eq. 16.6), p is estimated using

$$m = -1n\ (1-(H_{Tkulm} / A) / d) / e \qquad \text{(Eq. 16.7)}$$

where m=1 – (1/p) and d and e are parameters to be estimated.

Finally, the last parameter of Eq. (16.1) is calculated as

$$k = -\ 1n\ (1/p) / T_{kulm} \qquad \text{(Eq. 16.8)}$$

16.3.1.2
Diameter Growth Potential

Potential diameter growth is modelled using the non-linear model

$$z_{d-pot} = A \cdot \left(1-exp\ (-k \cdot d)\right)^{p} \cdot k \cdot p \cdot exp\ (-k \cdot d) \qquad \text{(Eq. 16.9)}$$

where z_{d-pot} is the potential growth (in centimetres per 5 years) of individual tree diameter at breast height (dbh), d is observed dbh (in centimetres), and A, k, and p are parameters to be estimated.

16.3.2
Calibration Data

Calibration data originated from 87 experiments in Norway spruce and 66 experiments in beech (Fig. 16.1). Several experiments included a range of different treatments in terms of spacing, thinning (thinning grade, frequency, and type), or other management practices, with a total of 359 plots for Norway spruce and 157 plots for beech.

Data represent all forest regions in Denmark, ranging from fertile till soils in eastern parts of the country to sandy outwash plains in the west. For Norway spruce, the earliest established stands date back to 1809, while measurements range from 1875 to 1998. For beech, the earliest established stands date back to 1792, and measurements range from around 1825 to 2002. Observation periods that were used for this study range from 2 to 62 years for Norway spruce and from 13 to 99 years for beech. Age at time of measurement ranges from 14 to 104 years for Norway spruce and from 15 to 174 years for beech.

16.3.2.1
Height Growth Potential

The selection of observations for calibration of the height growth potential was carried out in a multiple step procedure. First, parameters of Eq. (16.1) were

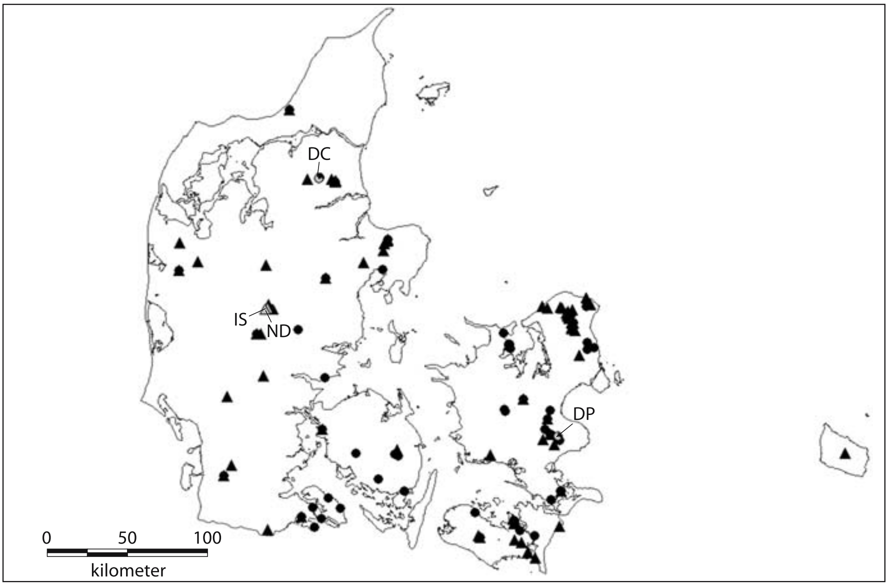

Fig. 16.1. Location of experiments used for calibration and evaluation of SILVA in Denmark. *Triangles* Norway spruce; *circles* beech; *letters* indicate experiments used for model evaluation

estimated for each experiment (site), in some cases pooling plots of different treatment within the experiment. For spruce, observations from 87 experiments were available. Out of 36 experiments that had been measured six times or more, only 26 resulted in biologically reasonable parameter estimates. For beech, observations from 64 experiments were available. Out of 36 experiments that had been measured at least six times, only 19 resulted in biologically reasonable parameter estimates. For both species, data were excluded from the subsequent analysis if observation periods were short or if data covered only phases of juvenile growth prior to culmination of height growth [fitting a sigmoid growth function (Eq. 16.1) to such data results in unrealistic parameter estimates for asymptotic height growth of older trees].

In a second step the dose-response function (Eq. 16.2) was determined based on estimates of A and T_{kulm}. The response function was visually fitted to the upper limit of the relative values of both variables. In case of contrasting patterns of A and T_{kulm}, higher priority was given to T_{kulm}, which varied more in the final model than A.

Next, for the estimation of H_{Tkulm} from T_{kulm} (Eq. 16.6) and the estimation of p from H_{Tkulm} (Eq. 16.7), parameter estimates from step 1 were used. For beech, three experiments were identified as outliers and not considered (experiments DM, Q, and X).

Finally, using different combinations of site variables the iterative calibration of the simultaneous Eqs. (16.3) – (16.5) led to further selection of observations. The complete set of nine site variables could not sufficiently explain the growth patterns of Norway spruce and beech in Denmark. As a first modification, the NO_x and CO_2 concentrations were removed from the model, because no data on the historical development of these airborne nutrients are available.

For Norway spruce, the remaining seven site variables could not sufficiently explain the observed variation in A and T_{kulm}, either alone, in combination, or in the simultaneous model (Eqs. 16.3 – 16. 5). A recent calibration of a national growth model for Norway spruce, based on the same data set, demonstrated that the percentage of coarse sand (0.2 – 2 mm) in the upper 1 m of the soil is closely correlated with the height growth potential (Leary et al., unpubl.). Based on this, the percentage of coarse sand was introduced as a new site variable. Soil texture data were available for 15 Norway spruce experiments. The percentage of coarse sand alone could explain the variation in height growth in the simultaneous model (Eqs. 16.3 – 16.5). Additional inclusion of any of the seven original site variables did not improve the model.

For beech, the three site variables related to precipitation did not sufficiently explain the variation in A and T_{kulm} as indicated by $\gamma_3=1$ in the simultaneous model. Two of the three site variables related to temperature, viz. the duration of the growth period and the annual variation in mean temperature, were discarded after careful analysis of their dose-response functions. Their failure to explain the variation in the response variables is probably due to their rather limited variation within Denmark. Consequently, only two variables, the soil nutrient class and the mean temperature during the growth period, were selected for beech. A total of 18 beech experiments were used for calibration of the height growth potential.

Parameters related to site variables that have not been used here were set to values (e.g., $\gamma_i=1$) that result in no influence of those parameters on the response variable.

The final models were tested using residual plots for calibration experiments as well as for independent data from experiments not used for calibration. Data not used for calibration included 19 experiments in young stands of Norway spruce, for which soil texture data were available, and 46 experiments in beech with complete information on site variables.

16.3.2.2
Site Variables

Data on temperature and precipitation originate from the Danish Meteorological Institute (Frich et al. 1997; Lauersen et al. 1999, 2001; Cappelen and Lauersen 2000). For each experimental site, data from the nearest meteorological observation point were used. Data on soil nutrients, moisture, and texture were obtained from published observations (Holstener-Jørgensen 1958; Callesen 2002, 2003; Leary et al., unpubl.) or original field notes (soil pit descriptions, texture analyses, etc.). In a few cases where local soil information was not available, information from the nearest published soil profiles was used (Sundberg 1999; Granat 2000).

Soils were classified according to the Danish national soil classification for forest land. In the Danish system, available water capacity in the upper 1 m of the root zone is estimated based on soil organic matter and the contents of clay, silt, and fine sand (Madsen and Platou 1983). Depending on available water capacity, precipitation during the vegetation period, and location of the ground water table, soil moisture is rated on a nine-point scale (Sørensen and Dalsgaard 1997; Granat 2000). Nutrient availability is rated on a six-point scale depending on the ratio of cation exchange capacity and base saturation to the number of soil strata (Sørensen and Dalsgaard 1997; Granat 2000).

16.3.2.3
Diameter Growth Potential

For Norway spruce, 419,267 observations were used to calibrate the diameter growth model. Diameter at breast height ranged from 0.2 to 70.1 cm with a mean of 14.4 cm. For beech, 178,222 observations were used. Diameter at breast height ranged from 0.2 to 100.9 cm with a mean of 18.2 cm.

For both species, the observations were divided into 2-cm-diameter classes, and 99% percentiles were calculated for each diameter class. The percentiles exclude extreme observations and were used in estimating the diameter growth potential function (Eq. 16.9). Due to infrequent observations in higher diameter classes, only observations with an initial dbh of less than or equal to 40 cm were used for spruce, and only observations of less than or equal to 66 cm were used for beech.

16.3.3
Calibration Results

16.3.3.1
Height Growth Potential

The dose-threshold values of the dose-response function (Eq. 16.2) were set as follows for the three selected site variables: for Norway spruce and the percentage of coarse sand, $c_1=0$, $c_2=0$, $c_3=24$, and $c_4=100$; for beech and the soil nutrient classes, $c_1= -0.2$, $c_2=0.6667$, $c_3=1$, and $c_4=1$ (units are the six soil nutrient classes transformed into [0;1]); and for the mean temperature of the growing season, $c_1=12$, $c_2=14.1$, $c_3=14.3$, and $c_4=18$ (in degrees Centigrade).

Estimates of all parameters for Eqs. (16.3) – (16.7) are summarised in Table 16.1 and model predictions for sites included in the calibration are shown in Fig. 16.2. For both species, absolute deviations amount to less than 3 m for most observations and less than 2 m for a majority of observations; for the independent test data, absolute deviations were also generally less than 3 m (not shown).

For spruce, the range of the model is set mainly by three experiments on poor heathland sites (IS, GG, KF, in order of increasing growth potential) and the large group of 12 remaining experiments on better sites. Only one site variable (percentage of coarse sand in the upper 1 m of the soil) was used to explain differences in growth behaviour. This site variable is easily measured or estimated roughly in the field.

Table 16.1. Parameter estimates of the model for site-specific potential height for Norway spruce and beech in Denmark. *N* Number of observations; R^2 coefficient of determination; *RMSE* root of mean squared error

Parameter	Norway spruce Estimate	 Standard Error	Beech Estimate	 Standard Error
Eqs. 16.3–16.5	N=1,315; R^2=0.9918; RMSE=1.5508		N=739; R^2=0.9958; RMSE=1.471	
γ_1	1	-	0.6277	0.0489
γ_2	0	-	0	0
γ_3	1	-	1	-
γ_4	1	-	0	0
γ_5	0.0175	0.1455	0.4581	0.0558
A_0	0	-	0	0
A_1	32.75	0.9477	34.19	0.651
T_0	80.80	7.2306	111.40	-
T_1	62.89	7.1699	90.77	0.1272
Eq. (16.6)	N=25; R^2=0.9937; RMSE=0.7215		N=15; R^2=0.9953; RMSE=0.6547	
b	9.4763	0.4584	9.7405	0.4638
c	-0.1173	0.0247	-0.0971	0.0194
Eq. (16.7)	N=25; R^2=0.9999; RMSE=0.0032		N=15; R^2=0.9999; RMSE=0.0045	
d	0.4651	0.00257	0.4427	0.00448
e	1.526	0.0157	1.665	0.0295

For beech, the range of the model is set mainly by three experiments (BL, DC, DD) on sandy moraine and the large group of 15 remaining experiments on better sites. Two of the former group are located close to each other (DC, DD) and their height growth almost coincides. The two variables (mean temperature of the growth period and soil nutrient class) reflecting the variation in height growth and the weights given to these variables in the model cannot be expected to be valid for the full range of site conditions for beech in Denmark.

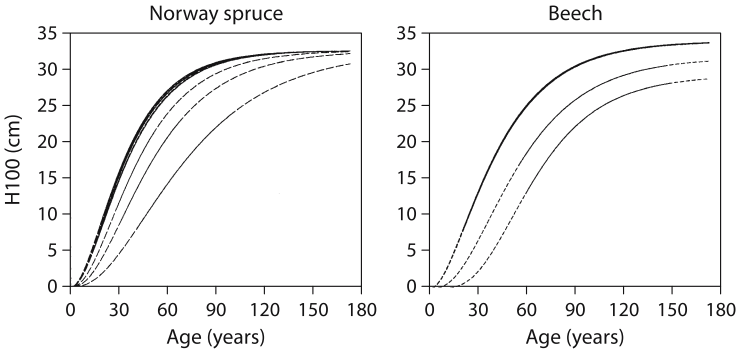

Fig. 16.2. Site-specific potential height model (Eqs. 16.3–16.5) for the experiments included in the calibration. Each *line* represents one experiment, *full lines* indicate the calibration range

For beech, many of the younger experiments not used for calibration show significant deviations from the growth patterns observed for the older experiments. This is taken as an indication of insufficient predictive ability of the two site variables relative to the total range of site conditions in Denmark. We did consider a model similar to that for Norway spruce, but soil texture data were available only for eight of the older beech experiments and showed no significant correlation between the percentage of coarse sand and A and T_{kulm}.

