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Analysing and Modelling Forest Stand Dynamics for Practical Application
- An European Review and Perspective -

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Abstract

A characteristic feature of European forest and ecosystem management is the concept of integration. While elsewhere plantations for intensive wood-production are separated from forests for conservation of biodiversity or recreation, in European forests a multitude of forest functions is supposed to be integrated. In order to assess and control the development of such multipurpose forests the European countries agreed on a list of criteria and indicators for ecological, economical and social sustainability. These criteria are not just an political paper tiger, they rather reflect and manifest the European ecosystem managers scope of thinking.

This paper firstly sketches how forest management functions in Europe, what kind of information is available and required for sustainable management, and how scientific knowledge can be instilled into the planning process. Secondly I review where our system knowledge springs from: long-term experimental plots, monitoring systems, and eco-physiological experimental stations. Explanations and biometrical formulations for the way how environmental factors and resource supply affect plant growth are described and existing model approaches for stand dynamics are discussed. Thirdly the deficiencies of these scientific approaches with respect to practical relevant knowledge for stand and ecosystem management, especially with respect to the criteria and indicators for sustainable management, are revealed. Considering these deficiencies, fourthly, conclusions are drawn concerning future topics and concepts for research. Recommendations are given for future experiments, integration of scattered system knowledge, up-scaling from tree to stand level, convergence of empirical and mechanistic model approaches, development of tools for decision support, integration of such tools into the information flow of forest management, and finally for a more successful instillation of scientific knowledge into practical forest ecosystem management.

Key words: Ecosystem management; decision support; criteria for sustainability; long-term experiments; up-scaling; surrogate variables; link variables; site-growth-relationship; deductive versus inductive approach of knowledge acquisition; model-building; end-user

1 Introduction

Forest ecosystem management in Europe is obliged to sustainability, participation and transparency. While in other parts of the world plantations for intensive wood-production are separated from forests for conservation of biodiversity or recreation, European forests integrate a multitude of different functions. Thus, ecological, economical, and social functions of forests should be considered together, trade-offs ought to be analysed and decisions made in order to figure out and achieve a multipurpose objective. The principle of integration causes more knowledge, negotiations and compromises than the principle of segregation, equivalent to a spatial or temporal uncoupling of different forest functions (Spellmann *et al.*, 2001). The more diverse the demands on a forest, the more demanding become inventory, planning, and decision making. However, this should not cause the retreat of forest science to basic research, it rather underlines the urgent need for appropriate system knowledge, innovative planning methods, efficient knowledge

transfer from science to practice, as well as a clear identification of research demand by end-users of scientific knowledge.

Concept of forest eco-system management

In order to grasp the potentialities of knowledge transfer into practice I sketch a concept of forest and ecosystem management (Figure 1). Let's assume a particular actual state of a forest, e. g., a pure stand of Norway spruce. Then forest ecosystem management means the development of a target state of the system and the transformation from the actual to the target state. The development of a target state, in our example a mixed stand of Norway spruce and European beech, results from negotiations with concerned people, e. g., forest owners and stakeholders. In the figure the negotiation process is symbolized by the round table. The negotiations are rather dominated by normative valuation by the society than by scientific knowledge. Vague arguments like "beech forests are good as they are attractive and natural", whereas "spruce forests are

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bad as they are un-ecological and artificial" often are much more decisive in this negotiation process than arguments based on scientific knowledge. However, forest science should instill as much system knowledge as possible into the negotiation and decision process. If the target state is defined clearly and formulated quantitatively, practical rules are to be developed as guideline for the operational realization of the aimed transformation (feed-back loop in the middle of Figure 1).

The concept presented in Figure 1 reveals the two most promising gateways for scientific knowledge into forest ecosystem management: (1) Supply of *target knowledge* for the development of the objective; e. g., which species mixture should be selected in order to optimizes the expected forest functions in a municipal forest with a given recreation use, economical expectation and demand for stand stability against

storms in the vicinity of houses? (2) Supply of *transformation knowledge* after fixation of the objective of the further development, e. g., by which practice can a pure stand be transformed to a mixed stand?, how should a stand be thinned in order to harvest a maximum number of trees with a prescribed threshold diameter?, or how should a stand be treated in order to maximize stability against wind-throw?

Of course, once developed target states for forests are not at all static, they rather change dynamically. Objectives of forest management are mainly the result of a changing environment, preferences of the society and economy: Looking back and forward, we can make out five paradigms concerning forest ecosystem management (Pretzsch, 2006; Yaffee, 1999). They reach from anthropocentric to bio-centric and eco-centric approaches in dealing with forest ecosystems: (1) multiple use, (2) dominant use, (3) environmentally
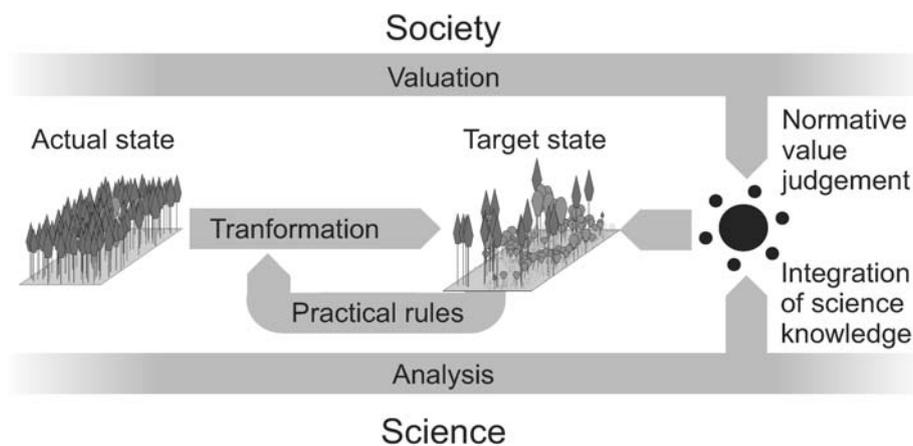

Fig. 1. Concept for the management of forest ecosystems. Starting with an actual state (forest stand, stratum of a forest estate, landscape unit) a system should be transformed into a target state. Normative valuation by the society and scientific knowledge contribute to the development and achievement of the target state.
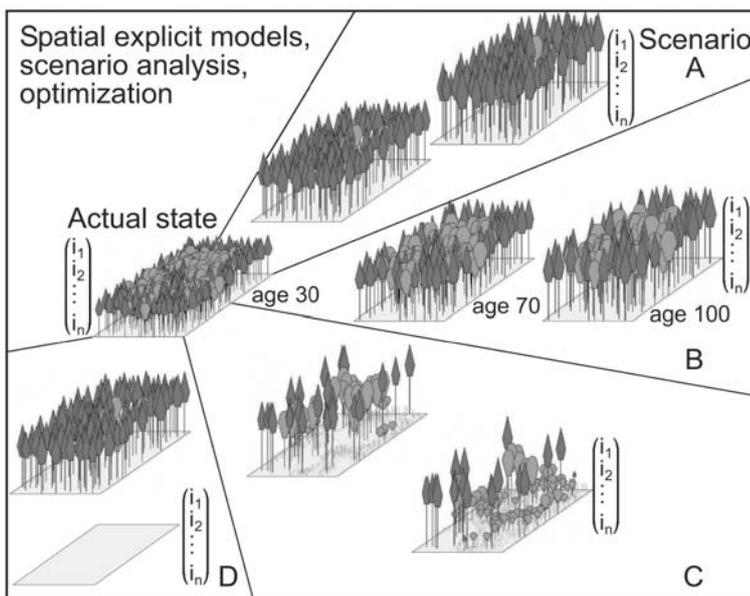

Fig. 2. Scenario analysis with forest stand models. Starting with an actual state of an ecosystem, models display the long-term consequences of the different management options A, B, C and D and the consideration of different objectives and target states.

sensitive multiple use, (4) the ecosystem approach, and (5) the eco-regional management paradigm.

Transfer of knowledge from science to practice

The two most helpful supporting tools for instillation of system knowledge into the process of development of target states and of transformation guidelines are training plots and simulation models. Both provide "what if"- information. How will a stand with a given initial state develop with respect to system variables if different treatments are applied? Experiments with differently treated plots show the consequences of a number of treatment options in nature; i. e., in the real world. If suitable data is available for model parameterization and calibration, models deliver different scenarios; i. e., they present the long-term consequences of different options in a virtual reality. Both approaches - experimental plots and models - enable the comparison of the consequences of different treatment options with respect to, e. g., volume production, stand structure, carbon-storage, biodiversity, or stand stability.

Models deliver tools for argumentation and decision at the round table (Figure 1), where ever it is: in the private forest company, in the state forest service or in a municipal forest. The strength of the models in forest research and management is that they display the consequences of management options "in quick motion". In contrast to many other branches of natural sciences, in forest research scenario analysis and models are extremely important. The reason is the longevity of trees compared to other organisms, e. g., compared to herbaceous plants. In forests we can not start experiments each time when we have a new management idea or question and wait for the results.

