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REVIEW

Models for Forest Ecosystem Management: A European Perspective

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• *Background* Forest management in Europe is committed to sustainability. In the face of climate change and accompanying risks, however, planning in order to achieve this aim becomes increasingly challenging, underlining the need for new and innovative methods. Models potentially integrate a wide range of system knowledge and present scenarios of variables important for any management decision. In the past, however, model development has mainly focused on specific purposes whereas today we are increasingly aware of the need for the whole range of information that can be provided by models. It is therefore assumed helpful to review the various approaches that are available for specific tasks and to discuss how they can be used for future management strategies.
• *Scope* Here we develop a concept for the role of models in forest ecosystem management based on historical analyses. Five paradigms of forest management are identified: (1) multiple uses, (2) dominant use, (3) environmentally sensitive multiple uses, (4) full ecosystem approach and (5) eco-regional perspective. An overview of model approaches is given that is dedicated to this purpose and to developments of different kinds of approaches. It is discussed how these models can contribute to goal setting, decision support and development of guidelines for forestry operations. Furthermore, it is shown how scenario analysis, including stand and landscape visualization, can be used to depict alternatives, make long-term consequences of different options transparent, and ease participation of different stakeholder groups and education.
• *Conclusions* In our opinion, the current challenge of forest ecosystem management in Europe is to integrate system knowledge from different temporal and spatial scales and from various disciplines. For this purpose, using a set of models with different focus that can be selected from a kind of toolbox according to particular needs is more promising than developing one overarching model, covering ecological, production and landscape issues equally well.

Key words: Ecosystem management, management paradigms, decision support in Europe, sustainability, models, spatial and temporal scales, scaling, scenario generation, visualization.

INTRODUCTION

A characteristic feature of European, particularly Central European, forest and ecosystem management is the concept of integration. Whereas elsewhere in the world it is common to separate plantations for intensive wood production from forests for nature conservation or recreation, in European forests a multitude of functions is supposed to be fulfilled at one and the same site. Thus, ecological, economical and social functions of forests have to be considered, trade-offs ought to be analysed and decisions made in order to determine and achieve a multipurpose objective. The principle of integration requires more knowledge, negotiations and compromises than the principle of segregation, with a spatial or temporal uncoupling of different forest functions (Spellmann *et al.*, 2001). The more diverse the demands on forest services, the more difficult planning and decision-making become. This 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 demands.

In order to indicate the potentials of knowledge transfer from science into practice, a theoretical concept of how forest and ecosystem management works is employed here. Imagine a particular initial state of a forest, for example a pure stand of Norway spruce. Then forest ecosystem management is equivalent to the development of a target state of the system and the transformation process into this state. The development of a target state, for example a mixed stand of Norway spruce and European beech, is a process of negotiations with concerned people, i.e. forest owners and stakeholders (see Fig. 1, in which the negotiation process is symbolized by the round table). The negotiations are determined rather by normative valuation by the society than by scientific analysis and knowledge. Vague arguments such as ‘beech forests are good as they are attractive and natural’, but ‘spruce forests are bad as they are of low ecological value and artificial’ are often far more easily accepted than they would be in scientific discourse. However, forest science should promote as much system knowledge as possible in the negotiation and decision-making process (Pretzsch, 2006). Only if the target state is defined clearly and formulated quantitatively can practical rules be developed as guidelines for the transformation process (feedback loop in Fig. 1). This reveals the requirements for introducing scientific knowledge into forest ecosystem management: (1) Provision of *target knowledge* for the development of objectives; for example, the species mixture that optimizes different

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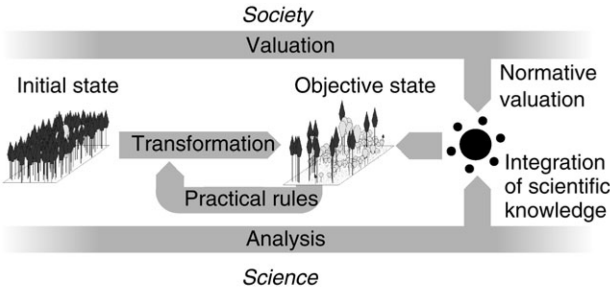


FIG. 1. Concept for the management of forest ecosystems. Starting with an initial state (forest stand, stratum of a forest estate, landscape unit) a system is transformed into a target state. Normative valuation by the society and scientific knowledge contribute to the development and achievement of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

forest services such as recreation demand and economic expectation in a municipal forest. (2) Provision of *transformation knowledge* after the objective has been defined; for example, the most efficient management to transform a plantation into a mixed forest.

The two most helpful support-tools for incorporating system knowledge into the process of target development and knowledge transformation are long-term observation plots and simulation models. Differently treated observation plots provide information about the consequences of particular management options. Models can be used for the generation of realistic scenarios, i.e. they demonstrate the long-term consequences of different options in a virtual reality. Both approaches enable the comparison of treatments with respect to various forestry target variables, e.g. volume production, stand structure, carbon storage, biodiversity, recreation value or stand stability. Given that forest management can hardly wait for the experimental evaluation of new concepts (in contrast to many other branches of natural sciences), the particular advantage of models is the fast provision of target values under a range of given conditions. This is illustrated in Fig. 2, which shows how a stand with a given initial state develops with respect to system variables ($i_1, \ldots, i_n$) if treatment A, B, C or D is applied. Scenario treatments are: (A) no management at all, (B) moderate thinning, (C) threshold diameter thinning and (D) classical clear-cut system. Scenario calculations can be repeated for various land-use options. The comparison itself as well as the selection of a particular option can be carried out with the help of optimization or multi-criteria analyses, possibly using sophisticated decision support tools (e.g. Hanewinkel, 2001). However, discussion of these tools is outside the scope of this review. Instead, we concentrate on the models that are employed for scenario generation in order to support argumentation and decision-making at the 'round table' independent from the stakeholder involved or forest ownership.

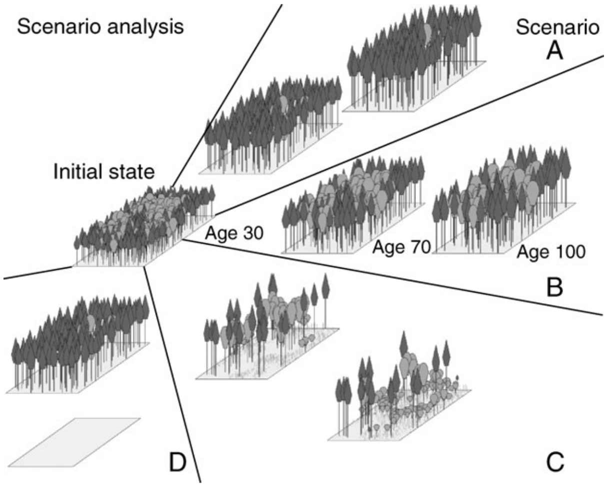


FIG. 2. Scenario analysis with forest stand models. Starting with an *initial state* of an ecosystem, models display the long-term consequences of the different management options A, B, C and D and the consideration of different *objective states*.

Once developed, target states for forests are not at all static, but rather dynamic. Objectives of forest management change with environmental conditions as well as society and economy: looking back and forward, five paradigms of forest ecosystem management can be identified that represent a refinement of the three paradigms considered by Yaffee (1999). They reach from anthropocentric to bio-centric and eco-centric approaches concerning forest ecosystems: (1) multiple uses, (2) dominant use, (3) environmentally sensitive multiple uses, (4) full ecosystem approach and (5) eco-regional perspective. The next paragraph gives a brief overview of the development of these paradigms in Europe.

The first, very early phase that in Europe persisted until the 17th century is characterized by *multiple use* forestry: hunting, bee-keeping, grazing in forests, forest assortment, wood felling and timber use. The mercantilism of the 17th century (need for daily firewood, wood for furnaces, salt works, the demand for construction timber for rebuilding after 30 years of war) resulted in the second phase, the *dominant use* paradigm. Because the forests where heavily exploited, von Carlowitz wrote his *Silvicultura Oeconomica* with the aim of ensuring a sustainable wood supply (von Carlowitz, 1713). Later, the *environmentally sensitive multiple uses* paradigm developed in order to ensure the supply of other goods and services from the forests (such as supply of high-quality fresh water, high recreation value or biodiversity). Utilization of timber was concentrated at specific regions, but was limited or restricted in areas where other services had high priorities. The three approaches – *multiple uses*, *dominant use* and *environmentally sensitive multiple use* – take an anthropocentric perspective and seek to foster human use. The *ecosystem approach*, however, takes a biocentric perspective: it originates from the perception that ecosystems are vulnerable and threatened by exploitation, acid rain, climate change, etc. Sustainable use and conservation are considered a primary ethical value of their own. This approach furthered system understanding and holistic consideration. *Ecoregional management* finally shifted the focus away from the biota and from the species composition of a particular forest towards the regional scale perspective, including the interaction between different land coverage types such as forests, grassland, arable land or limnological systems. These five paradigms do not follow each other in a strict chronological order, but rather reflect particular state values within a continuum: forest ecosystem management moves back and forth within this continuum; for example, the current neoliberalism in Central Europe drives forestry backwards from the ecosystem approach to the sensitive use or even to the dominant use paradigm. In contrast, countries in Asia, South America and Africa are moving at present gradually from dominant use to an environmentally sensitive use paradigm.