16.3.3.2
Diameter Growth Potential

Parameter estimates for potential diameter growth in Denmark (Eq. 16.9) are for Norway spruce: A=2,430, k=0.01370, and p=0.7342; and for beech: A=4,359, k=0.009717, and p=0.3128. These estimates reflect growth patterns considerably different from the German calibration (Pretzsch et al. 2002). Within the range of relevant diameters the diameter growth of Norway spruce in Denmark is much slower than in Germany, whereas for beech initial growth is slightly faster and maintains a higher level throughout. This may be due to differences between Denmark and Germany in treatment extremes and in selection principles. For Norway spruce, the German experiments include several plots with crown thinning, whereas there are only few such plots in the Danish experiments. For beech, the Danish experiments include extremely heavy thinnings (approaching free growth), while there are only few heavily thinned plots in the German experiments. These differences also indicate that the diameter growth potential does not represent growth, which is free of competition. Since growth records of individual trees from plots with extreme treatments are used to calibrate the potential growth function, the diameter growth potential is obviously influenced by thinning intensity and selection principles.

Subsequent tests of the model, which are not reported in this paper, revealed the need to further adjust the diameter growth potential and its dependency on site conditions. Results presented here are therefore only valid for the sites used in our tests and scenarios, but should not be uncritically extrapolated to other sites in Denmark.

16.4
Model Evaluation

The purpose of the evaluation of the calibrated model was primarily to test the diameter growth model, i.e., to test the modification of the individual tree diameter growth by the competition index. Note that the competition index was not changed from the original version of SILVA.

16.4.1
Evaluation Data

Observations from three experimental plots in spruce and four in beech were used for the evaluation of the growth model (Fig. 16.1). The chosen plots represent the range of site conditions relevant to the case study and a wide range of thinning practices. Individual tree positions were available only for one of the beech plots. Diameter at breast height was available for all trees for a number of observation years, whereas height was measured only for a sample of trees in each measurement period. The remaining heights were estimated based on height – diameter regressions for individual plots and years. The time of removal (or death) of individual trees is known for all plots.

For spruce, all three experimental plots are located in Gludsted Plantation in western Jutland, the location used for the subsequent scenario analyses. Two of the plots, representing different thinning strategies, originate from thinning experiment IS. The A-grade plot (no. m, 0.2395 ha) is the unthinned control. The D-grade plot (no. c, 0.2372 ha) has been thinned heavily from below, with an early and rapid reduction in stem number, and thinnings every fourth year to a residual basal area of about 20 m^2/ha (Fig. 16.3). The third spruce plot originates from spacing experiment ND. This plot (no. 5, 0.1836 ha) represents an initial spacing of 1.5×1.5 m. The plot has been thinned heavily from below.

For beech, two plots originate from thinning experiment DP in Totterup. This experiment is located on fertile moraine soils in eastern Denmark. The B-grade plot (no. 11, 0.1040 ha) represents a very light thinning from below; only suppressed trees were removed, and the basal area approaches 40 m2/ha. The C-grade plot (no. 9, 0.1717 ha) represents heavy thinning to a residual basal area of about 20 m^2/ha. During the juvenile years and towards the end of the rotation, thinning was predominantly from above. Throughout, an understorey of beech was maintained.

The third beech plot comprises experiment DC in northern Jutland (Rold Forest, 0.6944 ha). This plot is very old, has long been observed, and represents infertile site conditions. The plot has been thinned moderately to heavily, predominantly from below, to a residual basal area of about 20 – 25 m^2/ha (Fig. 16.4). The fourth beech plot comprises experiment Q (Jægersborg Fenced Forest, 0.3485 ha). This plot represents fertile site conditions, is quite old, and has been observed for more than a century. Throughout, experiment Q has been thinned heavily, predominantly from below, to a residual basal area of about 20 m^2/ha (Fig. 16.5). On this plot tree positions were recorded for all 727 trees in 1902.

16.4.2
Model Specifications

Stand development was simulated based on initial, observed diameters and heights using SILVA in batch mode. SILVA estimates crown dimensions based on dbh and height for each individual tree. Except for one beech plot, tree positions were generated by SILVA. Due to the stochastic nature of SILVA's tree position generator and its diameter and height growth models, each simulation was repeated 100 times. For beech experiment Q, individual tree positions were available and simulations were repeated only 30 times. The variation of individual simulation results is here shown only for the minimum and maximum diameters (Figs. 16.3 – 16.5). Natural mortality was not included in the model evaluation.

16.4.2.1
Site-Specific Calibration

For the model evaluation, height growth potential was defined directly by the three parameters of Eq. (16.1), implying that the estimation of the site-specific height growth potential by SILVA is not used. Parameters were estimated using all the data available from each experiment. Subsequently, estimates of the asymptote A were multiplied by the factor used in SILVA to convert from H_{100} to the individual tree height potential. For some plots A was further modified (2 to +3 m) until observed and predicted heights visually fitted (Figs. 16.3 and 16.4) to better reflect the plot-specific site conditions that apparently also varied within the experiments.

Five site variables are used in SILVA to define a site-specific diameter growth potential (Pretzsch and Kahn 1998). The aggregation of these five variables into the modifier W_{Sto} uses some of the parameters that are also used in the estimation of the site-specific height growth potential. Due to our ongoing calibration of these parameters, we adjusted some of the five variables only by best judgement. This resulted in a modification of the diameter growth potential with a good agreement between observed and predicted mean diameters. The resulting W_{Sto} values were 0.9691 for the three spruce plots, 0.9994 for beech experiments DP and Q, and 0.5089 for beech experiment DC.

16.4.2.2
Thinning

Even though the time of removal is known for every individual tree on the plots, this information could not be used for the definition of thinnings for the plots where no tree positions were available. For beech plot Q, thinnings were simulated according to recorded removals. For the remaining plots a random positioning of trees in combination with a predefined time of removal of individual trees would lead to significant deviations from the observed thinning strategy, for example by creating gaps at some places and leaving overly dense groups at others. Consequently, the standard algorithms of SILVA were used to select individual trees for removal, depending on thinning strategies.

For beech, simulations applied thinning from below on plots DC and DP-B and thinning from above on plot DP-C. Consistent with observed thinning practice, however, thinning from below was applied on plot DP-C during the period when H_{100} ranged between 18 and 24 m. For spruce, simulations applied thinning from below on plots IS-A and ND and thinning from above on plot IS-D. However, consistent with observed thinning practice, thinning from below was applied on plot IS-D on the thinning occasion at age 71. For all six plots thinning grade was modelled based on the observed stem number development (Figs. 16.3 and 16.4) using polynomials of up to fifth order. The simulated reductions in stem number indicate that SILVA reproduces the observed thinnings sufficiently accurately (Figs. 16.3 and 16.4).

16.4.3
Evaluation Results

There appears to be satisfactory agreement between predicted and observed quadratic mean diameters (Figs. 16.3 – 16.5). This is especially true for beech plot Q (Fig. 16.5) where deviations are within a few centimetres throughout the simulation period. Most of this deviation is caused by one tree, which grew much faster than all of the others and consequently was underpredicted by the model. Also the deviations of predicted from observed minimum and maximum diameters are caused by a few trees growing either much faster or much slower than all others. When these trees are removed in thinnings, observed and predicted maxima and minima agree much better (Fig. 16.5).

The tendency to overpredict minimum diameters in most experiments may be caused by the thinning algorithms in SILVA being stricter in thinning from below than observed on the plots. Overall, the observed deviations in dbh and basal area are more likely due to inaccurate specification of thinning strategies in the model runs as indicated by the smaller deviations for plot Q (Fig. 16.5), where simulations did not rely on thinning algorithms. The missing tree positions in most of our experimental plots do not allow a more realistic thinning in SILVA, and thus prevent a more strict evaluation of the diameter growth model.

Individual tree residuals for dbh and height in beech plot Q (Fig. 16.5, right) indicate only for a few individuals unacceptable predictions over the 100-year

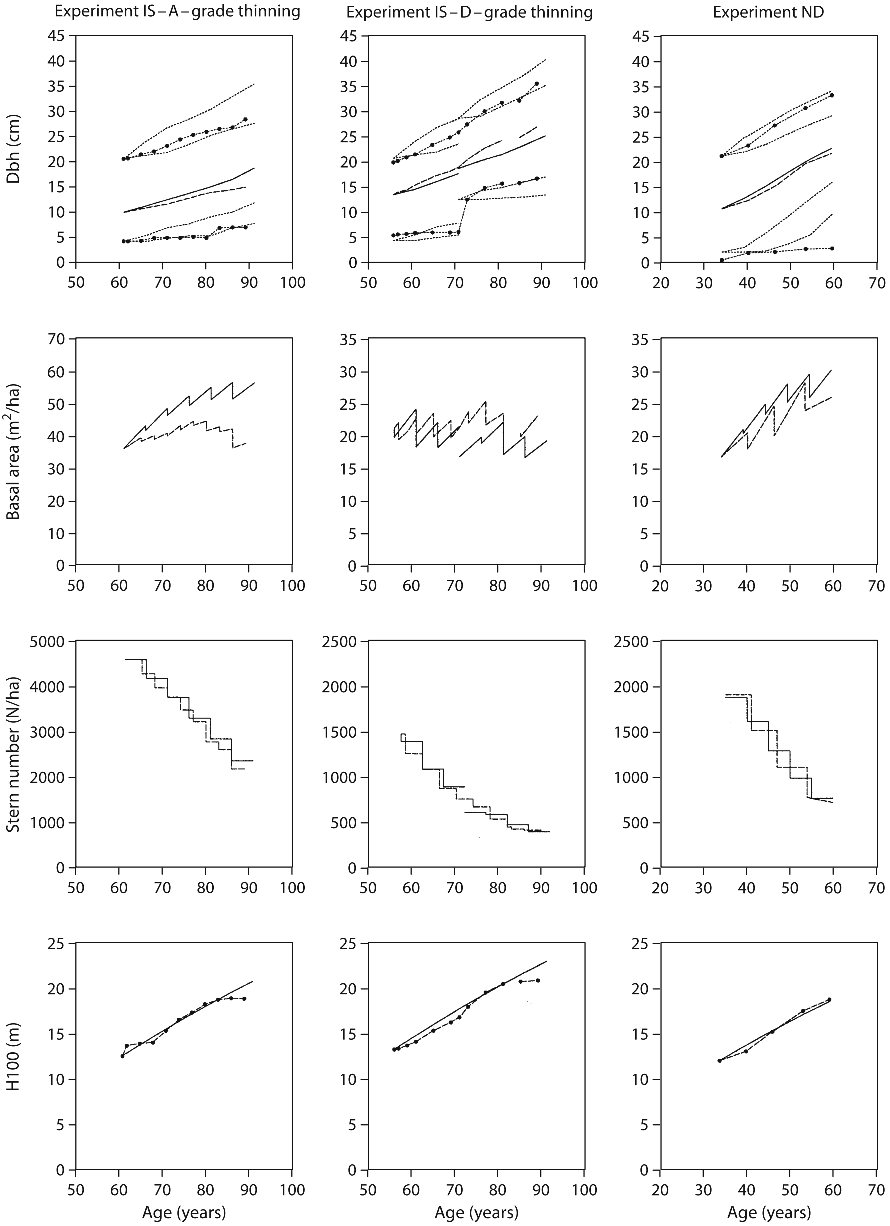

Fig. 16.3. Results of model evaluation for Norway spruce. *Full lines* Model predictions; *dashed lines* observations. For dbh *dotted lines* refer to predicted minimum and maximum diameter and *dots* to observed minima and maxima. The range of predicted minima and maxima is due to the stochastic nature of SILVA