Main benefit from models are scenario calculations, which display how a stand with a given initial state will develop with respect to system variables ($i_1 \ldots i_n$) if treatments A, B, C, or D would be applied (Figure 2)? In our example we distinguish between four scenarios (A) no management at all, i. e., self-thinning, (B) moderate thinning, (C) threshold diameter thinning, and (D) classical clear-cut system. How do these alternative treatments affect a given vector of indicator variables $\vec{i}$. Far developed models deliver for each considered scenario information about the achievement of objectives like carbon stock, stability, growth and yield, biodiversity, protective value, and usability of the forest for recreation. The scenario calculations can be repeated for different land use options. Given a certain weighting of the different indicator variables, the total value of each option can be assessed, compared with other scenarios, and ranked. In addition, an optimal treatment can be revealed by heuristic optimisation methods (Hanewinkel, 2001).

The conferences in Rio 1992 (Agenda 21), Helsinki 1993 (H1), Lisbon (L2) 1998, and Vienna 2003 underline the demand for quantitative criteria and indicators for steering, controlling and certification of sustainable management. The European countries agreed on a list of criteria $\vec{c}$ and indicators $\vec{i}$, for quantification of ecological, economical and social sustainability (Table 1). These criteria reflect and manifest the European ecosystem managers scope of thinking and are not just an empty political paper tiger (MCPFE, 1993). Models can apply these variables in order to make the simulation results understandable for practically working managers and supply the most relevant variables for support of decision making.

Objective of this paper and underlying material

The basic thesis of this paper is, that European forest science is provided with so much detailed information about forest functioning and structure as never before. However, it is in question whether this information, especially its spatial and temporal resolution, organization, and scattering, meets the requirement of forest ecosystem management. By sketching the development of experimental set-ups, forest and geo-data inventories, and simulation models I try to scrutinize (1) whether the experimental set-ups, monitoring systems and models for forests are able to meet the information requirements for a sustainable management, (2) when and why the link between science and application split, and (3) how the obvious

Table 1. Pan-European criteria 1-6 and examples for 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,...

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gap between science and application, between reductionism and holism, can be bridged.

This position paper is based on the author's experience with the management of long-term growth and yield plots in South Germany, the development of models as decision support tools, and the knowledge transfer to practice by silvicultural training on example plots. The author is responsible for the network of Bavarian plots which date back to 1860 and comprises the oldest plots in the world (Pretzsch, 2003). The allometry-based individual tree model SILVA (Pretzsch, 2001; Pretzsch *et al*, 2002) the process-based functional-structural model BALANCE (Grote and Pretzsch, 2002), and the visualization programs TREEVIEW and L-VIS (Pretzsch and Seifert, 2000) are developed, parametrized and evaluated, i. a., with the data of these long-term plots. When models supply decision makers with usable scientific knowledge they make the most of the laborious measurements on long-term plots. Especially the development of SILVA 3.0, its establishment and meanwhile routine application for sustainable forest management (e. g. forest management plans, timber supply prognosis, landscape change simulation) in Bavaria and some other states provides valuable experience for writing this paper.

It seems easier to concentrate on a detailed hypothesis about processes and structure on organ or cell level and report on its scrutiny, than to sketch the state-of-the art of analyzing and modelling whole stand dynamics, outline deficits of knowledge integration and requirements of further research. However, the dominating reductionism in science should always be coupled with the intention of integration. Exactly this interplay between reductionism and holism will make the red thread of the following review and perspective.

2 From forest stand to gene level. On the progressive spatial and temporal refinement in analyzing and modelling forest stand dynamics

Like other realms of science forest science looks with an ever-increasing spatial and temporal resolution on the functions and structures in stands, trees, organs etc. This trend towards details is motivated on one hand by human's innate thirst of knowledge, on the other hand by the increasing demand of knowledge by forest practice. Forest functions, wood and non-timber forest products are more and more esteemed, refined, exploited commercially; and that requires information. In the sequel I sketch this tendency towards a more and more deeper system analysis; than I scrutinize, whether forest management participates in this improving knowledge base about forest, stands and stand dynamics; in other words, whether the refined knowledge arrives at the end-user.

Experiments, inventories and measurement of structures and rates

Compared with the first attempts to survey forest land by usage of ell-chains, today's laser scanner inventories deliver more detailed results about forests (Figure 3, left resp. right). At the beginning of forest science, stand growth was measured and conceptualized as standing volume (cubic meter, cubic feet) per unit area (acre, hectare). Tree diameter or tree height were auxiliary variables for getting an accurate standing volume, i. e., they are measured as a means to an end (Cotta, 1821). Compared with agriculture, where a crop can be easily mowed and weighted in order to get biomass or volume, forest stands require labor-intensive sampling and up-scaling. Their sheer size in relation to size of humans requires particular tricks and techniques of sampling and measurement (Prodan, 1965).

Fig. 3. Progressing spatial and temporal refinement of measurements in forests. Forest inventory by means of an ell-chain according to Stephano and Libalto (1598, p. 566) (left) and 3D measurement on the crane-experiment plot Freising 813/2 near Kranzberg by terrestrial laser scanning in the year 2006 (right).

With rising appreciation of wood, beside quantity also quality aspects as stem dimension and form became relevant. On the early long-term experimental plots, which were established since 1860 and from which some are under survey till today, e. g., stem diameter and tree height were measured in order to get mean values for the stand and sum values for the expected yield (Prodan, 1965). Such surveys were repeated in 5 or 10-years-intervals in order to get increment and yield information.

The so far stand oriented approach was refined towards a population approach or even individual tree approach by distinguishing tree classes (Kraft, 1884), by inventory of crown sizes (Assmann, 1970), stem quality (Burschel und Huss, 1987) and growing space (Oliver and Larson, 1990). While such individual oriented approaches were exceptions before (Reventlow, 1879), since 1950 numerous long-term plots were upgraded by such additional measurements. Successive measurement of, e. g., crown projections, height to crown base, or length of sun crown, transformed former stand-oriented to individual-oriented and spatial explicit experiments (Pretzsch, 2002). By stem analysis and biomass measurements at selected trees on those plots the shift from stand to individual tree research is underlined.

In order to mitigate the effect of soil impoverishment by litter raking, wood exploitation or inappropriate stocking, in order to analyze the consequences of air pollution by fumes from smelting or steelworks, and aiming at assessing the effects of amelioration and fertilization, the recorded number of variables was raised again in the second half of the 20th century (Assmann, 1970; Ellenberg et al., 1986). Above ground tree and stand attributes like leave biomass, leaf area, leaf color, stem quality, crown morphology, or anomalies of branching and ramification were recorded. And in addition to the so far measured structural variables a completely new type of variable was considered: e. g., physiological, resp., physical rates of assimilation, respiration, transpiration, water and sap flow in phloem and xylem, radiation and light absorption in the canopy, or flow of water and nutrient solution in plant and soil.

As such measurements in the field are always superimposed by a number of disturbances which can not be controlled, e. g., weather conditions, pollutants, and insect activities, green house and chamber experiments followed. They enable ceteris paribus conditions while particular factors like CO_2, O_3, temperature or radiation were regulated. Soon scientists recognized, that the results of such chamber experiments are highly evident, however, they are often not relevant. Mature trees under field conditions don't behave always alike juvenile members of the same species under artificial cover (Matyssek et al., 2005; Ulrich, 1999).

Hunting for evidence is important for scientific progress and publication and it nourishes a large scientific community. Relevance of knowledge is something more profane and merely important for the factual real world. That's the reason why experiments

drill deeper and deeper from form and structure to allometry and phenotype, from phenotype to primary and secondary metabolism, to proteom, transcript and gene level. At best, links between one or two of the hierarchical levels are traced; but mostly the link to a practically relevant level is missing. For most central European countries even the application of knowledge on gene level for engineering genetically improved plants plays a minor role, due to the negative valuation of such products by the society (cf Figure 1). A more and more detailed analyses of stands and ecosystems is not inevitably a forward movement concerning knowledge which is relevant for ecosystem management. This is not a speech against basic research, however, it is plea for keeping a closer link to the real world by scale-overlapping experiments, evaluations, and model approaches.

From proxy variables to "first order" factors for explanation and estimation of stand and tree growth

The attempt to assess, classify, explain or even estimate primary production, growth, or yield for a given forest stand by causal variables is inherent in forest research since the first tentative experiments in the 18th century (Assmann, 1970). However, the approaches became more and more mechanistic and focused on the primary resource and environmental variables (Figure 4). Moving forward to an improved understanding by first order factors (resource supply and environmental conditions) on a selected number of experiments, science drifted more and more apart from the very restricted set of site characteristics which are available under normal practical conditions (Gadow, 2005). So, we consider a growing split-off between evident cause-and-effect relationships between growth and underlying factors revealed for a few selected sites and a rather shallow knowledge about site-growth relations regarding the rest of the forest. The rich experience of forest research in application of "surrogate variables" or "proxy variables" (Oliver and Larson, 1990; Zeide, 2003) combined with the tendency from "deductive" towards "inductive" knowledge derivation for ecosystem management (Spellmann, 1991; Spellmann et al., 2001) indicates the way to bridge this precarious gap.