In the following, we review different groups of models and discuss their potential to support forest management according to the five paradigms outlined. In particular, we investigate how such models can contribute or have been used for goal setting, decision support and development of operation guidelines. Additionally, we look at the state of current visualization tools that offer a new way to produce information for targets such as recreation value and beauty that cannot easily be expressed in numbers and graphs. To illustrate the potential of models, one example of each type (except yield tables) is used with which representative output variables are produced. Finally, we discuss the ways current models can or should be used in forest planning having in mind the broad range of issues that have to be considered depending on the target paradigm.

OVERVIEW OF MODEL APPROACHES

The history of forest growth models is not simply characterized by the development of continuously improved models replacing former, inferior ones. Instead, different model types with diverse objectives and conceptions were developed simultaneously. The objectives and structure of a model reflect the state of the art of the respective research area at its time, and document the contemporary approach to forest growth prediction. The history of growth modelling thus documents also the extended knowledge about forest functioning and structure.

Beginning with yield tables for large regions as a basis for taxation and planning, model development led on to regional and site-specific yield tables and culminated in the construction of growth simulators for the evaluation of stand development under different management schemes. Vanclay (1994) strived for an overview of growth and yield management models and their application to mixed tropical forests.

The 1960s brought a new trend towards development of eco-physiological models that give insight into the complex causal relationships in forest growth and predict growth processes under various ecological conditions. These models followed the biocentric view that management had to be sustainable in terms of carbon (and nutrient) balance. They first neglected the dimensional changes of trees but were further developed to aid forest management planning in the 1980s. The models were combined with yield simulators or complemented by explicit tree dimensional modelling, assuming either only one average tree, several tree classes or individual trees (for overviews see Battaglia and Sands, 1998; Mäkelä *et al.*, 2000; Le Roux *et al.*, 2001).

With increasing computer power, physiologically based models were applied on the landscape scale in order to serve eco-regional management. Only recently, however, models have been developed that actually consider horizontal flows of energy or matter between the sites. These landscape approaches are still in their early stages. At the same time, progress is also being made with graphical representations at both site and landscape scale, enabling the consideration of visual planning aspects such as landscape beauty.

Maps and yield tables

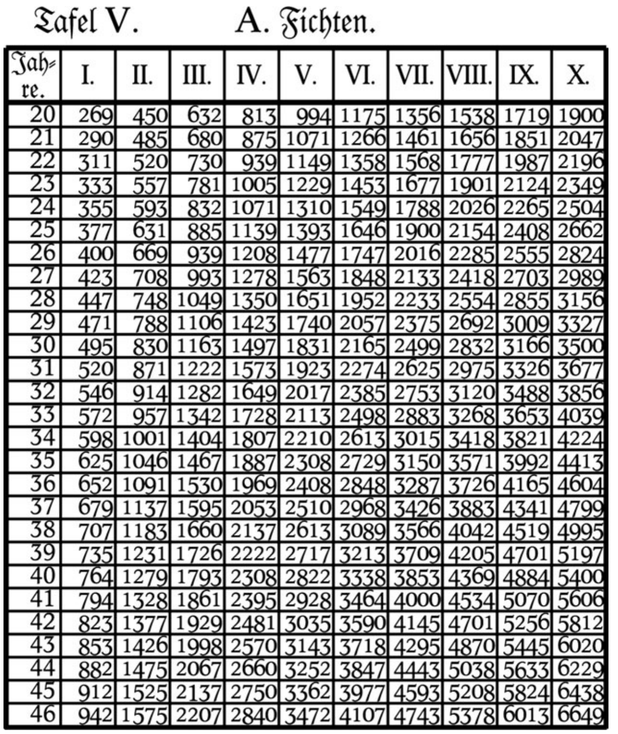
The earliest forest ecosystem models are maps. Displaying the availability and localization of resources such as hunting grounds, bee-hives, forests or forest pasturage, they reflect the multiple uses paradigm (see Fig. 3 for an illustration).

With a history of more than 200 years, yield tables for pure stands may be considered the oldest models in forestry science and forest management. They reflect stand growth over defined rotation periods and are based on long-term measurements of diameter, height, biomass, etc. Early experience applied standing volume for estimation of site fertility and volume growth; further developed yield tables applied mean height and stand age as surrogate variables to provide an indication and estimation of site fertility and growth. From the late 18th to the middle of the 19th century, German scientists such as G. L. Hartig (1795), Paulsen (1795), Von Cotta (1821), Hundeshagen (1825), Th. Hartig (1847), Heyer (1852), R. Hartig (1868) and Judeich (1871) created the first generation of yield tables. As they were based on estimations or rather limited data sets, they were called 'experience tables' and soon revealed great gaps in scientific knowledge (Table 1). In order to close those gaps, a series of long-term measurement campaigns on experimental plots were started. That was the origin of a unique network of long-term experimental plots in Europe, which was kept continuously under survey and expanded until today.

The second generation of yield tables, produced between the end of the 19th century and the 1950s, followed uniform construction principles proposed by the Association of Forestry Research Stations (predecessor organization of the International Union of Forest Research Organisations, IUFRO), and already had a solid empirical data basis. The list of protagonists involved in this work includes names such as Weise (1880), Grundner (1913), von Guttenberg (1915), Krenn (1946), Vanselow (1951), Zimmerle (1952) and, in particular, Schwappach (1893), Wiedemann (1932) and Schober (1972), who designed yield tables that are still being used today. In the 1930s and 1940s, the first models of mixed stands were developed by Wiedemann. Data material from some 200 experimental sites established by the Prussian Research Station led to the widely used yield tables for even-aged mixed stands of pine and beech (Bonnemann, 1939), spruce and beech (Wiedemann, 1942), and oak and beech (Wiedemann, 1939). World War II prevented Wiedemann from finishing the development, but his studies initiated systematic

FIG. 3. Map from the 'Lorenzer Wald' near Nürnberg, Germany, as simple model for forest ecosystem management. By locating forest resources like hunting grounds, beehives, and mature forests ready for harvest this map from Paulus Pfinzing supported the multiple use paradigm in the 16th century (Hilf, 1938, pp. 184–185).

TABLE 1. *Experience table for the yield of various species for light thinning (Von Cotta, 1821, p. 34)*