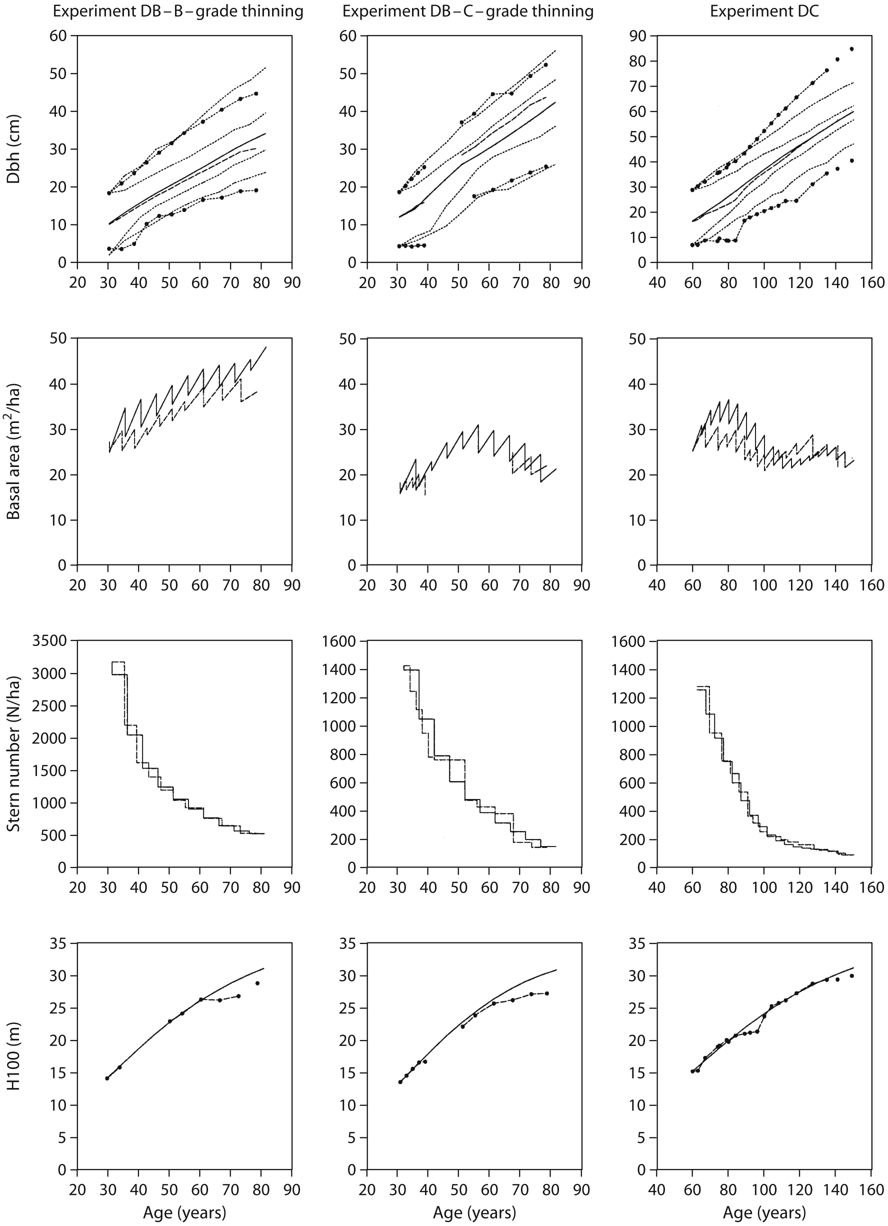

Fig. 16.4. Results of model evaluation for beech. *Full lines* Model predictions; *dashed lines* observations. For dbh *dotted lines* refer to predicted minimum and maximum diameter and *dots* to observed minima and maxima. The range of predicted minima and maxima is due to the stochastic nature of SILVA

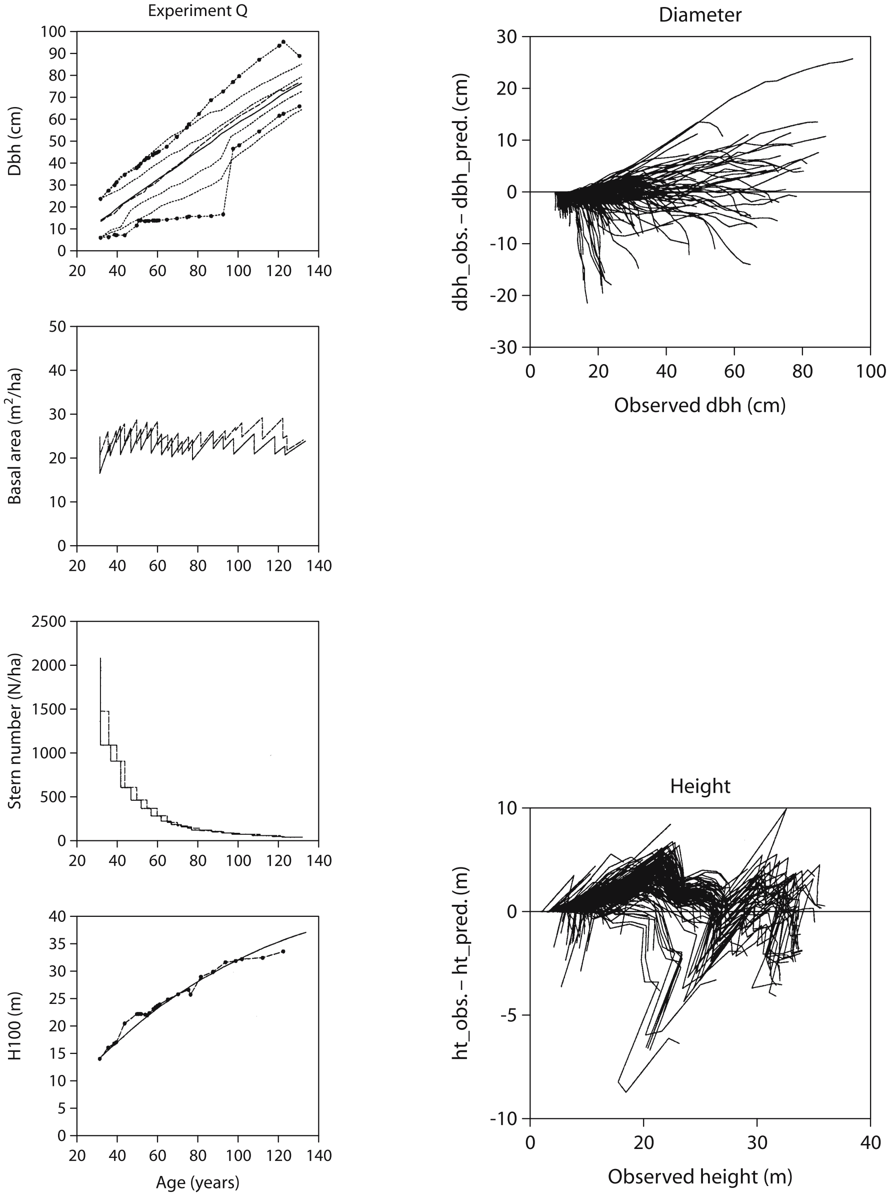

Fig. 16.5. Results of model evaluation for beech experiment Q. *Full lines* Model predictions; *dashed lines* observations. For dbh *dotted lines* refer to predicted minimum and maximum diameter and *dots* to observed minima and maxima. The range of predicted minima and maxima is due to the stochastic nature of SILVA. *Right* Residuals are for 727 individual trees

simulation period. As already mentioned, one particularly fast growing tree was severely underpredicted. A number of smaller trees kept growing in diameter and height in the simulations whereas in reality they stagnated immediately prior to their removal. Overall, these deviations for individual trees had only minor influence on stand values (Fig. 16.5, left).

16.5
Scenario Analyses of Conversion Silviculture

Conversion of even-aged Norway spruce may be carried out in numerous ways depending on, for example, site conditions, previous stand management, and management practices in the surrounding forest. This study is based on a model stand located in the western part of Denmark on former heathland, which is considered a particularly difficult environment for conversion of spruce. The problems relate to the management of the original stand as well as to the establishment of a new crop of one or more different tree species.

Silvicultural challenges for the original stand of Norway spruce include slow growth due to sandy soils, extensive root and butt rot, and a high risk of windthrow. To ensure production of merchantable timber while trying to reduce the risk of windthrow, Norway spruce is usually thinned heavily from below at regular intervals until the stand reaches a height of approx. 15 m; afterwards thinning is discontinued.

The establishment and early growth of regeneration may be hampered severely by deer browsing and the frequent occurrence of late frost. These influences make traditional clear-cutting less desirable. As a result, during regeneration shelterwood trees are usually retained in stands that are considered sufficiently stable and healthy. Alternatively, the stand may be regenerated by partial clearcuts progressing in narrow, alternate strips. On clear-cut areas nurse trees may be planted to protect the young crop trees.

In the case of conversion, the next generation is often planned to consist of one or more species that are more stable than spruce, such as other conifer species for timber production or deciduous trees. Unfortunately, these species are often more sensitive to harsh site conditions such as late frost, thus reinforcing the need for shelter trees during conversion. Most often, natural regeneration of spruce will establish among the planted understorey trees. Thus, and again due to harsh conditions for tree growth, more than one generation of forest may be required to reach the desired forest type, which is often envisaged to comprise some kind of uneven-aged, mixed stands.

16.5.1
The Model Stand

The model stand comprises 1 ha of a regeneration experiment located in Gludsted plantation (experiment no. 1512, dense shelterwood; Brunner et al. 2003). The stand was established in 1946 by planting and subsequently managed according to the schedule outlined above. The stand was 59 years old at the onset of conversion.

At that time all trees were measured for diameter at breast height and some trees were sampled for height measurement. Crown dimensions were derived from the diameter and height of each tree, using equations from SILVA (Pretzsch et al. 2002). The position of each tree was generated based on information on spacing at stand establishment, known positions of planting rows, and the known sequence of individual trees within each row. Tree positions within each row were drawn at random from all possible positions, taking into account original spacing and the actual crown size. The length of the planting row sections, where random positions within the row were assigned, was 45 m for one half of all trees and 12 or 25 m for the remaining half.

Average tree height was estimated at 16.7 m, H_{100} was 18.7 m, stem number 528/ha, D_g 22.6 cm, basal area 21.2 m^2/ha, and standing volume 175.6 m^3/ha. Immediately prior to this measurement the stand was thinned heavily to stimulate diameter growth and prepare for conversion. Thinnings were carried out in two cuts, reducing stem number from approximately 1,050/ha to the current level.

The conversion was initiated at a time when the stand had just started producing suitable timber dimensions, indicating that our scenarios do not reflect very early or pre-mature conversion.

16.5.2
Conversion Silviculture

For this study we considered three different conversion strategies: uniform shelterwood, irregular shelterwood, and target diameter harvesting. For each of these, alternative harvesting or rotation length criteria were applied. In all cases, conversion was initiated at the same time and included underplanting of beech (spacing 2×2 m, average tree height 0.5 m) and the possible occurrence of natural regeneration of Norway spruce.

16.5.2.1
Uniform Shelterwood

With the uniform shelterwood system the young trees are established under the shelter of the previous generation. The system implies a uniform opening of the canopy for regeneration purposes (Matthews 1994). In our scenario studies, canopy opening takes place gradually during a number of cuts, generally with thinning from below. The fast and the slow versions differ in the speed of reduction in shelterwood density (Fig. 16.6). In contrast to irregular shelterwood and target diameter harvesting, the uniform shelterwood scenarios do not differ in duration of the shelterwood phase. Planting is done on one occasion only at age 59, resulting in a regeneration period of 20 years until removal of the last shelterwood trees.

16.5.2.2
Irregular Shelterwood

The term irregular shelterwood implies a system of successive regeneration fellings over a long regeneration period, producing regeneration of a somewhat uneven-aged type (Matthews 1994). The regeneration patches may be of various sizes and with an irregular spatial distribution. The system may rely on natural openings in the stand, for example due to storm damages or attacks by insects or fungi, or on gaps that are cut deliberately for regeneration purposes. In our scenario studies, the regeneration patches are distributed evenly over the whole regeneration period. Their spatial distribution is random for each harvesting occasion, under the restriction that two neighbouring patches should not be cut simultaneously except for the final harvest. The remaining stand is left unthinned at all harvesting occasions.

Irregular shelterwood scenarios include fast and slow removal of the overstorey using either large (400 m^2) or small (204 m^2) regeneration patches. Both scenarios are initiated 5 years after the last thinning that was done to prepare for conversion. In forestry practice a predefined, irregular shelterwood regeneration is hardly realistic. However, even in the situation where management control is lost due to stand break-up, it should be possible to practise some kind of patch regeneration in a pattern similar to those applied here.

Planting is carried out immediately after cutting of each regeneration patch until about one half of the stand has been underplanted. At that point the stand has been opened up so much that natural regeneration is likely to occur on the remaining area. Consequently, the remaining half of the stand is underplanted with beech at once.

16.5.2.3
Target Diameter Harvesting

The term target diameter harvesting implies thinning from above using individual tree diameter as the main harvesting criterion for each individual tree (Heding and Jakobsen 1980). Generally, the target diameter is chosen to be economically optimal. Target diameter harvesting is applied only during the final part of the rotation, i.e., following the ordinary schedule of thinning from below. Generally speaking, target diameter harvesting should result in several light thinnings at short intervals and carried out for an extended period. In contrast to other silvicultural systems, target diameter harvesting does not put emphasis on the establishment and development of regeneration. Ideally, regeneration establishes throughout the whole period of target diameter harvest.

Target diameter scenarios include harvesting criteria of 30 or 35 cm diameter at breast height. Generally, 35 cm is considered economically suitable, while 30 cm is considered somewhat pre-mature. Preliminary simulation runs demonstrated that a target diameter of 40 cm results in a removal period up to an age of 150 years, a far too long period during which the stand would most probably start disintegrating. Target diameter harvest was simulated for 40 and 60 years for 30-

and 35-cm target diameters, respectively, at the end removing all overstorey trees in the remaining stand at once (Fig. 16.6). In the scenarios the stands were underplanted when the basal area had been reduced to 15 m^2/ha or less. Natural regeneration established before this time was not considered in the scenarios.