Examples for the application of a "surrogate variable" or "proxy variable" are the use of age-height records for estimation of stand growth, growing area or growing space for the estimation of a tree's resource supply, or application of competition indices for the estimation of height and diameter increment of an individual tree in dependence on limited resource supply. In all cases the first order factors remain unsolved, however, replaced by auxiliary variables, which circumscribe the hidden relationship and are easy to measure, but somehow unspecific and provisional. A "deductive" approach derives most of the relevant planning variables from general models and was hardly equipped with locally inventoried information about increment, growth and site conditions. In contrast, currently arising "inductive" approaches base mainly on locally available information from inventories and
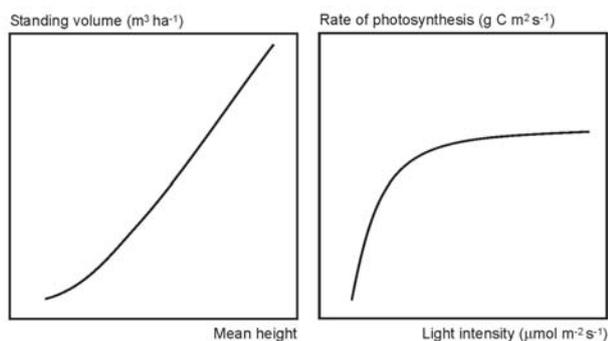

Fig. 4. Progressing refinement of growth and yield estimation from empirical to mechanistic approaches. Estimation of standing volume of a stand in dependence on stand height according to Eichhorn (1902) (left) and estimation of primary production in dependence on first order causes like light intensity etc. (Grote *et al.*, 2002) (right).

monitoring.

Initially, in the 18th Century, the standing stem volume of forest stands was applied for the classification of a site into a site quality system (Pressler, 1877).

$$\text{Site fertility class} = f\,(\text{standing volume}) \qquad (1)$$

Then the site fertility class was applied to estimate growth and yield, e. g.,

$$\text{Volume increment} = f\,(\text{site class}). \qquad (2)$$

This classification was somehow circular; the standing volume had first to be estimated in order to classify the site fertility class, in order to classify afterwards the site productivity. If at all, this approach only made sense as long as light and moderate thinning was common. With the change to more intensive management concepts in the 19th Century the thinning component of total production increased such that standing volume became an increasingly poorer indicator for the site fertility.

As the relationship between stand age and stand height correlates closely with total stand production (Eichhorn, 1902) and is less dependent on treatment measures, it provides an alternative for the previously used approach (Baur, 1876, 1881; Perthuis de Laillevault, 1803). Thus, the use of age and mean height

$$\text{Site fertility class} = f\,(\text{mean height, stand age}) \qquad (3)$$

for the classification of stand growth was established despite some reluctance in the beginning (Heyer, 1845). Estimation of stand growth and yield is based on the relationship

$$\text{Stand growth} = f\,(\text{site fertility class, stand age}). \qquad (4)$$

With intensification of thinning from below, which significantly influences calculations of mean height, a switch was made in the mid 20th Century towards the top height as an indicator for site fertility (Assmann, 1970). The notion of using stand volume or height growth as a "phytometer" for the productivity of a site has continued to the present day. However, this approach is again being questioned when forest practice turned to thinning from above in management regimes, and to structurally diverse mixed stands. The more a stand deviates from an even-aged, single-layered structure, the greater the influence of density and competition on the relationships between age and height and the less is the indicative value of age-height records for site fertility. Especially in rich structured mixed stands, mean and top height are hardly indicators for site fertility, rather result of the competitive process in the understorey.

Heyer (1845) had stressed the need for yield studies to be directed not exclusively towards the natural yield, but towards the investigation and gauging of "first order site factors", like temperature, nutrient supply, radiation etc.. One step into this direction made Cajander (1926). By developing a system of forest types for boreal forests and identification of corresponding yield characteristics for these types he enabled growth and yield estimation by assessment of forest floor vegetation as indicator (species lichens, mosses, grasses, herbs, shrubs). While the growth and yield estimation by indicator plant became standard in the rather uniform and undisturbed boreal forests, considerable heterogeneity and human influence conflict a transfer of this approach to central European forests.

However, the core of Cajander's idea was to combine locally available indicator variables for classifying a particular stand with growth and yield information deduced from site-related yield tables. The increasing availability of site information and growth and yield data from inventories lead to an growing interweaving between locally acquired information about site, growth and yield on the one hand and general growth and yield relationships deduced from models. Moosmayer and Schöpfer (1972), Wykoff *et al.* (1982), and Wykoff and Monserud (1988) developed relationships between site conditions and growth on tree or stand level by regression analysis

$$\text{Volume increment} = f\,(\text{stand attributes, site characteristics}). \qquad (5)$$

As independent variables are used metrical scaled information (e. g., annual precipitation, mean temperature, slope, exposition), nominal (e. g., levels of nutrition supply, levels of water supply), and ordinal (e.g., eco-region, degree of disturbance of top-soil by machines) scaled variables. A further step into this direction was made by Kahn (1994), who used a set of nine metrically scaled site variables for the estimation of the potential height growth, volume growth, and yield.

On a selected set of free air experimental areas,

monitoring plots, and chamber experiments, driving variables (environmental conditions, resource supply) as well as metabolic, physiologic, and growth process were studied in more and more refined spatial and temporal resolution. E. g. temperature is measured per day, hour or minute; radiation is recorded separately for different wave length and used to estimate biomass increment, according to the following approach

$$\text{Primary production} = f \text{ (leaf area, radiation, temperature, nutrient, water).} \qquad (6)$$

Simultaneously assimilation rate, respiration, height and diameter increment are recorded, so that parameters for refined estimation of gross production (gC min^{-1}) can be parameterized. Inventories, monitoring, and innovative regionalization methods are on the way, which deliver all relevant driving variables for such first order approaches, which already Heyer (1845) had in mind.

Knowledge about site-growth relation makes the backbone of forest growth models, and the availability of site variables is decisive for the applicability of models.

Forest stand models: From early experience tables to eco-physiologically based computer models

Before forest scientists understood even some of the basic processes governing tree growth, considerable empirical knowledge had accumulated through observation to quantify tree growth. While based on observation and not first order causes, it is no less a contribution to understanding how trees grow and what

affects them by looking at the way they respond in the forest stand. The presented progression from prototypes of stand oriented growth models, the pure stand tables from Schwappach (1893) and Wiedemann (1932), through to stand simulators for management purposes followed by eco-physiological process models as research tools (Figure 5) reflects the advance in forest ecosystems knowledge, the change in the aims of forest modelling, and the development of a theory of forest dynamics.

With a history of over 200 years yield tables for pure stands may be considered the oldest models in forest science and forest management. They model forest growth from stand level data, and represent in tabular form all important stand parameters (stem number, mean height, mean diameter, basal area, form factor, cumulative annual increment, total production and mean annual increment) in pure stands for defined treatments at five year intervals (Pretzsch, 2001). From the earlier experience tables (Cotta, 1821; Paulsen, 1795) at the end of the 18th Century, based on estimations or restricted measurements, through the first standardised yield tables (Gehrhardt, 1909; Schwappach, 1893), based on long-term observations, and subsequently the computer supported yield table models (Assmann and Franz, 1963; Schmidt, 1971) followed by yield tables produced by stand simulators (Franz, 1968; Hradetzky, 1972), models of this generation have become a decisive information base for sustainable volume production. Early experience tables are based on approaches following Equation (1) and (2), further developed yield tables applied Equations (3) and (4) for estimation of growth any yield in dependence on
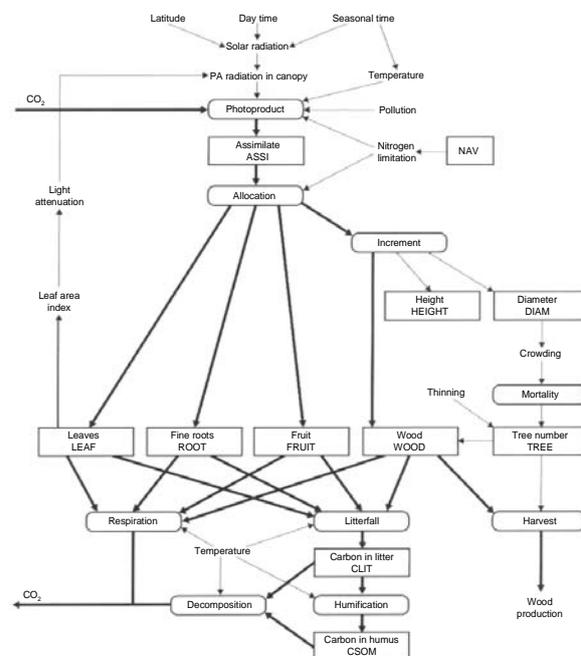
Fig. 5. Models for forest stand dynamics in past and present. Early experience tables according to Cotta (1821, p. 17) (left) and eco-physiological model approach according to Bossel (1994, p. 10) (right).

surrogate variables for site fertility like, e. g. site index or vegetation type.

In the 1960's a second generation of models was initiated, which, in addition to stand level data, also produced stem number frequencies and size classes to enable improved predictions of log grades and production values. Differential equation models (Moser, 1972), distribution extrapolation models (Clutter and Bennett, 1965) and stochastic evolution models (Suzuki, 1971) served this purpose in that they abstracted the development dynamics of even-aged homogeneous pure stands from the shift in the stem number-diameter distribution along the time axis.