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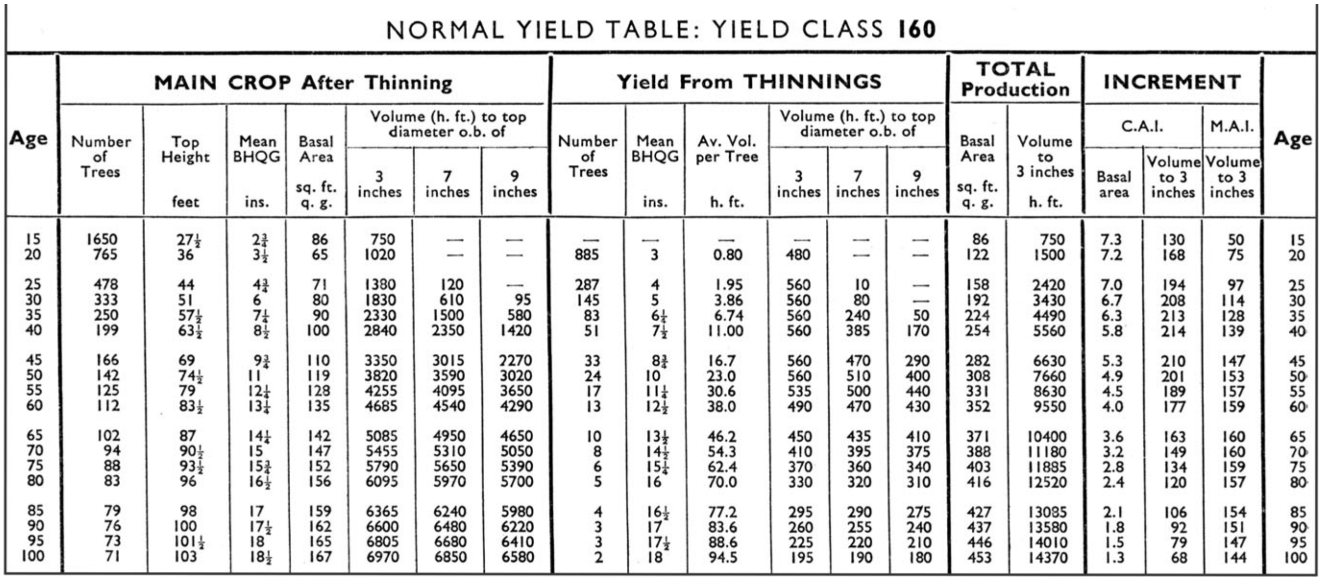
Jahre.	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.
20	269	450	632	813	994	1175	1356	1538	1719	1900
21	290	485	680	875	1071	1266	1461	1656	1851	2047
22	311	520	730	939	1149	1358	1568	1777	1987	2196
23	333	557	781	1005	1229	1453	1677	1901	2124	2349
24	355	593	832	1071	1310	1549	1788	2026	2265	2504
25	377	631	885	1139	1393	1646	1900	2154	2408	2662
26	400	669	939	1208	1477	1747	2016	2285	2555	2824
27	423	708	993	1278	1563	1848	2133	2418	2703	2989
28	447	748	1049	1350	1651	1952	2233	2554	2855	3156
29	471	788	1106	1423	1740	2057	2375	2692	3009	3327
30	495	830	1163	1497	1831	2165	2499	2832	3166	3500
31	520	871	1222	1573	1923	2274	2625	2975	3326	3677
32	546	914	1282	1649	2017	2385	2753	3120	3488	3856
33	572	957	1342	1728	2113	2498	2883	3268	3653	4039
34	598	1001	1404	1807	2210	2613	3015	3418	3821	4224
35	625	1046	1467	1887	2308	2729	3150	3571	3992	4413
36	652	1091	1530	1969	2408	2848	3287	3726	4165	4604
37	679	1137	1595	2053	2510	2968	3426	3883	4341	4799
38	707	1183	1660	2137	2613	3089	3566	4042	4519	4995
39	735	1231	1726	2222	2717	3213	3709	4205	4701	5197
40	764	1279	1793	2308	2822	3338	3853	4369	4884	5400
41	794	1328	1861	2395	2928	3464	4000	4534	5070	5606
42	823	1377	1929	2481	3035	3590	4145	4701	5256	5812
43	853	1426	1998	2570	3143	3718	4295	4870	5445	6020
44	882	1475	2067	2660	3252	3847	4443	5038	5633	6229
45	912	1525	2137	2750	3362	3977	4593	5208	5824	6438
46	942	1575	2207	2840	3472	4107	4743	5378	6013	6649

research on mixed stands. However, within the broad spectrum of possible site conditions, species combinations, intermingling patterns, age structures and thinning options for mixed stands, these yield tables represented only very particular cases that are difficult to generalize. Thus, they were never consistently used in forestry practice.

Yield tables developed by Gehrhardt (1909, 1923) affected a transition from purely empirical models to models based on theoretical principles and biometric equations, and led to a third generation. The core of these models designed by, among others, Assmann and Franz (1963), Vuokila (1966), Schmidt (1971), Hamilton and Christie (1973, 1974) and Lembcke *et al.* (1975) is a flexible system of functions that are based on general natural growth relationships, and parameterized with modern statistical methods. These biometric models have often been transferred into computer programs to predict stand development for a wide range of yield classes and thinning options (Table 2).

Since the 1960s a fourth generation of yield table models has come forward, i.e. the stand growth simulators by Hradetzky (1972), Hoyer (1975), Bruce *et al.* (1977) and Curtis *et al.* (1981, 1982), which simulate stand development not only for different site conditions but also for different planting densities and thinning. Stand development is computed using systems of empirically parameterized equations that form the core of growth simulators. Yield tables obtained in this way reflect the stand dynamic for

TABLE 2. *Normal yield table of Scots pine from Bradley* et al. *(1966)*



NORMAL YIELD TABLE: YIELD CLASS **160**

Age	MAIN CROP After Thinning							Yield From THINNINGS						TOTAL Production		INCREMENT			Age
	Number of Trees	Top Height feet	Mean BHQG ins.	Basal Area sq. ft. q. g.	Volume (h. ft.) to top diameter o.b. of 3 inches	7 inches	9 inches	Number of Trees	Mean BHQG ins.	Av. Vol. per Tree h. ft.	Volume (h. ft.) to top diameter o.b. of 3 inches	7 inches	9 inches	Basal Area sq. ft. q. g.	Volume to 3 inches h. ft.	C.A.I. Basal area	C.A.I. Volume to 3 inches	M.A.I. Volume to 3 inches	
15	1650	27½	2¾	86	750	—	—	—	—	—	—	—	—	86	750	7.3	130	50	15
20	765	36	3½	65	1020	—	—	885	3	0.80	480	—	—	122	1500	7.2	168	75	20
25	478	44	4¾	71	1380	120	—	287	4	1.95	560	10	—	158	2420	7.0	194	97	25
30	333	51	6	80	1830	610	95	145	5	3.86	560	80	—	192	3430	6.7	208	114	30
35	250	57½	7¼	90	2330	1500	580	83	6¼	6.74	560	240	50	224	4490	6.3	213	128	35
40	199	63½	8½	100	2840	2350	1420	51	7½	11.00	560	385	170	254	5560	5.8	214	139	40
45	166	69	9¾	110	3350	3015	2270	33	8¾	16.7	560	470	290	282	6630	5.3	210	147	45
50	142	74½	11	119	3820	3590	3020	24	10	23.0	560	510	400	308	7660	4.9	201	153	50
55	125	79	12¼	128	4255	4095	3650	17	11¼	30.6	535	500	440	331	8630	4.5	189	157	55
60	112	83½	13¼	135	4685	4540	4290	13	12½	38.0	490	470	430	352	9550	4.0	177	159	60
65	102	87	14¼	142	5085	4950	4650	10	13½	46.2	450	435	410	371	10400	3.6	163	160	65
70	94	90½	15	147	5455	5310	5050	8	14½	54.3	410	395	375	388	11180	3.2	149	160	70
75	88	93½	15¾	152	5790	5650	5390	6	15¼	62.4	370	360	340	403	11885	2.8	134	159	75
80	83	96	16½	156	6095	5970	5700	5	16	70.0	330	320	310	416	12520	2.4	120	157	80
85	79	98	17	159	6365	6240	5980	4	16½	77.2	295	290	275	427	13085	2.1	106	154	85
90	76	100	17½	162	6600	6480	6220	3	17	83.6	260	255	240	437	13580	1.8	92	151	90
95	73	101½	18	165	6805	6680	6410	3	17½	88.6	225	220	210	446	14010	1.5	79	147	95
100	71	103	18½	167	6970	6850	6580	2	18	94.5	195	190	180	453	14370	1.3	68	144	100

a wide range of possible management scenarios. Although model output was still identical to that of yield tables of earlier generations, simulator-created yield tables now describe just one of many potentially computable stand developments.

Despite a number of drawbacks, yield tables still form the backbone of sustainable forest management planning. As computing capacities, data availability for model development and information demand in forestry have increased, mean value and sum-orientated growth models were partially replaced. Nevertheless, they are still highly valued in forestry management. Prodan (1965, p. 605) commented on the significance of yield tables in the context of silviculture and forest sciences as follows: 'Undoubtedly, yield tables are still the most colossal positive advance achieved in forest science research. The realization that yield tables may no longer be used in the future except for more or less comparative purposes in no way detracts from this achievement.'

Growth- and yield simulators

Stand-orientated management models predicting stem number frequency. During the transition towards new intensive management concepts the information demand in forestry changed. Emphasis has been put on individual tree dimensions instead of average stand values. This resulted in the development of growth models predicting mean stand values as well as frequencies of individual tree dimensions (Fig. 4). Stem number frequencies in diameter classes are, for example, needed for precise prediction of assortment yield and overall stand value. Depending on their concept and structure, stand-orientated growth models considering stem number frequency are divided into differential equation models, distribution prediction models and stochastic evolution models. However, although frequently used in other parts of the world, this model approach did not obtain much practical relevance in Europe.