16.5.3
Model Specifications

Our studies focus mainly on the removal of the overstorey, which is simulated by SILVA, but include ingrowth of the understorey. Early understorey growth is simulated by the regeneration simulator Regenerator, and subsequently transferred to SILVA at a height of approximately 5 m. Stand development following removal of the last trees in the overstorey is simulated using SILVA only. Thus, the scenarios include two phases: one where SILVA and Regenerator run parallel to predict the development of the overstorey and the regeneration, respectively, and one where the development of the young stand is predicted by SILVA alone.

16.5.3.1
SILVA Specifications

Following a comparison of several experiments in the vicinity of Gludsted, the local height growth potential for spruce was set equal to that observed in thinning experiment GG (representing good heathland sites). Height growth in this experiment closely matched the observed height development of the simulated stand. Few local observations were available for beech. These included the model stand with recently planted beech under a shelter of spruce (experiment 1512; Brunner et al. 2003), a young beech stand (experiment 1009) observed for 32 years after establishment on a clearfelled area, and inventory data from relatively old stands. First, data from the young beech stand (1009) were adjusted to account for the better growth conditions under a shelterwood. Next, the adjusted data were combined with observations from old stands to provide an estimate of the local height growth potential for beech. The resulting height growth potentials for the two species (for spruce: A=36.6, k=0.0258, p=1.992; for beech: A=33.5, k=0.0378, p=2.927) were close to each other, with differences of less than 2 m up to age 120 years.

The site-specific reduction of the diameter growth potential was set to W_{Sto} =0.9691 for spruce, consistent with results for three plots in the Gludsted Plantation during model evaluation. This setting resulted in W_{Sto}=0.8236 for beech.

Growth predictions for the young stands emerging from the simulated conversion were carried on for a period of 45 years. During removal of the overstorey 30 replications of each scenario were calculated to eliminate the effects of stochastic model components. Only 10 replications were calculated for the subsequent phase because of run-time restrictions. The cutting cycle was simulated on a 5-year basis, corresponding to the mode of operation for SILVA. Thinnings of the resulting mixed stands of young beech and spruce were simulated using SILVA algorithms for a crop-tree-oriented thinning from above. One hundred crop trees of beech and 150 crop trees of spruce were selected at the beginning of this phase. The high number of crop trees was due to the very early age for crop tree selection. Thinnings were set to comprise two competitors per crop tree on each thinning occasion, with the goal of maintaining equal proportions of both species.

Simulation runs with SILVA did not include natural mortality during overstorey removal because of the early, heavy thinnings and frequent harvesting. In the subsequent phase, modelling of natural mortality was needed, particularly due to a dense admixture of naturally established Norway spruce.

With the uniform shelterwood scenarios, a special algorithm was used to select overstorey trees to remain in the stand. The algorithm chooses shelter trees to be retained from a list of all trees sorted by dbh, starting from the larger end and discarding trees that are closer than a given minimum distance from already selected trees. In the case of trees of identical size close to each other, one tree is chosen at random. The algorithm is implemented in the Regenerator software.

16.5.3.2
Regenerator Specifications

Based primarily on individual tree dimensions and positions, Regenerator predicts the availability of primary resources (light and water) and, in turn, the establishment, survival, and height growth of tree seedlings and saplings as a function of resource availability (Brunner 2003). Competition between saplings and with overstorey trees and ground flora is included through the effect of individual plants on resource availability. Regenerator uses SILVA to predict growth of trees taller than 5 m.

For our scenarios only light was included and, consequently, Regenerator was mainly used to predict the light-dependent survival and height growth of planted beech and naturally established Norway spruce saplings relative to their potential. The height growth potential in Regenerator is defined in the same way as in SILVA and the same species-specific parameters were used.

The simulation of a natural regeneration of Norway spruce involves seed production and seed dispersal as well as establishment and survival of seedlings. For our scenarios Regenerator was parameterised to predict a regeneration density potential rather than an average number of saplings. For beech Regenerator was only used to predict growth and survival. The scenarios do not consider the potential effects of browsing, which, in practice, could be eliminated by fencing.

A very dense regeneration of spruce established in the irregular shelterwood scenarios. To allow beech to survive, the number of spruce saplings was reduced to 50% through pre-commercial thinning 19 years after the onset of regeneration, i.e., at overstorey age 83 years.

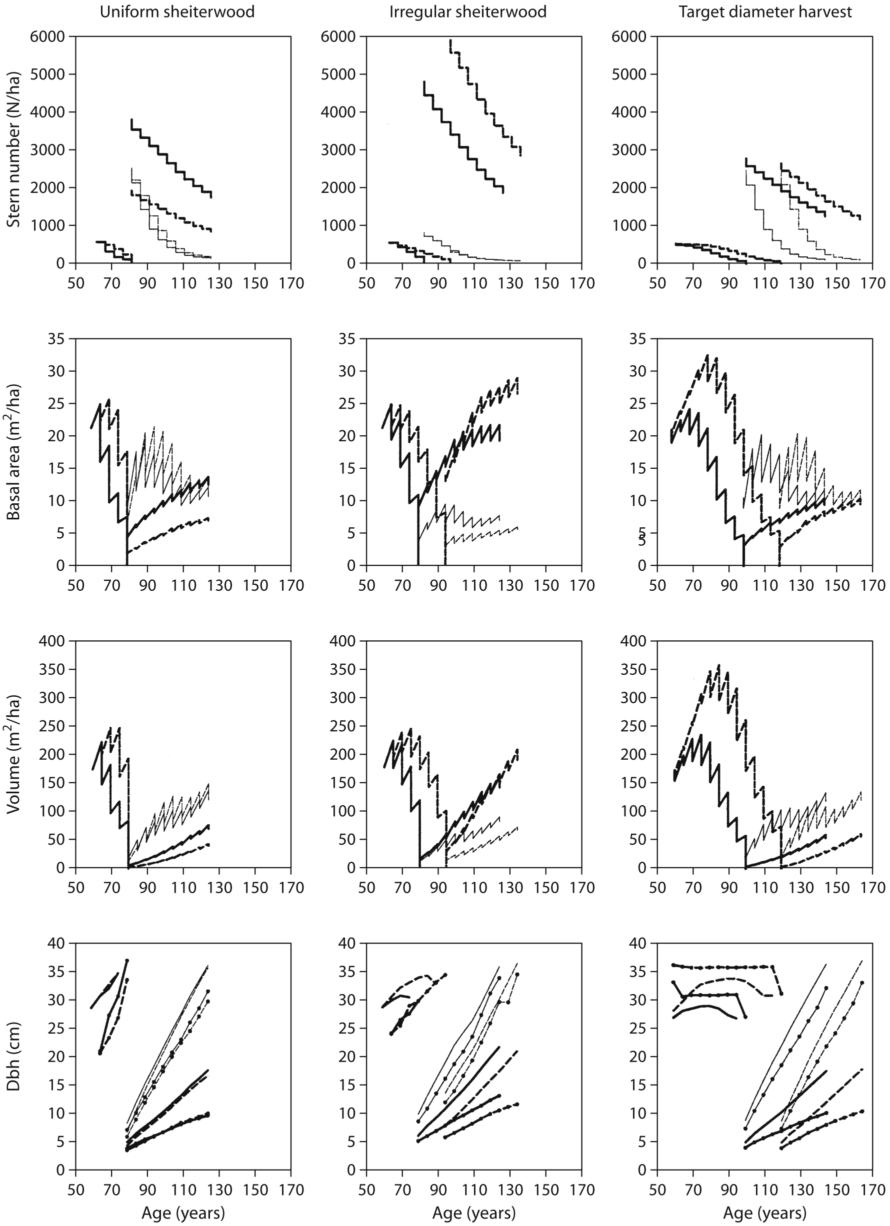

Fig. 16.6. Results of scenario analysis. *Full lines* fast scenarios; *dashed lines* slow scenarios; *thick lines* spruce; *thin lines* beech; for dbh: *lines without dots* D_g of the removed trees; *lines with dots* D_{100} (arithmetic mean diameter of the 100 thickest trees per hectare) of the remaining trees

16.5.4
Scenario Results

16.5.4.1
Overstorey Removal

During removal of the overstorey, stand basal area and stand volume rapidly declined for the fast versions of uniform and irregular shelterwood, indicating that current growth did not compensate for the thinnings (Fig. 16.6). For the slow versions of both systems and for target diameter harvesting at 30 cm, current growth compensated for the removed trees during an initial period of up to 20 years, maintaining stand basal area and stand volume at a stable level. For the 35-cm target diameter scenario, basal area and volume initially increased considerably because of the obvious lack of thick trees at that stage. In practice, the potential volume of trees at or above 35 cm would be too small during this period to actually carry out harvesting operations. Comparison of the two different target diameter scenarios strongly indicates that a target of 30 cm may lead to pre-mature depletion with a considerable reduction in the harvesting potential.

Diameter development during removal of the overstorey closely reflects the original scenario definitions (Fig. 16.6). For the uniform shelterwood the diameter of crop trees steadily increases throughout, but there appears to be little difference between the fast and the slow version when comparing the 100 thickest trees per hectare. This finding implies that the above-mentioned growth reduction primarily is located on smaller crop trees or results from the removal of smaller crop trees. At the same time the rapid shelterwood reduction immediately leads to removal of trees of a considerable size; resulting in a fast depletion of the growth potential. The patch pattern of the irregular shelterwood obviously leads to less growth on the crop trees as compared to uniform shelterwood and target diameter harvesting, and to similar harvest and crop tree dimensions. With target diameter harvesting the harvested trees by definition are the thickest trees in the stand. In practice, too much volume may accumulate periodically, leading to a tight balance between the maintenance of consistent harvesting criteria (the target diameter) and the desire to do only light thinnings. When initiating target diameter harvesting, the problem may rather be the opposite because there are too few trees of a suitable size to make each individual thinning operation profitable.

The total volume production of overstorey trees during their removal is summarised in Table 16.2. Generally, the faster versions are less productive. During the first 20 years the slow versions of uniform and irregular shelterwood and the 30-cm target diameter harvesting are remarkably equal in volume growth, ranging between 8.7 and 9.0 m^3 ha^{-1} $year^{-1}$. Target diameter harvesting at 35 cm appears to be the most interesting alternative. With this regime, thinnings include only trees of uniform size and good price, while volume growth is maintained at a relatively high level throughout. During the first 20 years this regime provides the highest growth rate, and considering the whole period until final harvest, still maintains an attractive level of volume growth. Overall, the attractiveness of each of these alternatives may be modified by other factors, for example

Table 16.2. Volume production during overstorey removal

Scenario	Periodic volume increment (m^3 ha^{-1} $year^{-1}$) Years 60–79	From 80 years to final harvest	From 60 years to final harvest
Uniform shelterwood			
Fast	5.86	–	5.86
Slow	8.65	–	8.65
Irregular shelterwood			
Fast	6.98	–	6.98
Slow	8.70	4.38	6.85
Target diameter harvest			
30 cm	8.99	3.49	5.93
35 cm	10.75	5.52	7.02

risk of windthrow or harvesting criteria that do not relate directly to stand level characteristics.

16.5.4.2
Understorey Development

The beech saplings planted under the shelter and the naturally established Norway spruce saplings grew in most scenarios in sufficient numbers to above the 5 m height threshold within 20 years (Fig. 16.6). Only for the slow version of the irregular shelterwood scenario was it necessary to run simulations for 25 years to reach the 5-m level. Uniform shelterwood and target diameter harvesting resulted in intimate mixtures of planted beech and naturally regenerated spruce (Fig. 16.7, left). The irregular shelterwood scenarios resulted in a dominance of beech in the early planted patches and finally a total absence of beech in the patches that were cut later (Fig. 16.7, right). Here, spruce established in such high densities after the first patches had opened up the stand that the planted beech saplings did not survive.