Individual-tree models nominate a much higher level of resolution for the abstraction of systems and modelling (Newnham, 1964; Ek and Monserud, 1974; Nagel, 1996; Pretzsch *et al.* 2002; Wykoff *et al.* 1982). They divide the stand into a mosaic of single trees and model their interactions as a spatial temporal system with the computer. The level of description is identical to the level of biological observation, and the information unit in the model (individual tree) is equally the basic unit of the stand. As single-tree models contain feedback loops between stand structure and growth they have greater complexity and flexibility than their precursors. We define position-dependent and position-independent individual-tree models as approaches in which stand competition has been modelled with, and without consideration of the spatial distribution pattern (stem coordinates, distances between tree pairs, crown parameters) respectively. Pretzsch (2001) reviews relevant approaches of competition indices, which form the core of such models, as they steer the individual tree's increment. By summarising and aggregating the changes in the situation of all individual trees stand level data required in forestry can also be produced (Pukkala, 1987; Sterba *et al.* 1995).

Small area or gap models reproduce the growth of single trees in forest patches (e.g., 100 m^2 areas) in relation to the prevailing mean growth conditions at the site (Shugart, 1984; Leemans and Prentice, 1989). As, in these models, the relationships between environmental conditions and growth are partially statistically described and partially explained in term of their eco-physiology, they plot a middle course between statistically based single-tree models and eco-physiological oriented models. They are used for investigating the occurrence of competition and succession in close to nature forests. Individual-tree and gap models estimate increment on tree or stand level, following Equation (5) with a combination of surrogate variables and primary factors as independent variables.

Eco-physiological process models project the reproduction of tree and stands from first order processes such as photo-production, respiration, or carbon allocation (Bossel, 1994; Mäkelä and Hari, 1986). They are based on basic physical, chemical and eco-physiological relationships as much as possible and apply statistical representations only for bridging knowledge gaps. These models predict the primary production on individual tree level (Grote and Pretzsch, 2002) or stand level (Landsberg, 1986, 2003) and also provide information about carbon, nitrogen and water cycles, thereby supporting a comprehensive understanding and management of ecosystems. Backbone of such model approaches are estimations of primary production following Equation (6). Due to the large demand for initialised data, time series of determinants of growth and their connection to a powerful computer, the eco-physiologically based process models have till now primarily served as research tools. However in future they will become increasingly involved in practical uses; especially the integration of structure beside functioning pave the way to practical relevance (Kurth, 1999). The increasing demand for information about forest ecosystems and the desire to understand and predict the responses of forest ecosystems to disturbances requires a degree of complexity inherent only in eco-physiological process models.

3 Deficiencies of analyzing and modelling forest stand dynamics. Suggestions for solutions

The present trends in environmental policy, forest practice and information technology influence research topics in various ways. However, in the sequel we ask rather how practically relevant knowledge can be achieved and processed towards decision makers, than which topics should be addressed by research. Although the main message is rather epistemological and conceptual, examples line the red thread.

Scale overlapping experiments, monitoring, and inventories in forests

Structures and processes can be analysed on different temporal and spatial scales, which reach from seconds to centuries, respectively from gene to mineral or regional level (Figure 6). The slow processes on large spatial scale fix the boundary to quicker processes on smaller scales. The other way round the quick and spatially bounded processes determine the processes on higher levels. The processes result in particular patterns and structures; e. g. branching, foliage coverage, tree rings, species composition in stands. If processes result in specific structure, the structures can serve as indicators for the processes, which are generally more difficult to assess (Ulrich, 1999). In section 2 we revealed a continuous tendency for experiments and models towards a refinement of temporal and spatial resolution. With other words, forest research tends more and more from the practically relevant levels +2 or +1 towards levels -1, -2, -3 (cf Table 2).

Integration of knowledge means either linkage between different system attributes investigated on the same level of organization in terms of temporal or spatial order or it can be achieved by linkage of investigation results from different levels (cf Table 2). Both linkages can be boiled down to a vector of link variables, which enable a relationship between research results.

We call the linkage between different attributes on the same level a horizontal linkage; the corresponding vector of link variables is named $\overrightarrow{hlink}$. Structural

Table 2. Processes in forest ecosystems, ordered according to their temporal and spatial scale with resulting scale-specific patterns and structures (adapted from Ulrich, 1999).

	Process unit	Process duration	Spatial compartment	Pattern / indicator
+2	*System regeneration in centuries (ecosystem)*			
+1	Stand developement (changes of pools in biomass / humus)	Decades	Forest stand (ecosystem section)	Age class / matter budget of the soil
0	Element cycle	Year	Tree / tree groups	Matter budget of the ecosystem
-1	Developement of plant organs (leafs, fine roots, fruits, wood)	Weeks-month	Tree + forest floor vegetation	Tree foliation
-1	Decomposition		Soil horizon	Humus form
-2	Assimilation / matter uptake	Hours-weeks	Leaf / root	Carbon and ion allocation
-2	Mineralisation		Soil aggregate	Soil solution chemistry
-3	*Fast reacting biochemical processes on cell or mineral level*			

system attributes, e. g., leaf area index, standing volume, diameter distribution, stand density, maximum diameter of trees, crown length, height to the crown base, or ring width, play an important role for horizontal knowledge integration. For instance, quantification of diameter distribution, standing volume and lying dead wood is comparatively easy to measure but closely related to occurrence of rare species of birds, beetles, and butterflies, which are much more difficult to record (Gadow, 2005).

Understanding of forest stand or tree dynamics requires at least measurements on two hierarchical levels, e. g., natural regeneration and mature stand, stand and tree, tree and organs (Matyssek *et al.*, 2005). Explanation means derivation of a symptom on level n by details revealed on level n-1. For that purpose the respective system attribute has to be measures on different vertical levels; as they aim at a vertical integration we call such variables or vector of variables $\overrightarrow{vlink}$. Usually integration of the knowledge on the lower level not at all enables to reproduce structure and process on the higher level: A detailed understanding and analysis of individual tree growth is hardly able to reproduce stand dynamics, as mortality, self-thinning and adaptation to crowding emerges on stand level, not on tree level. However, in order to trace the behaviour over the regarded levels, we have to measure the same system trait over different levels. Successive measurement of standing volume and volume increment on individual tree and stand level enables revelation of missing information which is essential for understanding and for scaling up.

Link between experiments, inventories and monitoring

Due to the long history of forest research in Europe experimental plots, monitoring systems, grids of inventories aren't designed on a drawing board. On the contrary, early long-term experimental plots are rather scattered, most inventories follow a systematic grid, stations for environmental monitoring are scattered

again as they should represent archetypical sites and ecosystems. In order to keep a link between different types of experimental plots, inventory and monitoring plots on grids, the concept of eco-coordinates is supportive. Eco-coordinates $\overrightarrow{ecocoord}$ form a vector of state and driving variables and comprise, i. a., first order or surrogate variables like mean annual temperature, precipitation, and length of the growth period; height above sea level, exposition, and slope; vegetation type, eco-region, soil water characteristics, nutrient supply; relevant information about matter import and export. Only if at least a subset of such eco-coordinates are recorded, the respective plot and its scientific contribution can be integrated into existing knowledge, classification systems, or identified eco-regions; and thus it can be used for teaching, model building and model evaluation. Without such a link, plots deliver fragmented unconnected knowledge, hardly usable for understanding or management. The other way round $\overrightarrow{ecocoord}$ can be used to identify such experimental plots which are representative for a particular stratum and display archetypical pattern and functioning.

Link between models and inventories. From deductive to inductive approaches

In particularly two features of modern forest inventories are worth noting, as they can improve information supply for ecosystem management considerably:

Current inventories move somehow towards models as they deliver start or initial variables for simulation runs (cf Figure 2). While yield tables applied mainly stand height and stand age as link between inventory and model, current inventories provide detailed information about standing volume, diameter distribution and even spatial explicit information about the stand structure like stem co-ordinates, height to crown base or crown length. As stand dynamic is closely related with the initial stand structure,

utilization of this information can raise the accuracy of the predictions. Stand structure generators are available which complete the set of required start values by replacement of incomplete data sets or missing values by appropriate estimates and serve as flexible linkage between models and inventory data (Nagel, 1996; Pretzsch, 1997).

Successive inventories on fixed permanent plots provide information about stand and tree growth. When at best primary information about environmental conditions and resource supply is available, this data can be used to parameterize the relationship between site fertility and productivity. The advantage over conventional model parameterization on the basis of long-term experimental plots is obvious: Inventories cover a much broader range of site conditions and stand structures. So, even when plots with unknown history are left out, the remaining datasets are more extensive and representative compared with experimental data (Gadow, 2005).

A somehow provisional but applicable solution for calibration of site-growth relationships in those cases when first order factors for growth are not available on inventory plots was recently proposed by Klemmt (2007). He applied data-mining algorithm to inventory data for detection of strata with similar pattern of height growth. After semi-automatic classification and revelation of relevant classification variables (e. g. proxy variables for site conditions, eco-region) potential height growth is modeled for these strata on the basis of the assigned inventory data. Finally a rule-based system assigns the correct height growth pattern to each stratum in dependence on the decisive classification variables. Such relations are use as backbone in growth and yield models as they set the site-specific potential growth, density etc. (Equation 5).