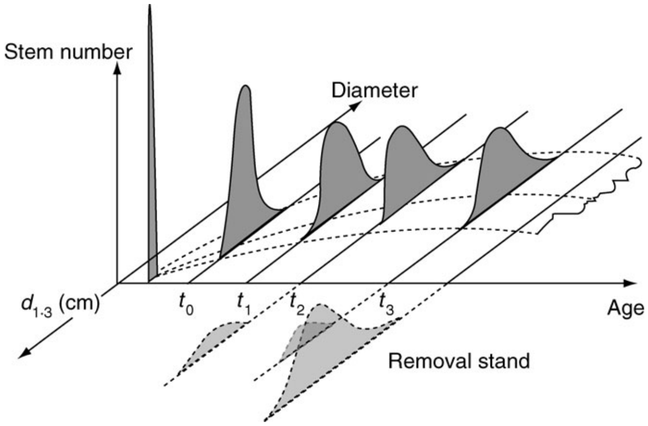


FIG. 4. Principle of management models predicting the shift of the diameter or height distribution along the *x*-axis (after Sloboda, 1976).

In the 1960s and 1970s, Buckman (1961), Clutter (1963), Leary (1970), Moser (1972, 1974) and Pienaar and Turnbull (1973) developed stand-orientated growth models based on differential equation systems. These models predict the change of stem number, basal area and growing stock within a given diameter class dependent upon initial stand characteristics. Development of the growth and yield characteristics within the diameter classes results from numerical integration of differential equations. In the mid-1960s, Clutter and Bennett (1965) suggested a completely new approach to stand development modelling. They characterized the condition of a tree population by its diameter and height distribution and described stand development by extrapolation of these frequency distributions. The precision of such models is decisively determined by the flexibility of the applied distribution function. The suitability of different distribution types (e.g. Beta, Gamma, Lognormal, Weibull or Johnson distribution) has to be assessed individually. In these models, in contrast to those reviewed earlier, stand development is controlled by the parameters of the underlying frequency distribution. Models of this type were further developed by McGee and Della-Bianca (1967), Bailey (1973), Feduccia *et al.* (1979) and von Gadow (1987).

The term 'evolution models' for stochastic growth models is derived from the fact that in these models, stand development evolves from an initial frequency distribution, e.g. from a diameter distribution known from forest inventory. These models predict individual stem dimensions rather than mere distributions of tree properties (Fig. 4). The mechanism used for the extrapolation is based on a Markov process, giving the transition probability for the shift between the diameter classes (Kouba, 1973). Stochastic growth models were introduced into forest science by the pioneering investigations of Suzuki (1971, 1983). These growth models, e.g. for pure stands of *Chamaecyparis* sp., have been elaborated by Sloboda (1976) and his team. Stand-orientated growth models based on stochastic processes have also been developed for mixed stands by Bruner and Moser (1973), and Stephens and Waggoner (1970).

Individual tree-orientated management models. Individual tree models represent a much higher level of resolution for the abstraction of systems and modelling than stand models (Newnham, 1964; Ek and Monserud, 1974; Wykoff *et al.*, 1982; Nagel, 1996; Pretzsch *et al.*, 2002). They explicitly simulate the development of single trees considering their interactions within a spatial–temporal system. The basic information unit in the model is the individual tree, which is at the same time the basic unit of stand development. This enables models in principle to simulate pure and mixed stands of all age structures and intermingling patterns equally well. Because individual-tree models account for feedback loops between stand structure and individual growth (Fig. 5), they have to be more complex but are also more flexible than their precursors. We can distinguish between position-dependent and position-independent individual tree models as the two approaches that represent competition either with or without accounting for the spatial distribution pattern (stem coordinates, distances between tree pairs, crown parameters). In Pretzsch (2001), the relevant approaches for the compilation of competition indices are reviewed. These indices form the core of such models and control the increment of an individual tree. Stand-level data for forestry management are provided by aggregation of the single tree results (Pukkala, 1987; Sterba *et al.*, 1995).

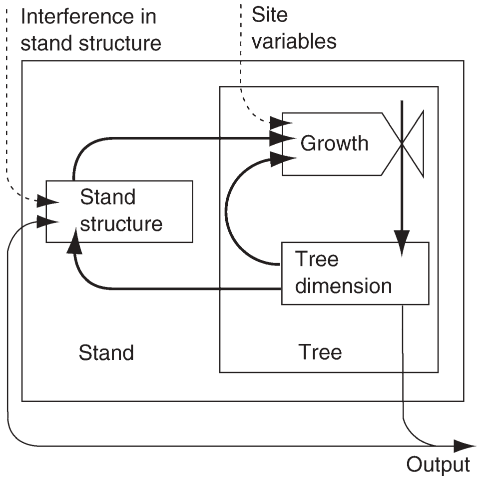


FIG. 5. Simplified system diagram of the growth model SILVA 2·2 with the levels stand and tree, the external variables inference in stand structure and site conditions and the feedback loop stand structure → growth → tree dimension → stand structure.

The first single-tree model was developed for pure Douglas fir stands by Newnham (1964). It was followed by other developments for pure forests of Arney (1972), Bella (1970), Mitchell (1969, 1975) and others. In the mid 1970s, single tree-orientated growth models were applied to uneven-aged pure and mixed stands (Ek and Monserud, 1974). The worldwide bibliography of single-tree growth models compiled by Ek and Dudek (1980) lists more than 40 different single-tree models, which group into about 20 distance-dependent and distance-independent models each. Single-tree models developed since the 1980s (e.g. Van Deusen and Biging, 1985; Wensel and Koehler, 1985; Wykoff *et al.*, 1982) have put more emphasis on user-friendliness, which was supported by the rapidly improving computer facilities.

Only recently has this kind of model been applied in forestry practice for management planning in pure and mixed stands (Pukkala, 1987; Kolström, 1993; Sterba *et al.*, 1995; Nagel, 1996; Pretzsch, 2003; Pretzsch *et al.*, 2006). The site sensitivity of these models is derived from basic eco-physiological knowledge as well as a wealth of growth and yield data. Version 2·2 of SILVA, a model developed in Germany for pure and mixed stands (Pretzsch, 1992; Pretzsch and Kahn, 1996; Kahn and Pretzsch, 1997; Pretzsch *et al.*, 2002), is presented below as an example for this category.

Gap and hybrid models. 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 (Botkin *et al.*, 1972; Shugart, 1984; Leemans and Prentice, 1989). In contrast to the models already discussed that calculate potential growth from site conditions and derive individual development from competition, in gap models environmental conditions act directly on individual growth. These relationships are generally considered separately and are based on physiological knowledge. However, physiological processes are not explicitly accounted for, requiring statistically fitting procedures between each environmental factor and growth development. Thus, they represent a middle course between statistically based and eco-physiologically orientated models (see also Bugmann, 2001). The major focus is on the development of competition and succession in close-to-nature forests, but thinning algorithms are seldom considered [with few exceptions such as the SORTIE model (Pacala *et al.*, 1993; Menard *et al.*, 2002)].

In general, individual-tree as well as gap models estimate the growth increment dependent upon a combination of surrogate variables and primary factors using regression procedures. As independent parameters, metrical information (e.g. annual precipitation, mean temperature, slope, exposure), and nominal (e.g. levels of nutrition supply, levels of water supply) and ordinal (e.g. eco-region, degree of disturbance of topsoil by machines) scaled variables are used.

The transfer of specific eco-physiological process knowledge to stand or single tree management models that are evaluated with long-term growth measurements results in so-called hybrid growth models (Kimmins, 1993). Their intention is to combine plausible responses to new combinations of environmental conditions with reliable growth estimations suitable to assist forest planning and management. Owing to species-specific relationships to site conditions they can be applied to pure and mixed stands alike. In Europe, few developments of this kind have been presented (e.g. Hauhs *et al.*, 1995) and neither gap models nor hybrid models have been found reliable enough to reach any practical relevance as management tools. In other countries, however, hybrid models are more commonly used for calculating plantation growth (e.g. Baldwin *et al.*, 2001; Schwalm and Ek, 2004), and for tropical forest management the gap type models FORMIX and FORMIND (Huth *et al.*, 1998; Köhler and Huth, 1998) have been used to address sustainability and nature preservation issues.

Matter-balance models

Compared with growth and yield models, mass or matter-balance models focus on the description of carbon balance, and in some cases also of nitrogen balance, based on biogeochemical processes. They are therefore also known as biogeochemical or process-based models. These models have in common that they consider vegetation development primarily as a change of matter in different compartments based on uptake (e.g. photosynthesis) and loss (e.g. senescence) processes that in turn depend on environmental conditions (e.g. temperature or water availability). This category includes models that were developed for a wide range of scales and purposes that can be differentiated broadly as follows:

(1) Models that provide only stand-scale biomass development throughout one or few years such as the PnET family (Aber and Federer, 1992; Aber *et al.*, 1995, 2002; Li *et al.*, 2000) or BIOMASS (Bergh *et al.*, 2003). These models usually provide detailed carbon and nitrogen balances and are thus primarily used to estimate ecological issues such as carbon sequestration and nutrient sustainability.