The development of the resulting mixture of young beech and spruce is very similar for the scenarios of uniform shelterwood and target diameter harvesting (Fig. 16.6), only with a time lag for the 35-cm target diameter. The fast version of

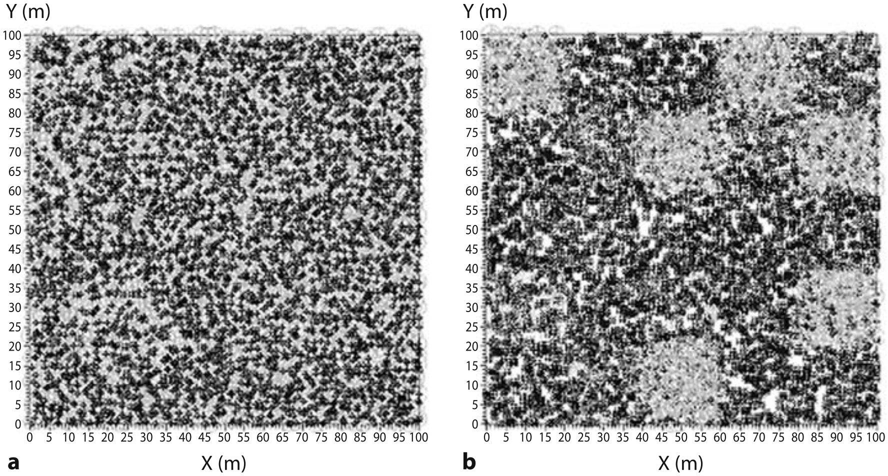

Fig. 16.7. Crown map of young stands as a result of scenario simulations. *Left* Uniform shelterwood – fast; *right* irregular shelterwood – fast. *Black* Norway spruce; *grey* beech; *crosses* stem position; *circles* crown projection

the uniform shelterwood results in a higher proportion of Norway spruce as compared to the slow version. The similarity of results from target diameter harvesting and uniform shelterwood regeneration may be influenced by the fact that the natural regeneration of spruce prior to planting of beech is not included in the scenarios. While all four scenarios were initiated without the presence of advance regeneration, this would in practice establish progressively, depending on light conditions and the spatial distribution of seed trees, or it might occur more or less simultaneously over larger areas. The irregular shelterwood scenario differs from the other two systems in creating young stands with a dominance of spruce over beech. This dominance is even more pronounced with the slow version.

16.6
Discussion

16.6.1
Model Calibration and Evaluation

Due to their complex nature, individual tree models are often hard to calibrate properly and even harder to evaluate to any consistent standard (Schmidt et al., this Vol.).

Regarding calibration data, spatially explicit growth models often require data that are frequently unavailable. In our case the missing tree positions for most plots prevented a strict evaluation of the growth model's predictive performance.

Our alternative, to evaluate the model based on predictions that involved the simulator's thinning algorithms, could not satisfactorily replace an evaluation based on information on individual tree positions and time of thinning. The tests revealed that thinning algorithms implemented in SILVA did not completely match the observed thinning strategies of our experimental plots. Most likely, this result stems more from the fact that even experimental thinnings often deviate in practice from postulated principles than from differences in thinning strategies between Germany and Denmark. Moreover, the tests of SILVA revealed a very sensitive response of the growth model to differences in thinning strategies and principles. We consider this to be a major strength of spatially explicit growth models and a necessary condition for application of these models to mixed-species stands and uneven-aged silviculture.

For one beech experiment tree positions were available and therefore thinnings could be simulated as observed on the plot. In this test, model predictions of mean diameter and basal area were in good agreement with observed values throughout a 100-year simulation period. It would be desirable to test SILVA in the same way for more plots before our calibrated version of SILVA is used for forest management planning.

Regarding model complexity, individual tree models generally combine a number of model components or modules. Combined with the large influence of stand structure on growth predictions for individual trees this situation prevents strict testing of individual model components or of the complete growth simulator. For example, the competition index used to reduce the diameter growth potential to actual diameter growth cannot be tested independently of the height growth model. Height relationships between competing trees are an important part of many competition indices. SILVA also uses actual tree diameter and height to predict crown dimensions, which, in turn, are part of the calculation of the competition index. Our approach to the problem of intertwined model components was to test the complete model and compare stand level predictions with observations. This approach of course limits the validity of our tests to the conditions represented by our observations.

Within our limited test of SILVA we found no indications of a failure of the competition index or other model components under Danish conditions. Under the assumption that this also holds in more strict tests of the model, it can be concluded that a calibration of the height and diameter growth potential to regional conditions could be sufficient to apply SILVA to the same tree species in other regions.

Clearly, the range of site conditions for our experiments is too narrow for a proper calibration of the site-specific height growth potential, or the site variables do not work properly because of limited variation in site conditions within Denmark. This limitation holds for Norway spruce as well as for beech.

16.6.2
Demonstration of the Growth Model

One objective of this study was to demonstrate the capability of an individual tree model to predict tree and stand responses to complex silvicultural practices in mixed and multi-aged stands. An obvious requirement is that predictions should be accurate and relevant for forestry practice. The nature of our studies does not allow a strict or thorough testing, but results are certainly within the range of our expectations. For practical purposes more flexible thinning algorithms would be desirable, and the need for smoother transitions between regeneration model and tree growth model is foreseeable. With the regeneration model, there also appears to be an immediate need to identify suitable, less detailed input variables and to develop sampling procedures for use in operational forestry.

16.6.3
Conversion Silviculture

Conversion of Norway spruce stands by underplanting of beech in a gradually opened stand of Norway spruce can be accomplished in different ways. Our scenario analysis demonstrated six alternatives of uniform shelterwood, irregular shelterwood, and target diameter harvesting. The predictions of growth and regeneration did not show any limitations to a successful conversion, but resulted in different growth patterns and species compositions.

During overstorey removal, stand volume growth depends mainly on how fast the removal progresses, but to some extent also on harvesting criteria and the spatial distribution of residual crop trees. The superior alternative in terms of volume growth is target diameter harvesting at 35 cm. In contrast, with a rapid stem number reduction in a uniform shelterwood or harvesting based on a small-sized target diameter the growth potential quickly deteriorates, resulting in suboptimal economic return at the stand level. However, target diameter harvesting at 30 cm still equals or outperforms the 20-year slow version of uniform shelterwood, but is slightly inferior compared to the slow version of irregular shelterwood.

The distribution of growth to individual trees obviously depends on their spatial arrangement. Interestingly, the fast irregular shelterwood with its dense patches of overstorey trees leads to better volume growth than the fast uniform shelterwood with trees more evenly distributed over the whole area although they each last 20 years. Next, during the initial 20 years, target diameter harvesting at 35 cm leads to a more efficient utilisation and distribution of stand volume growth than does the slow version of uniform shelterwood.

According to predictions from Regenerator, all six scenarios resulted in a young stand of planted beech mixed with a very dense natural regeneration of Norway spruce. The high density and spatially uniform distribution of the spruce regeneration might be overly optimistic. On the other hand, this outcome is not uncommon in recent natural regenerations of spruce on former heathland in Denmark.

The beech – spruce mixture of the resulting stands is of major importance for future management options. The proportion of the two species varies in our scenario results according to the speed of conversion and the conversion method applied. For those treatments that create a relatively uniform opening of the stand (uniform shelterwood, target diameter harvesting), the longer regeneration period of the slower scenarios generally favours beech. Results for the irregular shelterwood system indicate dominance of natural regeneration of Norway spruce over planted beech. This may be avoided by earlier planting or groupwise separation of the two species, for example through pre-commercial thinning. Regulation of the mixture could be accomplished in SILVA only by thinning for crop trees at a very early age. Application of this thinning strategy to the model stand would reflect more strongly a need to achieve a desired species mixture than an actual desire to apply the strategy in forestry practice in western Denmark.

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Modelling the Growth of *Quercus frainetto* in Greece

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Abstract. Coppice forests are degraded, low output forests. They fulfill poorly their environmental, social and productive functions, and conversion into high forests will improve them. *Quercus frainetto* (Ten.) is the most important oak in Greece, representing 13% of the standing volume. The objective of this chapter is to introduce the new modeling technology in Greece and to adapt the Austrian individual-tree, distance-dependent simulator MOSES for modeling the development of *Qu. frainetto*. The data for this study came from 25 permanent experimental plots across Greece. Four models driving the growth of *Qu. frainetto* were considered: diameter and height increment, crown recession and mortality models. Non-linear regression methodology was used for parameter estimation. The development of diameter and height increment models was based on the assumption that the potential increment for a given tree is reduced by a function of the crown ratio as an allometric multiplier representing the past growing conditions and an overstocking multiplier representing the current competition conditions. The crown model predicts future crown length depending on tree height, crown ratio and the competition index. Finally, in the mortality model, trees are stated to be either alive or dead, and the respective predicted probability of mortality in the next growing period is bound between 0 and 1. Therefore, a logistic equation was fitted using the crown ratio, competition index and diameter as independent variables. The simulator *DRYMOS*, a derivative software program of the Austrian simulator MOSES, incorporates the developed models for *Qu. frainetto* in a user-friendly interface. After the selection of a stand, the user has the opportunity to project the stand in two- or three-dimensional form, apply silvicultural treatments and produce results in tabular or graphical form. *Qu. frainetto* stands can be efficiently modelled with distance-dependent and site-potential approaches. Tree size, growth and competition are the main driving variables in predicting growth and development of *Qu. frainetto*. The simulator *DRYMOS* is capable of describing the evolution and future stand dynamics of *Qu. frainetto* under different stand densities and silvicultural scenarios.

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Hubert Hasenauer (Ed.)
Sustainable Forest Management
Growth Models for Europe

17.1
Introduction

Coppice management of hardwood forests has been carried out in Europe since the Roman era (Papaioannou 1939). The regeneration of coppice forests depends on the ability of stumps to produce sprouts from either dormant or adventive buds, which together with root suckers represent vegetative (asexual) regeneration.

Coppice forests are considered as low output forests. The shorter the rotations the lower the productivity in the long run especially when no care is provided and the grazing of livestock is not regulated. Heavily degraded coppices show, in addition to poor stem quality, low stem densities and poor soil coverage, creating high rates of erosion. In some regions coppices were abandoned after World War II, and they developed as high natural forests.

In central Europe conversion of coppice forests into high forests started in the 18th century. According to Georgopoulos (1940), the first published document in Greece on coppice management is that by Markopoulos and Michalopoulos (1927).

Of the 12 oak species that occupy 1,471,839 ha or 22.6% of the forest area of Greece, *Quercus frainetto* (Ten.) is the most important one. It represents 13% of the standing volume (Ministry of Agriculture 1992). The greater part of this area is managed as coppice forest producing fuel wood and timber in combination with grazing. *Qu. frainetto* in Greece grows on mountains from approximately 400 to 800 m.

As a consequence of the above, no effort has been made to develop growth and yield models for various types of oak stands. Most of the previous studies were concerned with analysis of their structure (Dafis 1966) or silvicultural features (Chatziphilippidis and Spyroglou 1996). It is self-evident that the rehabilitation of coppice forests is impossible without human intervention and planting. The choice of species for planting is restricted to a few conifers, mainly pine, cypress and cedar species, which meet the prerequisites of low nutrient demands, quick soil coverage and timber production. The change from one silvicultural system (coppice) to another one (high forest) is called conversion (Fig. 17.1).

The conversion into high forest through tending of the existing coppice stands is an ecologically sound method of rehabilitation, recommended in less degraded coppice forests. If quality of stands is insufficient, they can be clear-cut and thereafter tended as high forests. The introduction of conifers is an ecological shortcoming of the method. Nevertheless, if native vegetation is not destroyed during the conversion work, indigenous species will replace the conifers in the next rotations.

Dafis (1966) recommends the appropriate rehabilitation technique according to the site quality and the structure of the coppice stands: in severely degraded sites, conversion by introducing conifers, while in better sites, conversion through tending. These silvicultural recommendations were corroborated by Stamou (1981) from the economic point of view. Nevertheless, Serrada et al. (1992) recommend for Spain conversion of *Qu. ilex*, *Qu. faginea* and *Qu. pyrinaica* coppices into high forest without considering site criteria.

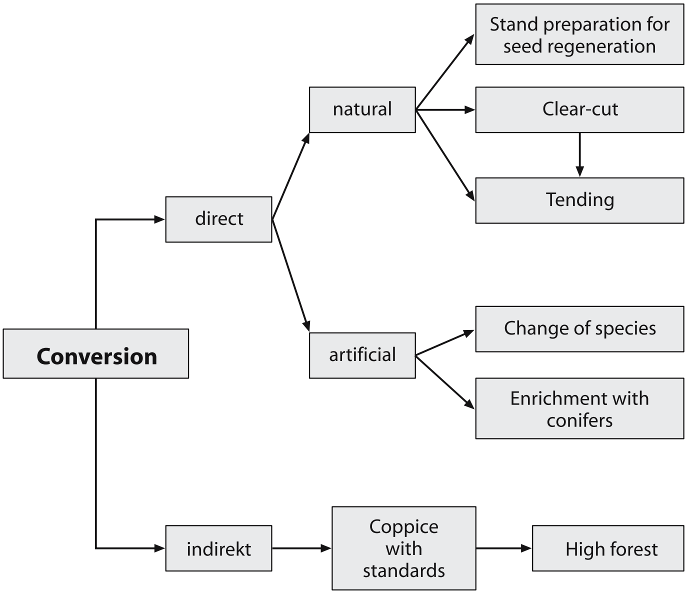

Fig. 17.1. Conversion options for coppice forests into high forests: *Direct conversion, naturally*: preferred when tree species composition and phenotypes of existing trees are acceptable in quality and quantity. If not then artificial regeneration, by changing of species, must be chosen. In the first case, the following options can be chosen: (1) preparation and natural seed regeneration: when a stand produces seeds, we can prepare the stand for seed regeneration; (2) clear-cut: when the quality of stems is not sufficient, but tree density is high and genetic material is good, the stand can be clear-cut and thereafter it is treated as a high forest; (3) tending: stands of sufficient quality can be tended as a high forest. *Indirect*: the coppice stand goes over an intermediate phase (coppice with standards) to high forest. At each rotation, additional standards are selected. In this way, after two to four rotations, the whole area is occupied by standards able to regenerate with seeds

The abandonment of mountainous areas after World War II resulted in cessation of any management of coppice forests. This trend led to an improvement of the stand structures and the ecological conditions in general, but, on the other hand, it led to an increased fire hazard (Morandini 1998). Cessation of the management for some time is not necessarily detrimental, but in the long term it can have adverse consequences for the coppice forests. As a result of intensive human use, forest owners, policy makers and the public will commonly decide on the future management of the coppice forests in order to address economic, social and environmental concerns.