The utilization of inventory data as start values for simulation runs and for the derivation of site-growth relations represents an inductive approach. In this case information for modelling and simulation are induced from the inventory data itself, while former approaches deduced growth and yield prognosis from general models (Böckmann *et al.*, 1998; Spellmann, 1991). As the underlying mechanisms remain a black box such statistical approach does not allow extrapolation to changing site conditions. However, the method extracts as much information as possible out of the existing local data and thus delivers useful site-growth relationships for short term prognosis of stand dynamics.

Model development

The review of the existing model approaches and current line of research reveals a progressive split into two different model approaches: On the one hand empirically based models with rather limited input and output variables, however, accurate predictions for those managers who are closely involved in forests, which are managed primarily as wood-production systems. On the other hand, mechanistic, eco-physiologically based models. They require an extensive and just occasionally available set of input variables, however, such models deliver a broad set of output variables for managers concerned with future directions of forest development, long-term considerations, and environmental policy. While the empirically based models deliver just a minor part of the criteria and indicators $\bar{c}$ resp. $\bar{i}$ for sustainability, mechanistic models have the potential to cover most of them. Such a split between empirical and mechanistic approaches may be an acceptable solution for those countries where plantations for intensive wood-production are separated from forests for conservation of biodiversity or recreation. For European forests, where ecosystem management follows the concept of integration, also model should integrate and deliver ecological, economical and social aspects in order to keep the link to the European ecosystem managers scope of thinking. Planning and decision making in the multifunctional European forests requires analysing and modelling the consequences of different treatment options, e. g., thinning, species selection, regeneration techniques, concerning their long-term consequences for growth and yield, water supply, wood quality, recreation, or esthetical value on stand level. Models should deliver different scenarios in order to reveal the trade-off between different treatment options and make their long-term consequences transparent. The following solutions for further model research are considered:

A first option would be the coexistence of empirical and mechanistic models. With other words, the application of conventional growth and yield models by forest managers for operational purpose and strategic planning of wood-production would remain separated from the application of mechanistic models by ecologists for higher level and long-term planning (Figure 6). Such a coexisting application would deliver accurate information for operational decision making (e.
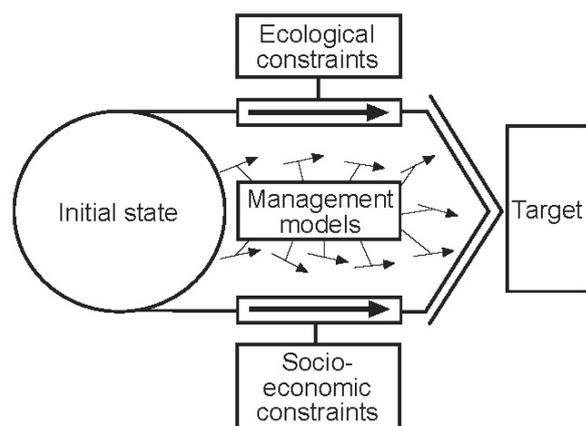

Fig. 6. Management models support decisions within a given decision corridor (framed arrows) by prognosticating the long-term consequences of treatment variants (mobile arrows). The corridor can be explored by application of mechanistic model approaches on stand and landscape level.

g., optimal density, annual cut) and at least conceptual and qualitative useful information for long-term considerations (e. g. climate change, carbon storage, water supply).

A tempting solution is the hybrid model approach, introduced by Kimmins (1993) and Landsberg (2003), but hardly applicable in European forest practice up to now. It aims at an mechanistic estimation of stand primary production by first order factors, and combines it with a statistical allocation of the produced biomass to individual trees. For the latter step expertise of growth and yield research is applied. Hybrid models comprise essential above and below ground processes and deliver a quite extensive list of sustainability variables $\vec{c}$ resp. $\vec{i}$. However, time seems to be not yet ready for a complete integration of mechanistic and empirical model elements and their application in practical management. Initial values are hardly available, existing approaches are overloaded and unbalanced with respect to the resolution of the integrated processes, and evaluation of hybrid models is at the early beginning. Compared to growth and yield models hybrid approaches are even more complicate to apply and far from being accepted or established in practice.

In view of these existing hurdles a well-aimed long-term convergence of both approaches is the favourite course and can be supported as follows: Development of a simple hybrid model by boiling down existing mechanistic approaches, linkage between mechanistic estimation of stand level production with empirical and allometry-based allocation procedures on tree level, and extensive evaluation on the basis of existing experimental plots (Zeide, 2003). An equipment of such simplified hybrid models with all relevant decision variables, a close contact to end-user in order to assure acceptance, and an integration into the information process of forest management would unfold the potential of such models.

Application of hybrid models requires definition and supply of standardized initial variables $\overrightarrow{initial}$ and relevant driving variables $\overrightarrow{resenv}$ indicating the resource supply and environmental conditions. In order to assure accuracy and acceptance of such models in future, a set of evaluation variables $\overrightarrow{evaluate}$ has to be defined and a standard set of output variables with respect to sustainability variables $\vec{c}$ resp. $\vec{i}$.

The initial variables $\overrightarrow{initial}$ can comprise inventory and monitoring data concerning present standing volume, stand structure, species condition; especially spatial information is highly relevant for an accurate prognosis of the further development. Resource supply and environmental condition $\overrightarrow{resenv}$ encompass proxy variables like code for the respective eco-region, elevation over sea level, however, in future more and more primary information like temperature, precipitation, radiation, nutrient supply etc, will be available with a reasonable temporal and spatial resolution. Environmental monitoring is nowhere further developed than in Central Europe; the

bottleneck is the integration, regionalisation, and processing of the results for practical application. The strength of the conventional growth and yield models was their extensive evaluation and high accuracy. For evaluation of future hybrid models vector $\overrightarrow{evaluate}$ of evaluation variables has to be defined; it should comprise both, variables on eco-physiological level like GPP and NPP as well as biomass growth and yield (Figure 7).

Extremely helpful for the convergence of mechanistic and empirical growth and yield models is the breakdown of gross photoproduction GPP (tC ha^{-1} y^{-1}), to net primary NPP (= GPP-losses by respiration), and finally to net biomass growth NG (=NPP-losses by turnover, mortality, dead of inner xylem). Mechanistic models estimate GPP or NPP on stand or tree level, while growth and yield models estimate NG. The more the site-specific relations between GPP, NPP and NG are quantified by assessing, i. a., respiration, turnover, and die-off in the inner xylem of trees, the better the potential of widely available growth and yield data can be applied for evaluation of Equation (6) as the decisive mechanistic part of hybrid models. Respiration, transpiration, and turn-over consume plenty of resources and modify the environmental factors to such an extend, that their integration in hybrid models will mean a effective step towards a completion of the vectors $\vec{c}$ resp. $\vec{i}$ (cf. Table 1).

Towards landscape level. Visualization

Decision for one or another management option is strongly influenced by normative values and esthetic aspects (Paivio, 1971; Stölb, 2005). By visualization of scenario results on stand or landscape level the long-term consequences of different species composition, thinning strategies or regeneration
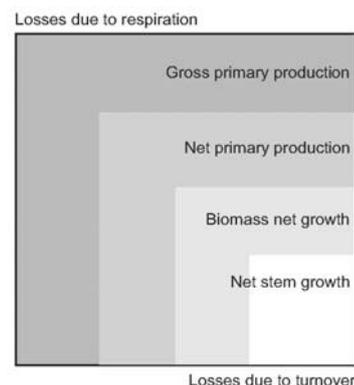

Fig. 7. Revelation of the relationship between primary production and volume increment is essential for convergence of mechanistic and empirical growth models. The breakdown of gross photo-production GPP (tC ha^{-1} y^{-1}), to net primary NPP (= GPP-losses by respiration), to net biomass growth NG (=NPP-losses by turnover, mortality, dead of inner xylem), and finally to stem volume growth (in schematic representation).

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systems with respect to forest esthetics, recreation value and scenic beauty can be conveyed to decision makers at the round table (Figure 1). From available data of landscape relief, surface structure, stand boundaries and stocking type, three dimensional landscape views can be generated (Wang *et al*., 2006). By coupling with spatial explicit individual tree-based growth models, static records can be assigned to a dynamic view. Figure 8 displays a section of the Municipal Forest of Traunstein in Bavaria visualized with the model L-VIS (Pretzsch and Seifert, 2000). The initial situation (top) forms a 25-years-old mixed stand of Norway spruce and European beech, which was inventoried by permanent sample plots. The stand dynamics of all inventory plots is prognosticated over the next 100 years with the individual tree model SILVA (Pretzsch *et al*., 2002), and the simulation results provide the input data for the visualization model L-VIS. Three management options are modeled and visualized: Development without any management of Norway spruce and European beech (left), development after thinning from above with moderate promotion of European beech (middle), and heavy promotion of beech (right). Without active promotion of beech and with heavy promotion of beech, rather homogeneous stands of Norway spruce (left), resp. European beech (right) would evolve. Beech underlies spruce in this eco-region and fails almost completely until age of 125 due to competition. With moderate promotion at the end of the simulation European beech's share amounts at

least to 20% and maintains the original esthetic expression.