(2) Forest growth models that include forestry relevant issues such as height and stem volume at the stand scale, usually running over one generation, such as EFIMOD (Komarov *et al.*, 2003), TREEDYN3 (Bossel, 1996), FORGRO (Mohren, 1987; Mohren *et al.*, 1995), FINNFOR (Kellomäki and Väisänen, 1997; Matala *et al.*, 2003) and 3-PG (Landsberg *et al.*, 2001, 2003). This type of model aims to provide forest yield estimations considering environmental impacts, including climate change.

(3) Single tree or tree cohort models that are primarily designed to represent forest development over several generations. Models such as 4C (Bugmann *et al.*, 1997; Lasch *et al.*, 2005), or PICUS (Lexer and Hönninger, 2001) feature several similarities with conventional gap models but differ by their explicit consideration of a closed carbon balance. They are particularly useful for the definition of long-term forest management directions in order to provide forest services (e.g. species selection to ensure sustainable yield or sufficient protection from erosion).

(4) Structural–functional single tree models. Most examples, however, such as LIGNUM (Perttunen *et al.*, 1998; Lo *et al.*, 2001) or EMILION (Bosc, 2000), are capable only of simulating a few small trees. Nevertheless, developments such as BALANCE (Grote and Pretzsch, 2002; Rötzer *et al.*, 2005) use a relatively simple structure but still represent the individual development of separate crown parts. With such models small stand sizes of mature trees have been represented, showing that this model type could eventually be used to aid single tree management in mixed forests and still dynamically consider various site conditions.

The given examples of each type are by no means meant to represent the full spectrum of available models in this field. It should also be noted that in the past few decades some models have shifted their primary purpose. Examples are the EFM (Thornley, 1991) or BGC models (Running and Gower, 1991; White *et al.*, 2000), which had been developed to simulate carbon and nitrogen balances and were later modified to cover stand dimensional variables for management purposes (Korol *et al.*, 1996; Thornley and Cannell, 2000; Petritsch *et al.*, 2007). Another approach is to modularize existing models to couple them to soil process or gap models (e.g. Peng *et al.*, 2002; Wallman *et al.*, 2005). In general, and eased by increasing computational capabilities, there has been a trend towards more complex models in each of the fields outlined above, which reflects a desire to consider a larger number of processes, impacts and feedbacks within the forest system. What are the benefits and drawbacks of this development? To answer this question, it is necessary to gain an overview of the processes and environmental impacts considered in matter-balance models.

The basic processes that are used in practically any model of this type are photosynthesis and respiration (or net carbon gain), allocation and senescence. For photosynthesis calculation, many different approaches are available, reaching from empirical light response curves to the explicit description of biochemical reactions that consider light, temperature and nutrient effects in an integrated way (see overview in Farquhar *et al.*, 2001). Respiration is usually divided into a fraction that depends linearly on growth and one that describes maintenance requirements as a function of biomass and temperature. Models of higher complexity only differentiate a larger number of biomass fractions. This deficit in self-regulating capacity has been recognized as representing a bias in physiologically based simulations. An interesting alternative has therefore been suggested by Thornley and Cannell (2000) who proposed a dependency on non-structural carbon availability, nitrogen concentration and nitrogen uptake using very few generally valid parameters. Although, for example, the allocation of carbon to compartments with slow and fast turnover is crucial for growth simulations (Poorter and Nagel, 2000; Barton, 2001), existing rules for this process are still very simplistic (see overview in Lacointe, 2000). Many approaches have been suggested reaching from empirical partitioning coefficients, functional balance and optimality principles, to resistance mass-flow and source-sink focused models (see Le Roux *et al.*, 2001). However, the control of environmental effects and the distribution of carbon into regenerative compartments, defence, exudates and mycorrhiza are far from being understood. Similarly, senescence or turnover of tissues is generally empirically described and rarely depends on environmental conditions or developmental stages. For overviews of the different representations of these processes in growth models the reader is referred to Constable and Friend (2000), Landsberg (2003) and Le Roux *et al.* (2001).

Due to these generalizations, actual forest yield predictions without any guiding empirical functions are not yet very precise. Simulations are furthermore complicated because all of the described processes depend on the availability of water and nutrients. Thus, the processes are not only directly connected by means of carbon transfer but also indirectly linked due to their use and depletion of resources. It is therefore not surprising that the majority of matter-balance models have been applied to ecological rather than to economic questions.

Model developments of type 2 are driven by the expectation that modelling progress on the representation of resource availability and distribution, as well as better descriptions of physiological processes, will improve the performance of conventional analyses such as growth and yield studies. This has been principally supported by Johnsen *et al.* (2001), who reviewed process-based models in terms of their suitability for management purposes and concluded that further research, particularly of soil processes, is needed. Further improvements would also broaden the range of model applications with respect to new environmental questions. However, with increasing number of resources considered, the computational effort, error propagation, and demand on knowledge about direct and indirect linkages between processes will also increase. In particular, the consideration of tree and stand structural complexity in structural–functional models is highly demanding on initialization and dynamic resource distribution processes.

Landscape models

The provision of ecosystem services depends crucially on the spatial arrangement of landscape elements and their interactions. For example, site-specific species composition and forest growth affect the probability of fires due to changes in fuel availability. Other examples are the impact of interception and transpiration processes on the risk of flooding and the effect of structural properties such as rooting depth and stand density on mass movements. Regional pattern of disturbances, on the other hand, impact species composition, accumulation of biomass and other stand properties.

Landscape models comprise a broad class of spatially explicit models that incorporate heterogeneity in site conditions, neighbourhood interactions and potentially feedbacks between different spatial processes. However, they differ widely in how detailed forest structure and matter fluxes are represented, and which interactions between spatial processes are taken into account.

In a management context, the role of these models is to assess potential effects of environmental change (climate, deposition, land-use changes) on landscape-scale sustainability of forest functions (resources, protection, socio-economic). This knowledge is useful, on the one hand, to inform responsible decision-making that aims to influence the course of environmental change (mitigation). On the other hand, it can guide direct management that aims to broaden the range of environmental conditions under which ecosystems services can be sustained (adaptation).

The first important area where landscape models are used is to analyse the relationship between landscape forest structure and regionally distributed risks. Examples include fire risks (Mouillot *et al.*, 2001, 2002; He *et al.*, 2004), windthrow risks (Ancelin *et al.*, 2004; Cucchi *et al.*, 2005; Zeng *et al.*, 2007), insect diseases (Lexer and Hönninger, 1998; Sturtevant *et al.*, 2004), mass movements (Kulakowski *et al.*, 2006), air quality (Schaab *et al.*, 2000; Parra *et al.*, 2004), water availability (Strasser and Etchevers, 2005) and water quality (Matjicek *et al.*, 2003). Although it is increasingly recognized that the long-term development of regionally distributed risks in response to environmental changes needs to take ecosystem properties into account that are themselves inevitably linked to those changes, landscape models that include the full feedback cycle from disturbance regimes to terrestrial dynamics and back are still scarce. Examples of such a development are applications of gap models in combination with regional assessments of fire risk (Laurence *et al.*, 2001; Weinstein *et al.*, 2005; Schumacher *et al.*, 2006).

A second application of landscape models are assessments of regional-scale matter fluxes, e.g. water, carbon and nutrients. This requires not necessarily a particularly designed type of model but is generally carried out with site-specific (matter-balance) models that are applied with global information system (GIS) data on a regional scale. Examples of this type of application concern the regional state or dynamic of specific ecosystem properties such as forest growth (e.g. Lasch *et al.*, 2002; Nuutinen *et al.*, 2006), species change (e.g. Hickler *et al.*, 2004), carbon budgets (e.g. Song and Woodcock, 2003) or changes in the water balance of catchments (e.g. Baron *et al.*, 2000; Wattenbach *et al.*, 2005). Other investigations have been concerned with more specific applications such as soil acidification (Alveteg, 2004) or nitrogen emissions (Kesik *et al.*, 2005, 2006). These analyses show a number of shortcomings because the applied models do not always account for the dynamics in both matter fluxes and forest structure. Important variables such as canopy coverage and leaf area index are often assumed to be constant in water and nutrient balance studies although they are closely linked to species composition and tree size distribution that continuously change. On the other hand, site conditions that are determined by water and nutrient availability are often assumed to be constant in forest growth studies. This is generally not the case because of changes in climate, deposition or soil weathering. In models that simulate the development of species composition it is the relationship between sensitivities to different environmental factors that is implicitly assumed to be constant. Again, these are likely to change with a changing relationship between the availability of different resources. The simplifying assumptions of a more or less constant forest structure, or equilibrium conditions for matter fluxes, restrict the regional application of such models to rather short periods.