Rehabilitation of coppice forests started in Greece in the 1920s. Since 1938 the Greek Forest Service has made a significant attempt to improve coppice forests either by planting conifers or by tending of the existing stands.

After 60 years of conversion there has been a prominent shift away from classical pure, even-aged coppice forests to uneven-aged and mixed species stands.

However,, there is a lack of knowledge about the development of these forests as well as about their silviculture. This fact renders the very few Greek yield tables designed for coppice and high oak forests (Kossenakis 1939; Apatsidis 1995) unreliable for predicting forest growth. This fact has created problems in forest management practice and decision-making, leading to a dead end as far as the construction of management plans is concerned. A new conceptual approach to this problem is mandatory today, more than ever.

An innovative method of predicting the growth of even or uneven-aged, pure or mixed species stands is to describe the stand growth development as the sum of variations of individual trees within the stand depending on the competition at tree level. This approach has led to a model with increased flexibility in stand growth predictions.

Modeling of ecological systems describes physical phenomena by means of mathematical equations. Two general types of models can be distinguished: those describing behaviour and those explaining the system. Descriptive models try to match system behaviour with model behaviour. Very often, regression functions are used in this context. Explanatory models try to correctly extract essential structures of the system and rebuild them in the form of a model. The advantage of the latter approach is the possibility to study systems with different environmental conditions. Models often describe very complex systems. Thus, it is necessary to reduce the number of modelled processes.

Although simplifying assumptions are necessary, not all questions can be answered with a certain modeling approach. To gain an overview of the quality of a model, several criteria in respect of the aim of modeling should be fulfilled. The dynamic behaviour of the model should qualitatively match that of the real system. Numerical and logical model results should correspond with the functions taking place inside the system. Deviations should be explainable through assumptions made during model building. Simulation results should be useful with respect to both potential applications of the model and the aim of modelling.

Growth and yield models describe forest dynamics over time (i.e. growth, mortality, regeneration and associated changes in the stand) and hence they have been widely used in forest management because of their ability to update inventories, to predict future yield and to explore management alternatives and silvicultural options, thus providing information for decision-making (Burkhart 1990; Vanclay 1994; Peng 2000). Consequently, predicting future forest growth under different scenarios is a key element of sustainable forest management (Kimmins 1990, 1997).

As the management of *Qu. frainetto* forests moves from simple to more complicated structures, modern tools can contribute to a more flexible and accurate prediction of stand development.

The objective of this chapter is to describe the innovative modeling technology in Greece and how an individual tree growth simulator has been adapted for *Qu. frainetto*.

17.2 Materials and Methods

17.2.1 Data

Qu. frainetto grows in the vegetation zone of *Quercetalia pubescentis*, which usually occupies the area between the zones of *Quercetalia ilicis* and *Fagetalia*. According to bioclimatic maps (Mavromatis 1980), the climate of *Qu. frainetto* forests is a transition from a typical Mediterranean to a continental climate with harsh winters and hot summers (Fig. 17.2). Frost and snow can cover the ground for 1 to 2 months each year and the number of dry days during the drought period ranges between 40 and 70.

For the purposes of this project, data from permanent experimental plots have been used (Fig. 17.3 and Table 17.1). Twelve of them were established in the 1960s by the Forest Research Institute of Athens (older plots) and 13 by the Forest Research Institute of Thessaloniki in 1986 (recently established plots). All plots were provided with buffer zones. The main objective of both projects was the study of the impact of different silvicultural treatments on the structure and the volume yield of *Qu. fraineto*. As can be seen, the plots in Larissa, Peloponnese and Mesologgi were 35 to 65 years old at the time of establishment, while the plots in Thessaloniki were complementary to the older plots, aiming to fill the gaps of age classes. The silvicultural treatments applied in the older plots correspond to three intensities of low thinnings, while in the plots in Thessaloniki crown thinnings of various intensities have been applied. The latter are designed to act also as demonstration plots for the consequent conversion of coppice stands into high forests.

The available data from experimental plots (dbh, tree height, height of live crown and X–Y coordinates) were very suitable for the application of a distance-dependent model like MOSES (Hasenauer 1994a). Another potential model ap-

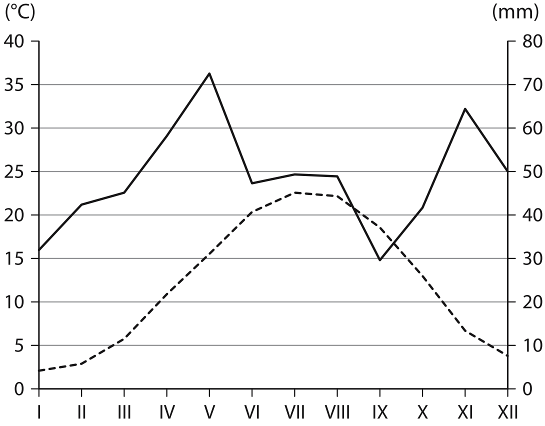

Fig. 17.2. Typical climatic diagram for the vegetation zone of *Quercetalia pubescentis*. Climatic station Lahanas, Serres. Altitude: 634 m; precipitation: 585 mm; mean annual temperature: 12.1 °C (1978–1995). *I–XII* January–December; *solid line* precipitation (mm); *dashed symbol line* temperature (°C)

Fig. 17.3. Map of Greece and location of permanent experimental plots of *Qu. frainetto*

proach would be that of SILVA (Pretzsch 1992), but this model needs environmental, site and species-dependent parameters (NOx, CO_2, precipitation, temperatures, nutrient supply, ecoregional classification parameters, etc.) in order to derive potential diameter and height growth. However, such data are not available in Greece and the approach of MOSES (Hasenauer 1994a) was therefore considered the most appropriate one.

17.2.2
The Diameter Increment Model

The prediction of diameter increment over time is based on the assumption that the observed diameter increment depends on the potential diameter increment as it results from open grown trees (Hasenauer 1997). This potential is reduced by a function of the crown ratio (CR) representing the past growing conditions, the competition index (CI) according to Monserud (1975) and the change in the competition (CI) as this results from stand treatments or natural mortality. The time scale of prediction is 5 years. Because the change of each tree's specific competition situation within a stand is formulated, the model is an appropriate tool for assessing growth response to different stand densities. In order to eliminate trivial correlations between the observed and the potential diameter increment within an observation period, the ratio between observed and potential increments has been used (Hasenauer 1994b):

$$\frac{id_{obs}}{id_{pot}} = CR^{a_1} \cdot \left(1 - e^{\frac{a_2}{CI \cdot (1 + a_3 \cdot \Delta CI)}} \right)$$

Table 17.1. Summary of oak permanent experimental plots. *dbh* Breast height diameter (cm); *H* tree height (m); *Hlc* height to the base of live crown (m); *X and Y coordinates* individual tree coordinates (m)

	Location Thessaloniki	Mesologgi	Larissa	Peloponnese
Establishment year	1986	1964	1966	1964
Age at establishment	8	65	35	50
Number of plots	13	4	2	6
Plot area (m^2)	1,200	5,500	2,800	5,200
No. of remeasurements	1	7	6	7
Altitude (m)	620	680	650	650
Topography (slope) (%)	5	50	30	3
Data recorded	dbh, H, Hlc, X and Y coordinates			
History to establishment	Coppice clear-cut	Fuelwood cuttings	Fuelwood cuttings	Fuelwood cuttings
Grazing	No	Heavy	No	Heavy
Treatments since establishment	Conversion thinnings	Thinning	Thinning	Thinning
Soils	Quartzite with phyllites	Flysch	Gneis	Lacustrine sediments

where:

id_{obs} is the observed diameter increment (in centimeters);
id_{pot} is the potential diameter increment (in centimeters);
CR is the crown ratio;
CI is the competition index after crown release;
ΔCI is the difference in competition index before and after crown release.

The potential (breast height) diameter increment is determined from empirical allometry of open grown trees. The calculation of the potential diameter increment works like this: once the potential height has been determined from the site index equation for a given age at the beginning of the growing period (5 years), the diameter of an open grown tree can be calculated from the height diameter model of open grown trees. Next, a new potential height is derived from the site index equation for the next growing period. This height corresponds to a new diameter as this results from the same height–diameter model for open grown trees. The potential diameter increment is then the difference of these diameters.

Monserud (1975) defined CR^{a_1} as the allometric multiplier, and the expression

$$\left(1-e^{\frac{a_2}{CI\cdot(1+a_3\cdot\Delta CI)}}\right)$$

as the overstocking multiplier.

17.2.3
The Height Increment Model

The prediction of height increment over time is based on the same assumption as the diameter increment model. The potential height increment is reduced to the current height increment by the same factors, the crown ratio and competition index (Hasenauer 1994b):

$$\frac{ih_{obs}}{ih_{pot}} = CR^{a_1}\cdot\left(1-e^{\frac{a_2}{CI\cdot(1+a_3\cdot\Delta CI)}}\right)$$

where ih_{obs} and ih_{pot} are the observed height and potential height increments respectively (in meters).

The potential height increment (ih_{pot}) cannot be determined from open grown trees as is done for the potential diameter increment because open grown trees tend to develop less in height than those that grow within the stands. The potential height increment can be determined from the dominant heights of site index functions.

Site index equations generally represent the average height increment of the dominant trees of a region. A tree height can be calculated with site index equations for a given site index and age. Conversely, given a site and height, it is possible to calculate an approximate age for a tree, more appropriately called an effective site age (Donnelly and Johnson 1997). Potential height growth can then be calculated by incrementing the effective site age by the growing period and solving the site index equation for a new height. Potential height increment is the difference in heights between the two points in time. For a specific site, this increment would be the best expected if the tree follows exactly the site or height increment curve. Figure 17.4 gives a graphical representation of the calculation of potential height increment.

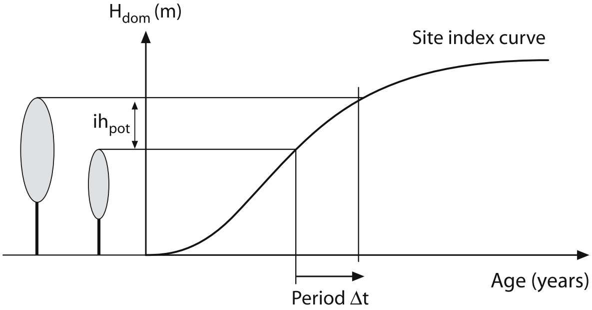

Fig. 17.4. Graphic representation of the calculation of potential height increment

17.2.4
The Competition Index

In distance-dependent individual tree growth models, the interdependence of individual stems is frequently assessed by a competition index, which is a function determining a particular tree's size and location in relation to the size and location of its competitors. Actual growth is then a function of potential growth and its measure of competition. At the heart of an individual tree model is its competition index and the manner in which the growth is affected by this (Ek and Monserud 1974).

Competition between individual trees affects a variety of tree and stand characteristics including growth and reproduction (Monserud 1975), tree form development (Arney 1972) and mortality (Keister and Tidwell 1975). Indices of competition are species- and site-specific (Burton 1993), but the "true" competition index of a given tree is never observable (Monserud and Ek 1977). Provided all factors remain constant, the same value for an index of competition may have different meanings under different site conditions. In effect, competition indices describe plant competition for scarce resources such as water, nutrients and light.

The competition index of every tree is calculated at each growing period, before and after thinning or at mortality as follows: trees are first given open-grown crowns (crowns that trees would have if they were grown without any competition). Next, the area of overlap of the crown of the subject tree that falls inside the crown of the competitor is calculated (Bella 1971). Finally, the overlap area is weighted by the ratio of the size (height and crown width) of the competitor to the subject tree (Ek and Monserud 1974). Equation (17.3) presents the mathematical formula of the competition index of the ith tree in a stand, as follows:

$$CI_i = \sum_{j=1}^{n} \left(\frac{O_{ij}}{\pi \cdot R_i^2} \cdot \frac{R_j \cdot H_j}{R_i \cdot H_i} \right)$$

where:

CI_i is the competition index for subject tree i;

O_{ij} is the influence-zone overlap between subject tree i and the competitor j (m^2);

R_j is potential radius taken from open grown tree dimensions of competitor j (in meters);
R_i is potential radius taken from open grown tree dimensions of subject tree I (in meters);
H_j is height of competitor j (in meters);
H_i is height of subject tree i (in meters).