Another demand just briefly mentioned here, is the development of landscape models which comprise forests, grassland, limnetic systems, arable and urban land. They should link these subsystems by exchanges via atmosphere and hydrosphere. The visualization tools TREEVIEW and L-VIS provide interfaces for coupling with such landscape models.

Customizing of models for end-users

The historical separation between research stations, which managed long-term plots and universities, which developed models, resulted in an equivalent separation between software for evaluation of experiments or inventories here and models for prognosis there. However, quite a number of modules in both types of programs perform exactly the same calculations, e. g., fitting of height curves, estimation of stem form, stem volume, and stand biomass. Prognosis models just repeat these steps for a number of successive surveys, but both procedures require exactly the same algorithms. By modularization of these two computer program libraries, they can be combined in one evaluation and prognosis tool. By doing so, only one software has be updated in future, where two different approaches had to be developed, adjusted, and reconciled in the past.

The best way to guarantee model application in practice is to tailor a model as suitable as possible to the requirements of the end-user. We can distinguish
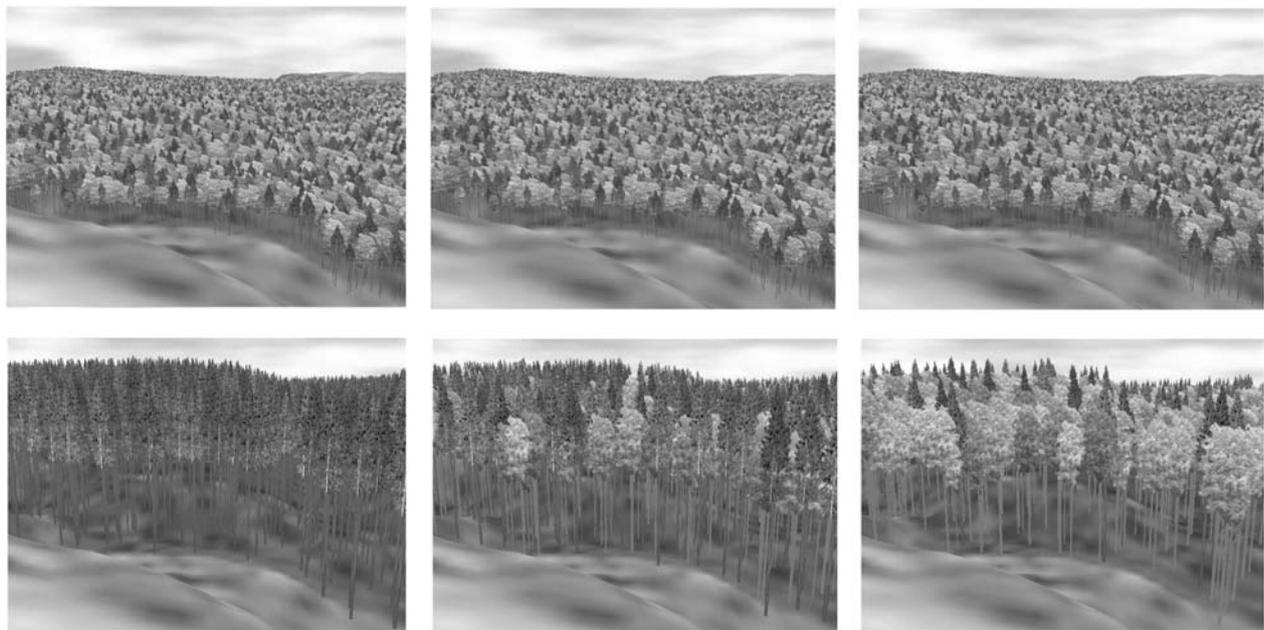

Fig. 8. Visualization at landscape level. Development of a mixed stand of Norway spruce and European beech in the Municipal forest of Traunstein, South Germany, from age 25 to age 125 (from top to bottom). Left column: Without management; middle column: thinned from above with moderate promotion of beech; right column: heavy promotion of beech.

completely different user-groups; a clear separation between graphical user-interface and the model itself makes the customizing easier. Most favorable appears a client-server solution, where the client represents the steering unit with user-interface developed in close contact with the end-user. On the other hand all essential elements like algorithms for estimation of growth, mortality, thinning reactions, and regeneration, are unspecific and run on a server so that they can be combined with different user-interfaces. By means of the user-interface the input of start data for a model run, the output of the simulation results, and the steps of a prognosis process can be specified by sequential usage of different modules of the model.

The following identification of end-users for the model SILVA 3.0 is probably transferable to other models:

(1) A rather unproblematic user group comprises scientists at universities, research stations, experts, and consultants. They apply the model in the interactive mode for a rather limited number of cases, e. g., for analysis of silvicultural operations, for expert's opinion for lawsuits, or economical forest valuation. Usage on the levels stand, enterprise, region, or nation, or even for different countries requires no standard application. This user group familiarizes conscientiously with new demanding tools, adapts existing software easily for their special purposed, and requires the lowest customization, introduction and training.

(2) A very labor-intensive user group are forest managers and planners, responsible for state, municipal, private or communal forests. They apply models for development of silvicultural guidelines, preparation of forest management plans, timber volume prognosis, or assessment of sustainable annual cut. They use SILVA mainly in batch mode for some 1000 - 10.000 inventory plots, calculate several thinning options per plot or stratum, and repeat each run 5-20 times in order to get mean and standard error as results. This user-group requires the development of a transparent and easy user-interface, while enterprise-specific algorithm are developed and integrated permanently as special selectable modules, e.g., modules for stratification of inventory data, thinning options, assortment rules, or harvesting techniques. Especially in this user group models meet on a general scepticism or ignorance towards software application in forestry. For some users models seem to be a threat to their silvicultural expertise and they call the former knowledge monopoly in state forest headquarters into question. Remedies for these hurdles are training courses, model application in team work, technical support of scenario analysis and treatment of the results as internal affair of the enterprise. Students education in model application helps to overcome the skepticism towards models; finally, like in other management sectors, demographical shift will pave the way for modern decision support tools.

(3) A considerable group of lecturers, trainers, teachers, and consultants for private and communal forests apply the model SILVA for education, teaching, or advisory services. Like private asset consultants,

these users apply software to base their advice on calculations and quantitative analyses of different options. For this purpose they use the interactive version of SILVA and they simulate just a few stands and silvicultural options to show striking and simplistic the effect of alternative decisions. In the case of any insecurity and reservation towards simulation results we supply such users with a set of pre-calculated scenarios for archetypal forest stands and management options. Those calculations are selected and worked out together with the users in advance. After approval by the model development team, such pre-calculated scenario results are prepared for the lecturers for their teaching and consultancy work.

4 Conclusions

Behind the trend towards a more and more detailed analysing and modelling of ecosystems is primarily human's innate thirst for knowledge. Our mechanistic understanding concerning forest dynamics comes from a limited number of experimental stations, where system dynamics is analysed in high spatial and temporal resolution. Often it turns out that evidence on gene, cell, or organ scale doesn't mean relevance on tree or stand scale (Zeide, 2003). Processes on lower levels (e. g., gene, transcript, organ) can be buffered and thus become irrelevant for system behaviour on higher levels. Forest dynamics, for instance, can not be understood merely by analysing organ or tree growth, as stand level processes like self-thinning or adaptation to density emerge on stand level. Evidence found at one experimental station can't be simply transferred to another site, due to divergence with respect to site conditions, stand structure, species provenance, or genotype. So, in forest science it is difficult to scale up, even more difficult to generalize, and hardly possible to lay down site-independent "rules of thumb" for management. If forest management applies any scientific knowledge at all, then it is integrated knowledge about stand level or landscape level, rather than scattered details about system functioning, as interesting as they are. In contrary to the reductionism in science, system management requires integration and a holistic view upon the system in question.

Models can bridge the gap between increasing but more and more detailed and scattered system knowledge and increasing information demand about dynamics on stand level. Models shouldn't dictate, but support decisions and training by prognosis and scenario analysis. Prerequisite for a successful development, integration and application of models requires further research and development, specified in the sequel.

(1) The following aspects of stand dynamics are persistently neglected by forest science and thus hardly integrated in decision support models: Systematic research about dynamics of mixed stands, interaction between species, effect of mixture on growth, yield, stability, disturbances, and risk are at the early beginning. Also in pure stands, some aspects of trees' and stands' growth processes are neglected: Resource allocation to growth and defence, adaptation, and

allocation of resources to reproduction. Finally, European forest research is still practised on a green island, without the necessary links to the landscape level; quantitative connections with grassland system, arable land and urban landscapes are not yet established.

(2) For a considerable spectrum of system variables plenty of knowledge is available, however, it is not quantitatively linked with knowledge from other sectors. With the aid of suitable link variables, $\overrightarrow{hlink}$ resp. $\overrightarrow{vlink}$, relationships between different topics and results from different hierarchical levels can be integrated. Variables like diameter distribution, lying dead wood, or maximum stem diameter, quantify stand structure and enable a quantitative link towards stability, biodiversity, and potential habitats within this stand. Only some few additional measurements are required to enable such linkages. Such links are initially based on statistical relationships, however, they can be based more and more on mechanistic knowledge, when knowledge grows. In view of the demanded criteria and indicators for sustainable management, we can't wait for a first order explanation of such links, but have to bridge missing mechanistic knowledge by statistical relationships.