The importance of a full coupling between vegetation dynamics and dynamics of matter fluxes is most obvious for water, where the division between evapotranspiration into the atmosphere (which affects regional cloud distribution and precipitation) and runoff/percolation into groundwater and streamflow (which determines water availability and flood occurrences downstream) depends on the state of the vegetation. Examples have been published of coupled terrestrial/hydrology models for studying water availability (e.g. Walko *et al.*, 2000; Cui *et al.*, 2005) and climatic effects (Lu *et al.*, 2001). Coupled terrestrial/hydrology models can also serve to determine the impact of forest dynamics and silvicultural management on nitrate concentration in streams and groundwater. Promising approaches in this direction have been developed for Sweden (Arheimer *et al.*, 2005), The Netherlands (Wolf *et al.*, 2005) and the USA (Hartman *et al.*, 2006; Hong *et al.*, 2006). Another important area where long-term effects under climate change can only be estimated with coupled terrestrial/climate models are air pollution issues such as ozone concentration, which depends on the emission of biogenic carbohydrates in rural areas. The particular importance of ozone episodes has already been shown (e.g. Derognat *et al.*, 2003; Solmon *et al.*, 2004).

Overall, current developments clearly point in the direction of models that describe growth and regeneration of individual trees or tree cohorts on the basis of physiological processes that are linked to the water and nutrient balances of the particular sites. Such models are sensitive to environmental changes as well as different kinds of disturbances, and can be used for planning short- and long-term corridors of forest management.

Visualization models

As already mentioned, forest landscapes are highly complex systems, which fulfil multiple demands of society with respect to resource supply, climate and air chemistry conditions, protection from erosion, maintenance of water quality, and provision of recreation area and biodiversity. Effective landscape management in such a complex environment, considering forest as well as landscape structure, is demanding with respect to information transfer to decision-makers and stakeholders. One of the most direct ways to explain the results of scenario-based simulations is visualization. Portraits and photographs were among the first media to describe forest landscapes. Realistic illustrations make use of the intuitive human potential of pattern recognition and imagination (Paivio, 1971). Modern computer technology now provides the means to produce a three-dimensional visualization of forest stands and landscapes. A substantial development in this field is the provision of easy-to-use tools that allow the user to choose the perspective arbitrarily and interactively. A further advance is the ability to combine visualization tools with simulation models of forest growth, enabling the visualization of scenario runs that show forest landscape development over decades or even centuries. This allows us to compare visually different simulation scenarios, which makes this approach particular suitable for participatory landscape-planning.

For this purpose we identify four main criteria for an effective forest landscape visualization tool. First, visualization needs to cover temporal scales that are suited for human perception as well as tree growth and forest development. This necessity arises from the fact that our perception of landscapes is rather short term compared with forest regeneration cycles. People are not aware of changes that occur slowly over a long period of time whereas they are able to detect fast changes easily (Pretzsch, 2004; Meiner *et al.*, 2005). The representation of long periods in small time steps, however, represents a challenge to any visualization tool.

Secondly, visualization must be data-driven (e.g. Sheppard and Harshaw, 2001). Any planning purpose should therefore recognize Arthur Conan Doyle's comment that 'it is a capital mistake to visualize before one has facts. Intensively, one begins to start to twist facts to suit imaginations instead of plans to suit facts.' However, it seems to be a common feature that the primacy of real data over artistic licence in the visualization process has not been fully acknowledged (Wang *et al.*, 2006).

Thirdly, visualization must heed realism. To support the intuitive recognition pattern of the human brain, it is essential to display plants and landscapes as realistically as possible (Meiner *et al.*, 2005). This implies for instance that visualization of forests needs to be based on single trees to account for structural differentiation, which is an important element of forest recognition.

Finally, visualization must allow free choice of perspective. A single static view is considered to be insufficient for an adequate impression of a forest landscape. Different viewpoints and perspectives are required for decision-making processes. It has been stated that the free choice of the perspective is as important as the ability to immerse oneself in the forest to experience the properties and aesthetics of a landscape (Bell, 2001). The technical aspect of a fast and smooth immersion is therefore a crucial point of visualization. It helps to create a three-dimensional impression and provides the user with a feeling for size proportions. Bishop (2005) emphasizes that real-time visualization could be a helpful tool for public participation in the decision-making process. This goes further than considering only different views of the landscape. Real-time visualization enables the user to switch interactively between different scenarios and even to manipulate the boundary conditions for simulations, and then see the results of changes instantly as changes to the visualized scenery.

Many different approaches to the visualization of trees (e.g. Gilet *et al.*, 2005) and forest landscapes (Deussen *et al.*, 2002; Decaudin and Nayret, 2004) are available. The range of technical solutions reaches from point-based rendering to full ray-tracing. Software packages for the visualization for forest landscapes which allow data-driven visualization, however, are not particularly common. First, there are 'all-purpose-landscape-visualization' systems, which use typical object arrangements to display different ecosystems and do not allow any interactive movement within a scenery. One of the most common systems of this kind is the Visual Nature Studio (VNS; 3D Nature, Vancouver, Canada), which complements these object arrangements (called ecotypes) with single objects representing, for example, solitary trees. The ecotypes are predefined and the objects are randomly arranged according to prescribed density parameters. The coupling with simulation tools is done via GIS systems. If different forest structures are to be displayed, either a new ecotype has to be defined or all trees have to be placed separately according to the simulation output. Thus, we acknowledge that tools such as VNS are very useful if the forest structure is not important. However, they require considerable computing resources and are not able to render the scenes in real time. Although similar methods are applied, the Envision program (McGaughey, 2006) was explicitly developed for forest management purposes. Thus, data exchange with the forest inventory databases has been optimized and it is possible to retrieve numerical information about stands directly through the visualization system.

Instead of the 'ecotype' approach, which in most cases displays only abstracted tree objects or images, the programs Lenné3D (Werner *et al.*, 2005) and the software system AMAP/Imagis (Blaise *et al.*, 2004) visualize single plants with detailed geometrical resolution, representing even branches and leaves. These plant objects give a highly realistic impression even if the viewpoint is in a stand or near the canopy. Furthermore, Lenné3D, at least, is able to display real-time, interactive animations of the scenery.

The third group of software solutions concentrate on the visualization of (forest) landscapes and on the opportunity for the user to walk or fly through the scenery to gather a realistic impression. Examples of this latter group are ViewScape3D (ViewScape3D Inc., BC, Canada), Lenné3D (only for small areas) and L-VIS (Seifert, 2006). These software packages enable a direct linkage to simulation systems, which is an important feature for the display of dynamic changes in the landscape. As already shown, it is important to provide an interactive display as well as the ability to move back and forth in time in order to understand the processes of landscape change. Currently, only L-VIS (Seifert, 2006) and Silvisio (http://www.silvisio.de 2007, under development) provide both through a tight coupling with a simulation model.

EXAMPLES OF MODELS FOR DIFFERENT APPLICATIONS

SILVA, a forest growth simulator

SILVA2·2 reflects the spatial and dynamic character of mixed stand systems, updating spatial stand structures in 5-year intervals. This permits the recording of the individual competitiveness of every tree and the simulation of tree growth competitiveness in relation to this competitive state (Fig. 5). The external variables determining tree growth increment and stand structure are treatment indicators, risk probabilities and environmental site factors. The model simulates the effects that tending, thinning, regeneration and natural hazards such as storms have on the stand dynamics. The feedback loop 'stand structure → tree growth → state of the tree → stand structure' forms the backbone of the model. The step-by-step modelling of the growth of all individual trees via differential equation systems results in information about assortment and financial yield, stand structure, stability, and diversity of the stand. This is far more than the data required in yield calculations of height, diameter at breast height (dbh), number of stems, etc. Input and output data used in the model correspond to the data available from or required by forestry practice. This enables the weighting between yield-related, socio-economic and ecological effects between different forest types and management options. Parameterization is based on yield measurements and site characteristics obtained from pure and mixed stands that have been under observation for more than a century.

The position-dependent individual tree model SILVA2·2 considers a forest stand as a mosaic of individual trees and reproduces their interactions as a space–time system (Fig. 6). It can therefore be used for pure and mixed stands of all age combinations. Primarily it is designed to assist decisions in forest management. Using SILVA2·2, predictions about the effects of changing site conditions and silvicultural treatments are possible, which makes the program a valuable research instrument.