17.2.5
The Crown Model

To date, most crown models predict each tree's new crown size after each growing period, based on stand and site characteristics and updated tree variables such as diameter, height and competition index. It is accepted that incrementing crown height through time, in much the same way as diameter and height are incremented, would subsequently improve the prediction of tree growth and mortality (Short and Burkhart 1992).

For the prediction of the future crown length, the dynamic crown height increment model (Hasenauer 1994c) was compared:

$$\Delta HLC = a_0 \cdot H^{a_1} \cdot e^{\left(a_2 CR^{0.5} + \frac{a_3}{CI} + a_4 \cdot dbh\right)}$$

where:

H	total tree height (in meters)
CR	crown ratio;
CI	the competition index after crown release;
dbh	breast height diameter (in centimeters);
a_0–a_4	regression coefficients.

The dynamic model estimates the periodic increase of the height to the base of the live crown (HLC) in relation to the total tree height and crown ratio in order to determine the competition index after crown release and the diameter at breast height at the beginning of each growing period.

17.2.6
The Mortality Model

Plant death is a complex process, influenced by physiology, environment, successional development, age and chance (Harcombe 1986; Franklin et al. 1987). In general, trees die when they cannot acquire or mobilize sufficient resources to recover from stress, heal injuries or sustain life, or when they are killed by some external factor. However, the interactive and sequential nature of the complex mortality mechanisms makes it virtually impossible to produce a definitive classification of what caused the ultimate death of a tree (Franklin et al. 1987). While a tree's death might ultimately have resulted from a negative carbon balance (i.e. where respiration exceeds photosynthesis), the deficit might have been caused by an insect infestation brought about by poor vigour during a drought period. Botkin et al. (1972) identified two mortality processes.

1. The inherent risk of death, which we refer to as intrinsic mortality, is the mortality expected to occur under favourable conditions with or without competition from other trees.
2. Competition-induced mortality or growth-dependent mortality is due to poor growth that is often due to competition for resources (i.e. suppression) and is frequently modelled as a stochastic function of diameter growth increment (Hawkes 2000). This assumes that the slowest growing trees are most likely to die because they are weaker and less able to defend against insect or disease attacks, or are less prone to survive snow pressure and other abiotic disturbances. Other causes of mortality, including insect pests, pathogens, drought and nutrient limitations, may also be more likely to affect slower growing trees. The mortality of a tree resulting from competition during the growth process is a dichotomous classification problem. For individual tree models, the dependent variable has two possible options, live or dead (0,1). Consequently the predicted probability of mortality for the next growing period is between 0 and 1. In order to ensure that the predicted probabilities range between the two possible values, a logistic model has been used based on the available data. The model will predict the probability of individual tree mortality (P) within a 5-year period as a function of crown ratio (CR), competition index after crown release (CI), and breast height diameter (dbh):

$$P = \frac{1}{1+e^{\left(a_0 + a_1 \cdot CI + a_2 \cdot CR + a_3 \cdot dbh + a_4 \cdot \frac{1}{dbh}\right)}}$$

The logistic function or slight modifications have proven to be useful when developing models of probability of mortality (Hamilton and Edwards 1976; Monserud 1976; Buchman et al. 1983). Specific advantages of the logistic model are as follows:

- The function is bound by 0 and 1.
- With the selection of the proper set of variables and transformations, the logistic function can be used to describe the most naturally occurring patterns of mortality.
- Non-linear estimation routines (in this case maximum likelihood) can efficiently estimate the parameters of the logistic function.
- Knowing an individual tree's likelihood of dying within the next year is essential to a forest growth simulator.

A tree's probability of dying depends upon its ability to cope with its environment. The tree itself, its neighbouring trees and numerous additional influences including light, moisture, nutrients, insects and fungi are combined to form the unique niche for the individual tree. Diameter growth rate is the key tree characteristic in the species-specific mortality function.

The resulting value of P for a tree is then compared with a threshold value T obtained from a uniform random numbers generator with a mean of 0 and a standard deviation of 1. If the P value is less than T, the tree is assumed to be dead.

17.3
Results

17.3.1
The Diameter Increment Model

From all the available data (almost 28,500 increment periods) only 11,552 increment periods were used for the parameterisation of the diameter increment model because of the missing tree heights. All variables used in the model were statistically significant at level p=0.05. The competition index appears to have the greatest influence on diameter increment compared with the other two variables, i.e. crown ratio and crown release. The influence of the crown ratio is smaller in

Table 17.2. Results of the non-linear regression for the diameter increment model for *Qu. frainetto*. The estimated coefficients are significant at 5% probability level

N	R^2	p_1	p_2	p_3
10.650	0.2283	0.1990	−2.4318	0.1915

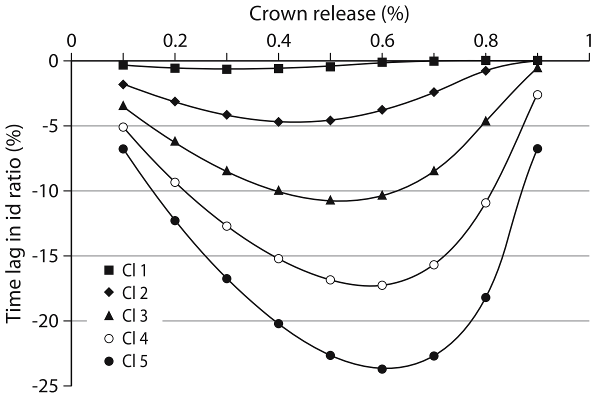

Fig. 17.5. Percentage of the time lag in the diameter increment (*id*) ratio caused by crown release (Δci) at five different competition indices (*CI*) before crown release. Rates in diameter increment delay represent the influence of crown release in comparison to a tree that always had these growing conditions

this case than in that of *Qu. petraea* which was 0.65 (Böheim 2001). The driving variable in the diameter increment model is the competition index (Table 17.2).

The parameter a_2 of the competition index is negative (–2.43), indicating a rather steep decrease of the overstocking multiplier as the competition index increases. The parameter for the crown release a3 is positive and relatively high (0.19) compared with that of other oak species. The positive sign of the parameter indicates that instead of having an acceleration of growth as the crown release increases, there is a decrease in growth. This indicates that *Qu. frainetto* does not take advantage of the greater space that becomes available after a thinning to accelerate diameter growth and cover as much of the newly created space as it could, at least for the first 2 years after the intervention. This is illustrated in Fig. 17.5. It is clear that as the competition index increases and the percentage of crown release approaches 60%, the time lag in the diameter increment ratio reaches its minimum.

Based on Fig. 17.6, it is very interesting to observe that diameter increment appears to be very sensitive to an increasing competition index, which confirms that this species is light demanding and cannot tolerate shading. The same results were presented by Monserud (1975) in the case of the American red oaks.

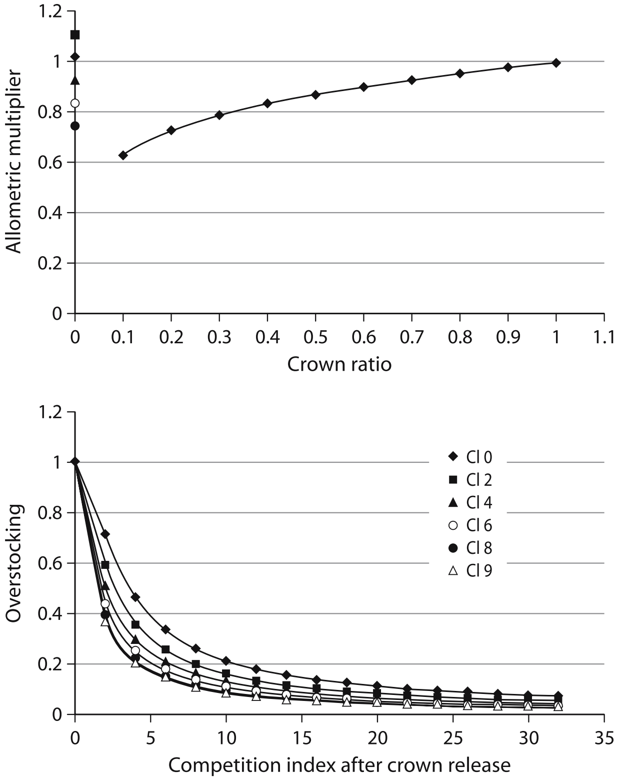

Fig. 17.6. Allometric multiplier (*upper graph*), which represents the past growing conditions of oak, and overstocking multiplier (*lower graph*) depending on the competition index after crown release, which represents the current competition status for the diameter increment model

Based on Fig. 17.5, it can be said that *Qu. frainetto* does not benefit from the crown release after thinning in order to occupy available growing space by accelerating its growth. Instead, there is a recession of the diameter increment ratio for a tree that has been released from competition compared to a tree that had the same growing conditions in the past. A possible interpretation of this result could be a combination of the high light demands of this species and the site fertility. Canopy closure is lower in both light-demanding species and marginal sites as well. *Qu. frainetto* needs time to adapt itself to the improved conditions.

17.3.2
The Height Increment Model

All available data (11,552 increment periods) were used for the parameterisation of the height increment model (Eq. 17.2). All variables used in the model were statistically significant at level p=0.05. The competition index appears to have a much smaller influence on height increment than the other two variables crown ratio and crown release. The influence of crown ratio is also smaller than in the diameter increment model.

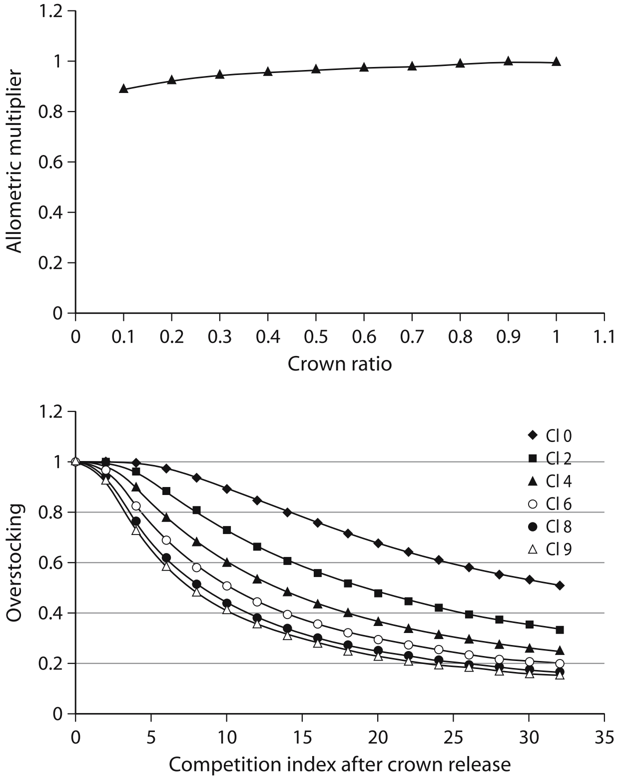

Fig. 17.7. Allometric multiplier (*upper graph*) and overstocking multiplier (*lower graph*) for the height increment model

The height increment model is not as sensitive to the competition index and crown release as the diameter increment model (Table 17.3). However, the pattern is the same as in the diameter increment model.

The most apparent difference between the height growth multiplier shown in Fig. 17.7 and diameter growth multiplier shown in Fig. 17.6 is the greater rate of decrease in the diameter growth curve with respect to increasing competition. This decrease is primarily controlled by the parameter a2 in the overstocking multiplier (Eqs. 17.1 and 17.2). From Tables 17.1 and 17.2 it can be seen that parameter a2 is larger in the diameter growth model. Another large difference that Figs. 17.6 and 17.7 reveal is the larger influence that crown ratio has on diameter growth. These effects are expected because fewer photosynthetic materials reach cambial tissue as resources become scarce due to increasing competition (Kozlowski 1971; Monserud 1975).

In Fig. 17.8, for the competition index preset values 1 and 2, the effect of crown release on the percentage of height increment delay is zero, and for competition index value 3, it is less than –0.1%. Yet again, the pattern of deceleration of height growth as the competition index increases is confirmed. However, this happens only to heavily suppressed trees and to a much smaller degree.