(3) Currently applied management models already go beyond conventional growth and yield output variables, but they are far away from covering all relevant criteria and indicators for sustainable ecosystem management (Table 1). Especially information about criterion 2 (chemical soil state, matter import and export, defoliation), criterion 4 (habitats, species diversity), and criterion 5 (protection of climate, water, soil) are rather incomplete. A convergence of empirical and mechanistic model approaches could remedy these deficiencies: Future hybrid models, on the one hand simple enough with respect to input data, driving variables, and application, on the other hand sufficiently mechanistic to display matter and energy flow. Many relevant components for building such hybrid models are already available; its rather a question of simplification, integration, standardization and modularized programming, and evaluation, to realize such models. A commitment of standardized initial variables $\overrightarrow{initial}$, driving variables $\overrightarrow{resenv}$, and evaluation variables $\overrightarrow{evaluate}$ will foster the development of such models, their linkage with inventory data, and their integration into the data flow of forest management and planning.

(4) Forest practice is far away from an accurate estimation of net primary production or net biomass growth in dependence on first factors like radiation, temperature, water availability, and nutrient supply. However, data from forest inventories offer a provisional solution. They can be applied as start values for simulation runs. And by methods of classification and data mining site-growth-relationships can be induced from the inventory data itself, while former approaches deduced it from general models. Until sufficient data for a really mechanistic estimation of growth is available the calibration of models by inventory-based site-growth-relationships can bridge the knowledge gap. Such approaches apply proxy variables for coding site conditions and rules for assigning net growth to classified eco-units.

(5) Client-server solutions enable an optimal combination of two model software attributes: The client can be tailored for the respective end-user
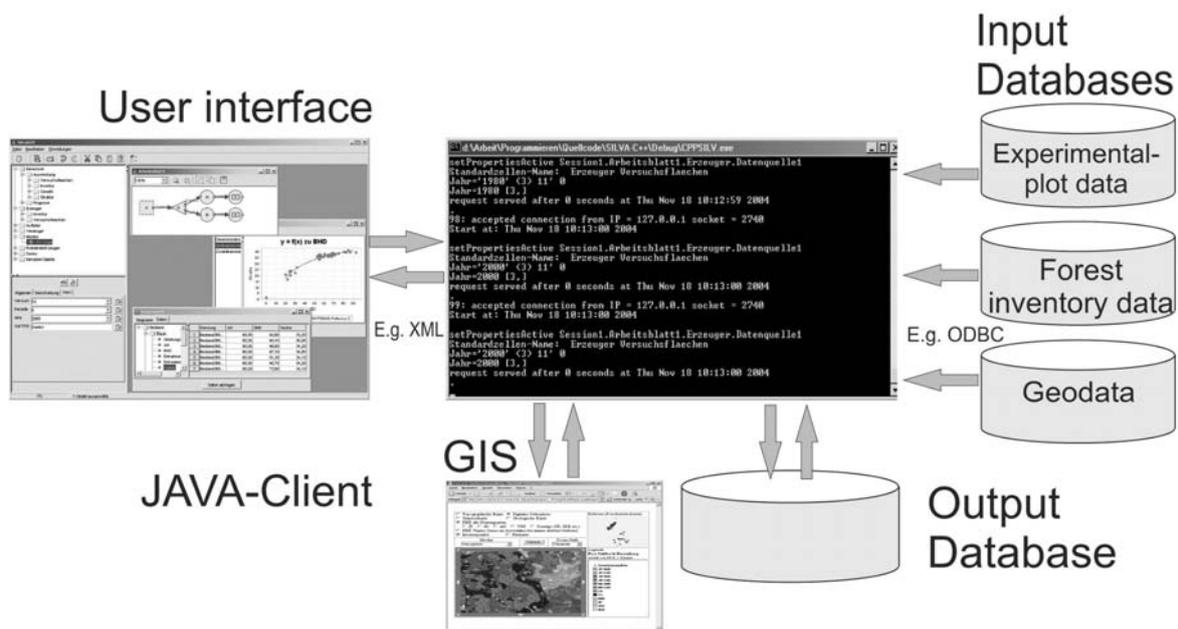

Fig. 9. Client-server solution for the management model SILVA 3.0: Main elements are the client with the user-interface, the server with the simulation model, the linkages to different data bases for the input of start values for simulation runs (e. g., inventory data, geo-data) and output of results (e. g., criteria and indicators of the system state).

without interference in the program code located on the server. The user-interface's complexity depends on the addressed user group; scientific application need more flexibility than long-term prognoses, following a standard set of scenarios for thinning and final cut. The more modularized the model itself is, the easier are exchanges with other research groups, model extensions, convergence of so far separated algorithms for evaluation and prognosis.

(6) The more diverse the demands on a forest, the more complicate and discouraging becomes planning and decision making. However, this should not cause the retreat to basic research, it rather underlines the urgent need for appropriate concepts and tools for decision support. Currently we consider a trend towards a „toolization" of planning; developers shower tools upon users who can hardly cope with these manifold models. But tools are only helpful, if they fit exactly into the concept and data flow of the planning procedure. Guiding principles and concepts for future planning are scenario analysis including visualisation and optimisation. The consequences of different planning options should also be foreseeable on landscape level, what requires quantitative linkages between forests, grassland and arable land. However, up-scaling on landscape level necessitates primarily quantitative analysing and modelling of forest stand dynamics.

5 Variable description

Each of the following vectors represents a set of variables, relevant for analysing and modelling forest stand dynamics:

$\vec{c}$, $\vec{i}$ list of criteria, resp., list of indicators for ecological, economical and social sustainability

$\overrightarrow{hlink}$ variables, suitable for the link between ecosystem attributes from the same hierarchical level, e. g., between stand structure and habitats within the stand

$\overrightarrow{vlink}$ variables, suitable for the link between ecosystem attributes from different hierarchical level, e. g., link between tree and stand level

$\overrightarrow{ecocoord}$ Metrically, ordinal or nominal scaled variables which indicate the resource supply and environmental conditions at a given growing place. The variable set can comprise primary variables (e. g., annual precipitation, length of vegetation period) as well as proxy variables (e. g., elevation above sea level, slope, eco-region)

$\overrightarrow{initial}$ present stand variables, which can be applied as start or initial values for simulation runs; e. g., diameter distribution, height, stem-coordinates

$\overrightarrow{resenv}$ standard set of driving variables for hybrid models, comprising a subset of $\overrightarrow{ecocoord}$

$\overrightarrow{evaluate}$ standardized set of variables for model validation, e. g., primary production, net biomass growth, standing above ground biomass

References

Assmann E. (1970) The principles of forest yield study. Pergamon Press, Oxford, New York, pp. 506.

Assmann, E. und Franz, F. (1963) Vorläufige Fichten-Ertragstafel für Bayern, Institut für Ertragskunde der Forstlichen Forschungsanstalt München, pp. 104.

Baur, F. von (1876) Die Fichte in Bezug auf Ertrag, Zuwachs und Form, Stuttgart.

Baur, F. von (1881) Das Forstliche Versuchswesen I, Stuttgart, pp. 359.

Böckmann, Th, Saborowski, J., Dahm, St., Nagel, J., and Spellmann (1998) Die Weiterentwicklung der Betriebsinventur in Niedersachsen, Forst und Holz, 53:219-226.

Bossel, H. (1994) TREEDYN3 Forest Simulation Model. Mathematical model, program documentation, and simulation results. Berichte des Forschungszentrums Waldökosysteme, Reihe B, Bd. 35, Göttingen.

Burschel, P. and Huss, J. (1987) Grundriß des Waldbaus. Pareys Studientexte 49, Hamburg, Berlin, pp. 352.

Cajander, A. K. (1926) Theory of forest types. Acta Forestalia Fennica 29, 1-108.

Clutter, J. L. und Bennett, F. A. (1965) Diameter distributions in old-field slash pine plantations, Georgia For. Res. Council Rep., No. 13, p. 1-9.

Cotta, H. von (1821) Hülfstafeln für Forstwirte und Forsttaxatoren, Arnoldische Buchhandlung, Dresden, pp. 80.

Eichhorn, F. (1902): Ertragstafeln für die Weißtanne. Julius Springer Verlag, Berlin, pp. 81.

Ek, A. R. and Monserud, R. A. (1974) Trials with program FOREST: Growth and reproduction simulation for mixed species even- or uneven-aged forest stands, In: J. Fries (Ed.) Growth models for tree and stand simulation, Royal College of Forestry, Research Notes, Nr. 30, p. 56-73.

Ellenberg, H., Mayer, R. and Schauermann, J. (1986) Ökosystemforschung. Ergebnisse des Solling-Projekts, Ulmer, Stuttgart, pp. 507.

Franz, F. (1968) Das EDV-Programm STAOET - zur Herleitung mehrgliedriger Standort-Leistungstafeln, Manuskriptdruck, Ludwig-Maximilians-Univesität München, München pp.

20.

Gadow, K. von (2005) Forsteinrichtung. Analyse und Entwurf der Waldentwicklung. Universitätsverlag Göttingen, Göttingen, pp. 342.