A first model element reflects the relationship between site conditions and growth potential and aims at adapting the increment functions in the model to actual, observed site conditions. With the aid of nine site factors reflecting nutritional, water and temperature conditions, the parameters of the growth functions are determined in a two-stage process (Kahn, 1994). The stand structure generator STRUGEN facilitates the large-scale use of position-dependent individual tree growth models. The generator converts verbal characterizations as commonly used in forestry practice (e.g. mixture in small clusters, single tree mixture, row mixture) into a particular initial stand structure with which the model can subsequently commence its forecasting run (Pretzsch, 1997). The model uses tree attributes such as stem position, tree height, diameter, crown length,

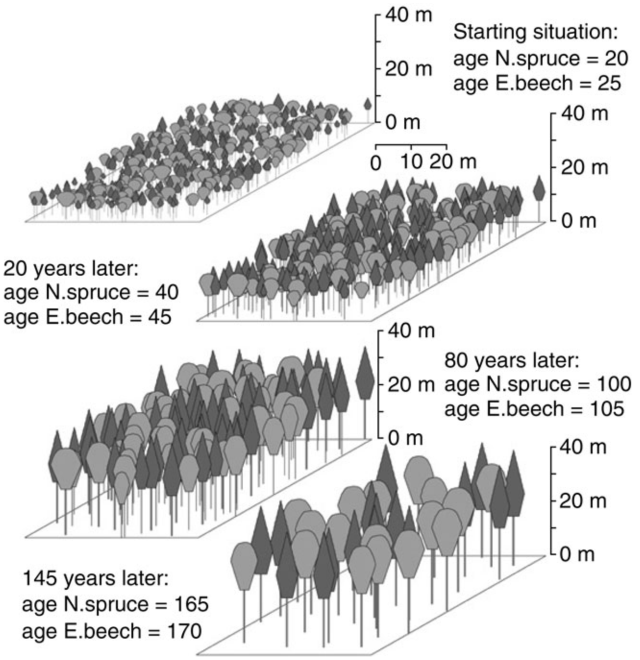


FIG. 6. SILVA 2·2 breaks down forest stands into a mosaic of individual trees and reproduces their interactions as a space–time system. Excerpt of a simulation run for a mixed stand with two species (slight thinning from below) (Pretzsch, 2001, p. 256).

crown diameter and species-related crown shape functions to build up a three-dimensional virtual stand.

Thinning is also considered on the basis of the individual tree and can represent a wide spectrum of treatment options (Kahn, 1995), including various thinning methods (thinning from below and selective thinning) and thinning intensities (slight, moderate and heavy). The core of the thinning routine is a fuzzy logic controller and an individual competition routine. The latter uses the light-cone method (Pretzsch, 1992) to calculate competition indices for every tree on the basis of its size and position in stand. Diameter at breast height, tree height, crown diameter, crown base height, crown shape and survival status are in turn calculated at 5-year intervals in relation to site conditions, and interspecific and intraspecific competition. Finally, yield information on stand and single tree level for the simulation period is compiled and presented as listings and graphs. Calculated information on stem quality, assortment and financial yield complete the growth and yield characteristic. Additionally, the program employs a routine for structural analysis which produces indices for habitat and species diversity and forms a link to the ecological assessment of forest stands.

The algorithmic sequence for predicting forest development comprises the following steps. The first step is the input of data on the initial structure and site conditions of the monitored stand. Secondly, the parameters of the growth functions are adjusted to actual site conditions. If initial values (as, for example, stem position) are unknown missing data are complemented using the stand structure generator. Once the spatial model set-up has been completed (step 4) the silvicultural treatment program is specified (step 5). The competition index calculated for each tree (step 6) is used to simulate individual tree development (step 7). Steps 4–7 are repeated using 5-year steps until the end of the forecast period.

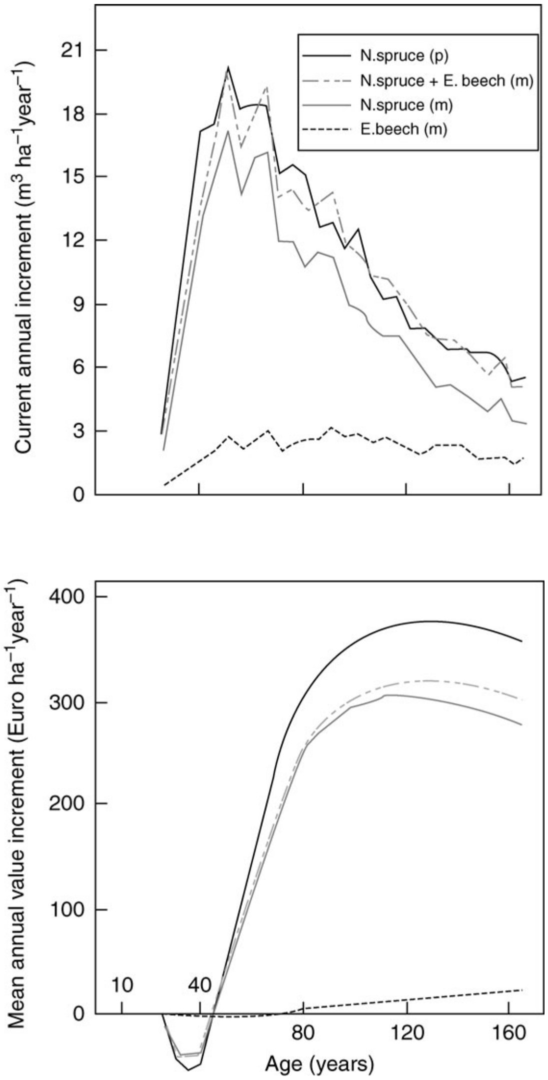


FIG. 7. Scenario analysis with SILVA2·2 on stand level. Current annual volume growth (top) and mean annual value increment (bottom) in pure stands of Norway spruce compared with mixed stands of Norway spruce and European beech (Pretzsch, 2001, pp. 258–261).

Figure 7 shows results from a scenario analysis with SILVA2·2 on stand level. Current annual volume increment (top) and mean annual value increment (bottom) are compared for pure stands of Norway spruce and mixed stands of spruce and beech. Similar evaluations can be made on tree, stand, enterprise or regional scale.

SILVA2·2 is mainly applied by three groups of users. A first group includes scientists at universities, research stations, other 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, to support experts' opinions in lawsuits or for economic forest valuation. Applications require careful adjustment to the specific conditions on stand, enterprise, regional or country level. A second group is formed by forest managers and planners, responsible for state, municipal, private or communal forests. Models in this field are required for development of silvicultural guidelines, preparation of forest management plans, timber volume prognosis or assessment of sustainable annual cut. This user group applies SILVA2·2 mainly in batch mode for some 1000–10 000 inventory plots, calculates several thinning options per plot or stratum, and repeats each run 5–20 times in order to get mean and standard errors. Finally, a considerable group of lecturers, trainers, teachers and consultants for private and communal forests apply SILVA2·2. Like private asset consultants, these users apply software to corroborate their advice with calculations and quantitative analyses of different options. For this purpose they use the interactive version of SILVA2·2 and simulate just a few stands and silvicultural options to present the effect of alternative decisions in a simple and convincing way.

BALANCE, a matter-balance model

BALANCE, a representative of the matter-balance model group but also a functional structural model, simulates growth responses on the single tree level (Grote and Pretzsch, 2002; Rötzer *et al.*, 2005). Similar to SILVA, it accounts for the influence of competition, stand structure, species mixture and management impacts on single tree growth. This is established with the explicit calculation of tree development dependent upon individual environmental conditions on the one hand, and the dependency of environmental conditions on individual tree development on the other. The three-dimensional development of the individual trees and of the forest stand, respectively, are calculated in annual time steps based on the biomass increase of woody tissue that has accumulated during the past year. The simulation of the interrelated carbon, water and nutrient balances of single trees, currently parameterized for the species beech, oak, spruce and pine, forms the core processes of the model.

Each tree of a forest stand is structured in crown and root layers, which are in turn divided into up to eight crown and eight root sectors. For each layer or each sector respectively, micro-climatic conditions are calculated. Whereas these calculations are computed daily, the physiological processes of assimilation, respiration, nutrient uptake, growth, senescence and allocation are calculated in monthly or decadal (=10-day periods) time steps from the aggregated driving variables. This provides a high sensitivity of the physiological processes to weather conditions, CO_2 concentration, water and nitrogen availability, as well as air pollution, for every tree without a high demand of computation time. To depict the relationships between the environmental influences and growth, the seasonal development of foliage has to be considered because light availability and radiation absorption change with leaf area and foliage distribution. In BALANCE the beginning of bud burst is modelled by using a temperature sum model (Rötzer *et al.*, 2004), while foliage senescence is estimated dependent upon the respiration sum. Because tree development is described on an individual basis, it is possible to use the model for the assessment of environmental impacts independent of species mixture or stand structure.