Table 17.3. Results of the non-linear regression for the height increment model for Qu. frainetto. The estimated coefficients are significant at 5% probability level

N	R^2	p_1	p_2	p_3
8.862	0.3895	0.0496	–22.8723	0.3707

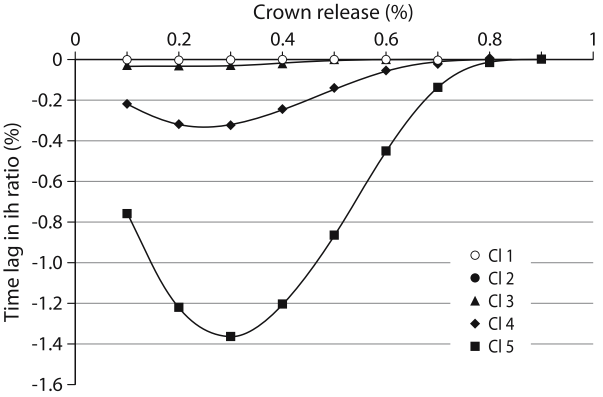

Fig. 17.8. Percentage of the time lag in the height increment (*ih*) ratio caused by crown release (Δci) at five different competition indices (*CI*) before crown release. Rates in height increment delay represent the influence of crown release in comparison to a tree that always had these growing conditions

17.3.3
The Crown Model

For estimation of the change in the height to the base of live crown over the next 5-year period, the model of Hasenauer (1994c), developed for uneven-aged spruce stands, was used (Eq. 17.4). From a conceptual point of view, height to the base of live crown cannot decrease due to changes in the independent variables. This artificial effect is sometimes evident in the static crown model approach. The advantages of such an approach are that negative values are avoided and the thinning intensity observed in experimental plots can be used as a predictor variable to influence the projected results directly. However, as discussed in Section 17.2, the downside of such an approach are the repeated measurements of height to the base of live crown and the data quality because of the high measurement error.

In Eq. (17.4) the estimated coefficient a3 must be negative (Table 17.4), so that the influence of the competition from neighbouring trees expressed by the competition index (CI) is explained. A small value of the competition index will result in a small change in the height to the base of live crown (hlc). A clear advantage of the above model is that it is age independent, which is of great significance for the uneven-aged stands. Additionally, the competition index is suitable because this index can be used in the same way as in the height and diameter increment models (Hasenauer 1994b).

17.3.4
The Mortality Model

The starting point for the development of a suitable mortality model was the determination of the individual tree probability of mortality as a function of the tree variables, which were available at the end of one observation period.

Table 17.4. Results of the non-linear regression for the height to the base of live crown increment model for *Qu. frainetto*. The estimated coefficients are significant at 5% probability level

N	R^2	p_0	p_1	p_2	p_3	p_4
5.584	0.1528	0.034	−0.083	5.5682	−0.8041	0.00152

Table 17.5. Results of the logistic mortality model for *Qu. frainetto*. The estimated coefficients are significant at 5% probability level

N	p_0	p_2	p_3	p_3	p_4
26.754	3.1054	−0.0574	4.3058	0.0111	−10.0058

Individual tree records were coded as either live (probability of dying, 0) or dead (probability of dying, 1) at the end of each growing period. For the 18 plots used for calibration this resulted in 24,337 records classified as live and 2,417 (9.93%) classified as dead.

For the estimation of the probability among dead and live trees the procedure LOGIT of the statistical package SAS (SAS Institute 1999) was used. Table 17.5 shows the parameter estimates of the mortality model.

The competition index after crown release expresses the competition status for the current observation period. Thus it is assumed that a decrease in the probability of mortality is due to crown release in the competition index. The crown ratio can be interpreted as an expression of the past competition situation, while the diameter describes the age trend.

17.3.5
The Computer Program DRYMOS

DRYMOS, which in Greek means forest, is a derivative software program of the Austrian forest simulator MOSES (Hasenauer 1994b). It consists of a system of equations 1 to 5), based on regression analysis, which have been incorporated in a user-friendly interface. The objective of this program is to function interactively with the system of equations and to visualize the evolution of the forest in time.

For the initialization of a stand into *DRYMOS*, the following starting values are needed: plot dimensions, site index, X and Y coordinates of each tree, breast height diameter, total tree height and height to the base of live crown. Additional information that would be useful but not essential for stand initialization includes the characterization of plus trees or future trees, cut trees from thinning and stem quality classes.

Once the program has loaded the required initial tree data, it can visualize the stand in a two- or three-dimensional format. On the right-hand side of the simulator various stand parameters are displayed, such as tree species (in this case only *Qu. frainetto*), site index, quadratic mean diameter, dominant and Lorey height, height/diameter ratio, basal area and standing volume per hectare.

The button 'Growth' is the kernel of the system. When it is pushed, it activates all the growth functions simultaneously. All computations of single tree growth take place for one 5-year period. The program starts calculating the competition index after crown release (Eq. 3); then the estimation of individual diameter and height increment takes place and the results are added to the previous values (Eqs. 1 and 2). The next step is the determination of the change of the height to the base of live crown (Eq. 4). As a last step, the computation of the probability of individual tree mortality takes place (Eq. 5). The decision whether a tree at the end of the 5-year growth period lives or dies is made by a normally distributed random-number generator. If the computed by the model probability of individual tree mortality is larger than the determined random number, the tree dies.

At the end of each growth period, diagrams of the dead and live trees can be displayed. Stand information such as current annual volume increment, standing volume and total production per hectare are also displayed on the right-hand side of the simulator. The updated single tree dimensions at the end of the period are at the same time initialisation data for the next growth period. After the completion of a simulation period, information concerning the evolution of the stand can be represented either as diagrams or as yield tables.

Within a simulation run, the user has the option, through the 'Thinning' button, to choose different thinning scenarios, such as whether to apply a clear-cut or to define a certain area for cutting or to mark individual trees according to specified criteria. When an individual tree or an area of trees is marked for thinning the percentage of the removed trees is presented at the same time on the right-hand side of the simulator in terms of number of trees, basal area and volume, thus giving the user a measure of the thinning intensity. At the end of the simulation period these different scenarios can be compared and give an insight of how the stand responds to different silvicultural treatments.

17.3.6
Oak Stand Simulation

With the simulator DRYMOS, questions of how an oak stand will develop on a given site and under specific thinning scenarios can be easily answered.

Simulation runs can predict stand parameters (basal area, standing volume, mortality, dominant height, mean height and diameter) in tabular form or as diagrams. As an example, a 15-year-old stand of *Qu. frainetto* was simulated under three thinning scenarios for a period of 40 years. The applied thinning scenarios were control (no thinnings) and removal of 10% and 15% of the basal area every 10 years. The results are shown in Figs. 17.9 and 17.10. Although the development of basal area shows some differences between treatments, the total volume production is slightly different among treatments. The highest values are observed in the control and the lowest ones in the simulation with the higher thinnings.

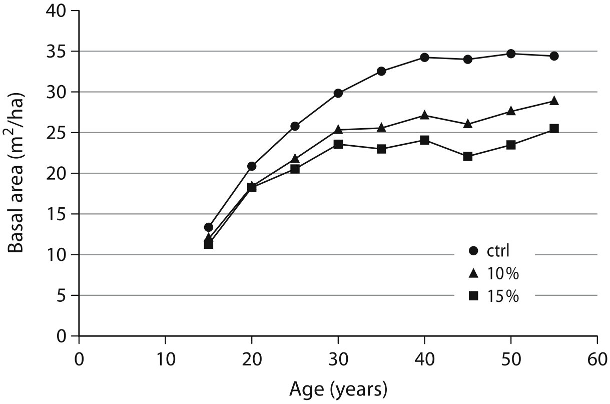

Fig. 17.9. Simulation results for basal area development of a 15-year-old *Qu. frainetto* stand for 45 years

17.4
Discussion and Conclusions

All regression analyses carried out in Section 17.3 were based on real values of the experimental plots and not on smoothed data (data derived from equations). More specifically, for each tree and growth period, the individual tree coordinates, the breast height diameter, the tree height and the height to the base of live crown were used. Smoothed tree height data of missing tree heights were only used for the calculation of the competition index.

17.4.1
Diameter and Height Increment Models

Diameter and height increment models have three important input variables: crown ratio (CR), competition index after crown release (CI) and crown release (CI). All the coefficients used in parameterization of these models were significant at the significance level of 0.05.

Competition index after crown release is the quantification of the current competition status of the trees. It provides a measure of the availability of scarce resources such as light, moisture and nutrients.

Crown ratio can be interpreted as an index of the ability of a tree to utilize the above-mentioned resources. The size of the tree's crown is the outcome of the past growing conditions attained by the tree.

The crown release variable is the difference in the competition index calculated before and after a thinning or natural mortality. It can describe the growth accelerations or growth decelerations where the parameter estimate (a3) is negative or positive, respectively. For *Qu. frainetto* this variable is significant and positive in the diameter and height increment models, resulting in a temporary decrease in the growth in both models (Fig. 17.6 and 17.7). A possible explanation of this effect might be the long period of intense competition prior to thinning

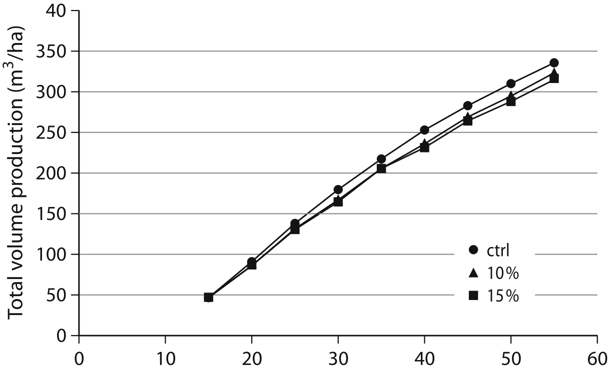

Fig. 17.10. Simulation results for total volume production of a 15-year-old *Qu. frainetto stand for 45 years*

commencement. Unthinned stands could have been too dense to allow satisfactory development of individual trees. As a result, many of the surviving trees in the plots at the time of plot establishment and the first thinning were small, low vigour trees with narrow crowns, deteriorating crowns, poor bole quality, many epicormic branches and less than satisfactory growth rates.

Growth of *Qu. frainetto* was restricted by a combination of excessive summer drought periods, low to medium fertility due to overgrazing and past land overexploitation. Although thinning improved some of the competition for soil moisture and nutrients, the inherent low productivity of the site itself limited the ability of the residual tress to respond positively to the thinning. Figures 17.5 and 17.8 depict this inability to respond positively to thinning, especially for the dominated and suppressed trees compared to unthinned trees, which had the same growing conditions in the past.

17.4.2
The Crown Model

The model yielded quite accurate results for the trees on which the change of the height to the base of live crown was around 50 cm. However, for changes close to 0 or above 1 m, the predictions were poorer.

A big advantage of the dynamic crown model developed by Hasenauer (1994b) is that it holds for stands of any ages. The age trend in this model is expressed by the breast height diameter.

The problem of the subjectivity in the judgment of where the base of live crown is causes difficulties in the development of crown models, especially in light-demanding species such as *Qu. frainetto* where thinnings can cause large epicormic branching, and variations in judgment and measurement error definitely affect the results.

17.4.3
The Mortality Model

Individual tree mortality for *Qu. frainetto* depends on the competition index after crown release (CI), crown ratio (CR) as an indicator of the past growing conditions and the breast height diameter for the description of the age trend.

Breast height diameter is a reliable measure of a tree's size. It is known that as the diameter of a tree becomes larger, the competing ability of the tree becomes greater and thus the mortality rate should decrease. In the regression analysis of the mortality model it has been found that the breast height diameter and the inverse diameter (1/dbh) variables are highly significant for the prediction of the mortality. The inverse diameter variable described well the rapid decline from high mortality for small diameter trees to a more gradual decline in mortality for large diameter trees.

Tree crown is an important attribute for tree survival because it is an expression of a tree's vigour. Generally, it is expected that mortality should be lower for trees with large crowns. Crown ratio was statistically significant in the mortality model. Monserud and Sterba (1999) found the crown ratio variable not significant for oak species in their mortality model. A possible explanation could be the small number of oak trees (784) used in the regression analysis.

Competition index was also a significant predictor of mortality. The probability of mortality increases as the competition index after crown release increases and as the crown ratio decreases.

In distance-dependent individual tree simulators, mortality is considered a discrete event because of the nature of the competition index calculation. Each tree is registered as either completely dead or alive. In the DRYMOS simulator the predicted probability of mortality is compared with a uniform random number generator with mean 0 and standard deviation 1. If the generated random number is less than the predicted mortality, the tree is considered dead and is removed from the tree list.

The major conclusions that can be drawn from this study are as follows:

- *Qu. frainetto* stands can be efficiently modelled with distance-dependent and site potential approach.
- Tree size, growth and competition are the main driving variables in predicting growth and development of *Qu. frainetto*.
- The DRYMOS simulator is capable of reflecting the evolution and future stand dynamics of *Qu. frainetto* under different stand densities and silvicultural treatments.

As public opinion on multiple uses of forests is getting stronger, it is becoming increasingly unlikely that the traditional yield tables will be able to provide solutions and answers to conflicting interests of forest management. The concept presented here offers an alternative solution to this problem.

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Subject Index