Gehrhardt, E. (1909) Über Bestandes-Wachstumsgesetze und ihre Anwendung zur Aufstellung von Ertragstafeln, Allg. Forst- und Jagdztg., 85: 117-128.

Grote, R. und Pretzsch, H. (2002) A model for individual tree development based on physiological processes, Plant Biology, 4: 167-180.

Hanewinkel, M. (2001) Neuausrichtung der Forsteinrichtung als strategisches Managementinstrument, Allg. Forst- und J.-Ztg., 172: 203-211.

Heyer, C. (1845) Wedekinds Neue Jahrb. 30:1-127 (Cited by Assmann, 1970).

Hradetzky, J. (1972) Modell eines integrierten Ertragstafel-Systems in modularer Form, Ph. D. thesis, Univ. Freiburg i. Br., pp. 172.

Kahn, M. (1994) Modellierung der Höhenentwicklung ausgewählter Baumarten in Abhängigkeit vom Standort, Forstliche Forschungsberichte München, Vol. 141, pp. 221.

Kimmins, J.P. (1993) Scientific foundations for the simulation of ecosystem function and management in FORCYTE-11, Information Report NOR-X-328, Forestry Canada, Northwest Region Northern Forestry Centre, pp. 88.

Klemmt, H.-J. (2007): Anwendung von Entscheidungsbaumverfahren und Regressionsanalysen zur semiautomatischen Feinkalibrierung des Wuchsmodells SILVA mit Hilfe von Forstinventurdaten, Dissertation, Technische Universität München, Freising-Weihenstephan, pp. 228.

Kraft, G. (1884) Beiträge zur Lehre von den Durchforstungen, Schlagstellungen und Lichtungshieben, Klindworth's Verlag, Hannover, pp. 147.

Kurth, W. (1999) Die Simulation der Baumarchitektur mit Wachstumsgrammatiken. Wissenschaftlicher Verlag Berlin, Berlin, pp. 327.

Landsberg J. (1986) Physiological Ecology of Forest Production. Academic Press, London, Orlando, New York, pp. 198.

Landsberg, J. (2003) Modelling forest ecosystems: state of the art, challenges, and future directions. Can. J. For. Res. 33: 385-397.

Leemans, R. and Prentice, I., C. (1989) FORSKA, a general forest succession model, Inst. Ecol. Bot., Univ. Uppsala, Meddelanden fran Växtbiologiska Institutionen, Vol. 2, pp. 45.

Matyssek, R., Agerer, R., Ernst, D., Munch, J.-C., Oßwald, W., Pretzsch, H., Priesack, E., Schnyder, H. and Treutter, D. (2005) The plant's capacity in regulating resource demand, Plant Biology, 7: 560-580.

Mäkela, A. and Hari, P. (1986) Stand growth model based on carbon uptake and allocation in individual trees, Ecological Modelling, Vol. 33, p. 205-229.

MCPFE (1993) Resolution H1: General guidelines for the sustainable management of forests in Europe. In: Proc 2nd Ministerial conference on the protection of Forests in Europe, Helsinki, Finland, pp. 5.

Moosmayer, H.-U. and Schöpfer, W. (1972) Beziehungen zwischen Standortsfaktoren und Wuchsleistung der Fichte, Allgemeine Forst- und Jagdzeitung, 143: 203-215.

Moser, J. W. (1972) Dynamics of an uneven-aged forest stand, Forest Science, Vol. 18, p. 184-191.

Nagel, J. (1996) Anwendungsprogramm zur Bestandesbewertung und zur Prognose der Bestandesentwicklung, Forst und Holz, 51: 76-78.

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

Oliver D.O and Larson, B. C. (1990) Forest Stand Dynamics, Biological resource management series, McGraw-Hill, Inc., New York, pp. 467.

Paivio, A. (1971) Imagery and Verbal Processes, Holt, Rinehart and Winston, New York, pp. 592.

Paulsen, J. C. (1795) Kurze praktische Anleitung zum Forstwesen. Verfaßt von einem Forstmanne, Detmold, Hrsg. von Kammerrat G. F. Führer, pp. 152.

Perthuis de Laillevault, R., de (1803) Traité de l'aménagement et de la restauration des bois et forêts de la France, Madame Huzard, Paris, pp. 384.

Pressler, M. (1877) Forstliche Zuwachs-, Ertrags- und Bonitierungs-Tafeln mit Regeln und Beispielen, Selbstverlag, Tharandt, pp. 72.

Pretzsch, H. (1997) Analysis and modelling of spatial stand structures. Methological considerations based on mixed beech-larch stands in Lower Saxony, Forest Ecology and Management, 97: 237-253.

Pretzsch, H. (2001) Modellierung des Waldwachstums, Blackwell Wissenschafts-Verlag, Berlin, Wien, pp. 341.

Pretzsch, H. (2002) Grundlagen der Waldwachstumsforschung, Blackwell Verlag, pp. 414.

Pretzsch, H. (2003) Strategische Planung der Nachhaltigkeit auf Forstbetriebsebene. Forstwissenschaftliches Centralblatt, 122: 231-249.

Pretzsch, H. (2006) Wissen nutzbar machen für das Management von Waldökosystemen. AFZ-DerWald, 61: 1158-1159.

Pretzsch, H. and Seifert, St. (2000) Methoden zur Visualisierung des Waldwachstums, Forstwiss. Cbl., 119: 100-113.

Pretzsch, H., Biber, P. and Dursky, J. (2002) The single tree based stand simulator SILVA. Construction, application and evaluation, Forest Ecology and Management, 162: 3-21.

Prodan, M. (1965) Holzmesslehre, J. D. Sauerländer's Verlag, Frankfurt am Main, pp. 644.

Pukkala, T. (1987) Simulation model for narural regeneration of pinus sylvestris, picea abies, betula pendula und betula pubescens, Silva Fennica, Vol. 21, p. 37-53.

Reventlow, C.D.F. (1879) Forslag til en forbedret Skovdrift grundet, paa Undersogelser over Traeernes Vegetation i Danmarks og Slesvigs Skove. In: Kjobenhavn, 1879, Ed. In English 1960: A treatise of forestry, Society of Forest History, Horsholm, Denmark.

Schmidt, A. (1971) Wachstum und Ertrag der Kiefer auf wirtschaftlich wichtigen Standorteinheiten der Oberpfalz, Forst. Forschungsber. München, Bd. 1, pp. 178.

Schwappach, A. (1893) Wachstum und Ertrag normaler Rotbuchenbestände, Verlag Julius Springer, Berlin, 104 p.

Shugart, H. H. (1984) A Theory of Forest Dynamics. The Ecological Implications of Forest Succession Models, Springer Verlag, New York, Berlin, Heidelberg, pp. 278.

Spellmann, H. (1991) Beiträge der Forsteinrichtung und Ertragskunde für ein forstliches Informationssystem, Forst und Holz, 46:57-65.

Spellmann, H., Hillebrand, K. and Cornelius, P. (2001) Konzept zur Erfassung und Sicherung der Nachhaltigkeit in multifunktional genutzten Wäldern, Forst und Holz, 56: 469-473.

Stephano, C. and Libalto, J. (1598) XV Bücher von dem Feldbau und recht volkommener Wolbestellung eines bekömmlichen Landsitzes, Bernhart Jobins, Straßburg, pp. 763.

Sterba, H., Moser, M and Monserud, R. (1995) Prognaus-Ein Waldwachstumssimulator für Rein- und Mischbestände, Österr. Forstzeitg., H. 5, p. 1-2.

Stölb, W. (2005) Waldästhetik. Über Forstwirtschaft, Naturschutz und Menschenseele. Verlag Kessel, Remagen-Oberwinter, pp. 400.

Suzuki, T. (1971) Forest transition as a stochastic process, Mitt. d. Forstl. Bundesversuchsanstalt Wien, 91. H., p. 137-150.

Ulrich, B. (1999) Entwicklungsprognosen für Waldökosysteme aus der Sicht der Hierarchietätstheorie, Forstw. Cbl., 118: 118-126.

Wang, X., Song, B., Chen, J., Crow, T.R., and LaCroix, J.J. (2006) Challenges in Visualizing Forests and Landscapes, Journal of Forestry, 104: 316-319.

Wiedemann, E., (1932) Die Rotbuche 1931, Mitt. a. Forstwirtschaft und Forstwissenschaft, 3. Jg., H. 1, 189 p.

Wykoff, W. R., Crookston, N. L. and Stage, A. R. (1982) User's Guide to the stand prognosis model, U. S. For. Serv., Gen. Techn. Rep. INT-133, Ogden, Utah, pp. 112.

Wykoff, W. R. and Monserud, R. A. (1988) Representing site quality in increment models: A comparison of methods, In: Ek, A. R., SHIFLEY, S. R., BURK, Th. E. [Hrsg.] Proc. IUFRO conference, Aug., 1987, Gen. Tech. Rep. NC-120, Minneapolis, p. 184-191.

Yaffee, St. L. (1999) Three faces of ecosystem management, Conservation Biology, Vol. 13: 713-725.

Zeide, B. (2003) The U-approach to forest modelling. Can. J. For. Res. 33: 480-489.