BALANCE needs position, stem diameter and stem height for every tree to be initialized as well as a rough description of the soil (field capacity, wilting point, nutrient status, rooting depth). Daily meteorological input variables (temperature, radiation, wind speed, humidity and precipitation) are used to drive the simulation. Additionally, deposition data can be considered. Output is obtained from 10-day up to annual values in a spatial resolution of single tree compartments up to stand values. Apart from growth parameters such as diameter, height or carbon content, variables describing stand micro-climate and water balance can be obtained.

The following example demonstrates the influence of climate on growth and water balance on the development of a forest stand. The test site 'Kranzberger Forst' is located in southern Germany about 40 km north-east of Munich at 500 m above sea level (a.s.l.). The long-term annual mean (1951–1980) of temperature is between 7·0 and 8·0 °C, and the mean annual precipitation sum (1961–1990) between 750 and 850 mm. For the period 2000–2005 the annual mean temperature was relatively high (8·7 °C), while the mean precipitation sum was well within the long-term observations (816 mm). Soil conditions for growth are very good, e.g. field capacity of the soil is 350 mm m^{-1}, providing available soil water content within the rooting zone (=100 cm) of about 200 mm. The forest site is a mixed stand of Norway spruce and European beech. The initialized stand includes 172 spruce trees and 37 beech trees. The spruces are about 50 years old at the beginning of the simulations (year 2000) with a mean dbh of 27·5 cm, and a mean height of 23·8 m. Beech trees are approximately 56 years old with a mean dbh of 23·3 cm and a mean height of 23·0 m. For a more detailed description of the site see Pretzsch *et al.* (1998).

Simulations were run with measured weather data from the period 2000–2005 as well as with a climate scenario in which temperature is increased by 3 °C, radiation is increased by 20 % and precipitation is decreased by 20 %. Figure 8 presents the dbh development of all spruce and beech trees for the simulations with real weather data and with the climate scenario, respectively. It shows that the difference between the two simulation runs is only small. However, whereas for spruce trees diameter growth is somewhat higher in the scenario compared with measured climate, beech trees show a small decrease in dbh growth. According to the larger proportion of spruce trees, the mean annual biomass increment of the entire forest stand is higher for the climate scenario (Fig. 9). Under the conditions of the simulation run (a mixed spruce–beech stand, southern German site conditions, period 2000–2005) and averaged over the 6 years the forest is a net sink for carbon (increasing biomass). The sink is simulated to be about 13 % stronger under the scenario assumptions.

In addition to the above forestry (dbh and productivity) and environmental (carbon sequestration) issues, the development of ecosystem services can also be simulated with matter-balance models. Depending on premises of

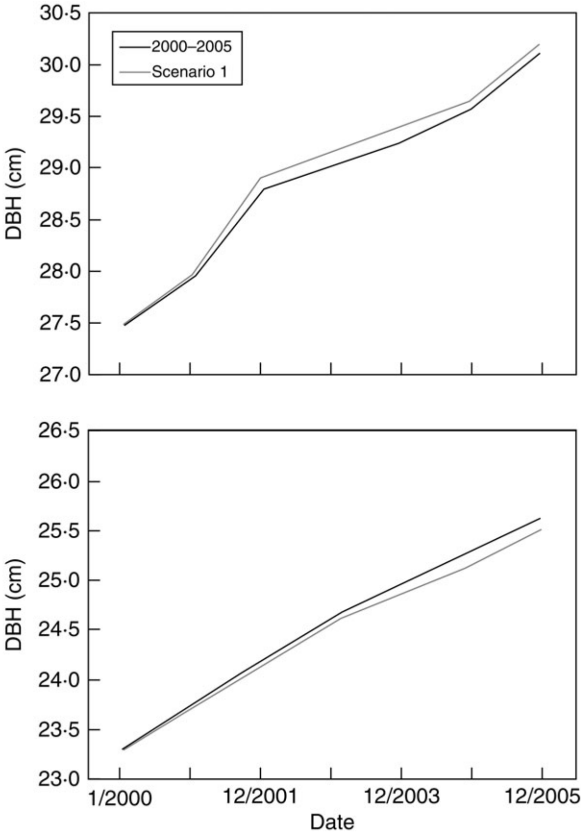


FIG. 8. Mean course of the diameter at breast height for the spruce (above) and the beech trees (below) of a mixed forest stand in southern Germany over the period 2000–2006 and of the climate scenario.

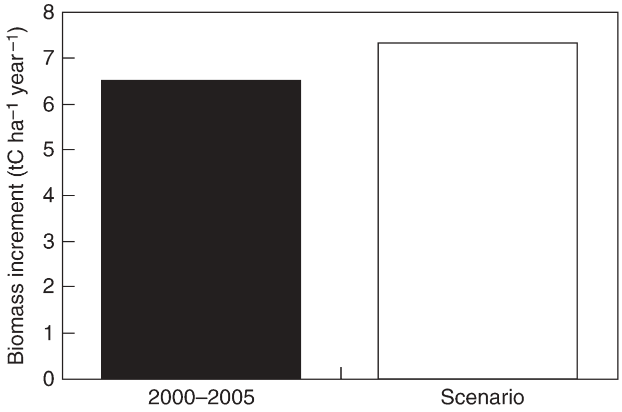


FIG. 9. Mean annual biomass increment (tonnes carbon) of a mixed forest stand in Southern Germany for the period 2000–2006 and for the climate scenario.

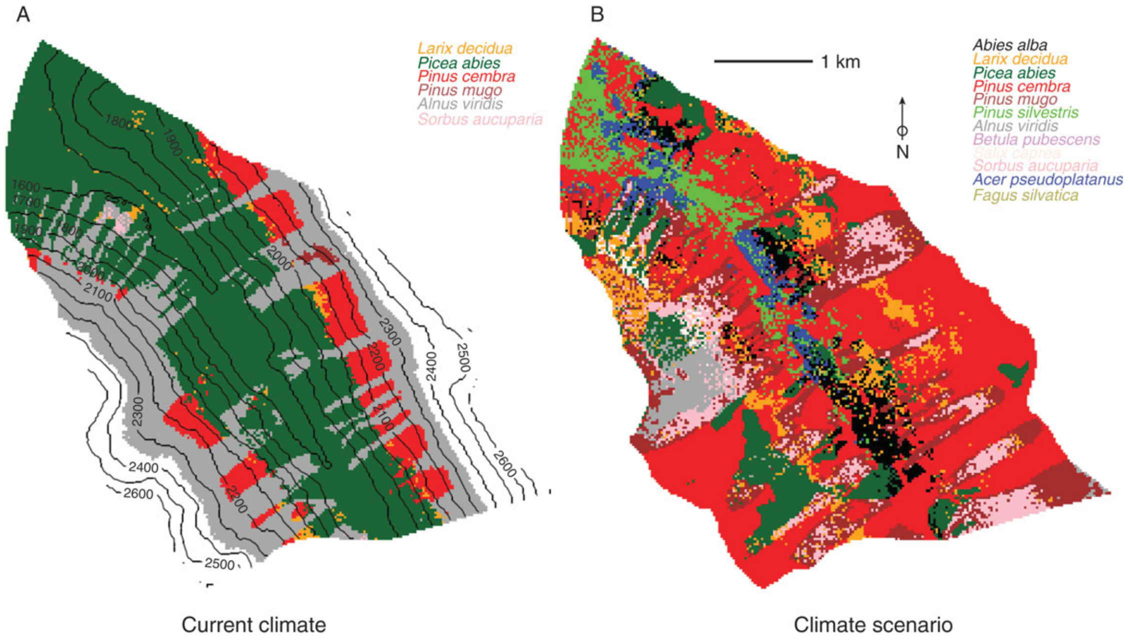
temperature increase and precipitation decrease in the scenario run, the average actual evapotranspiration (which in this case also includes evaporation from interception) increases only slightly from 651 mm year^{-1} for the period 2000–2005 to 657 mm year^{-1}. However, a huge change can be seen in the average runoff values with an annual sum of 221 mm for the period 2000–2005 and only 51 mm for the scenario run. This means that groundwater recharge is strongly influenced, which in turn might affect the regional supply of drinking water. A closer analysis of the seasonal development of soil water content reveals that in the last 2 years of the scenario run, field capacity is no longer reached, which is in contrast to the general experience in southern Germany during the winter months. If soil water is no longer recharged, water availability during the summer months decreases from year to year. That means that in the following years drought stress will presumably increase and affect tree growth negatively. The example presented highlights the close relationship between climate, water and tree growth as well as possible consequences for ecosystem services.

LandClim, a landscape model

LandClim was developed to study the effects of topography, climate and land use on forest structure and dynamics. A particular focus is on large-scale natural disturbances such as fire (Schumacher *et al.*, 2004, 2006; Schumacher and Bugmann, 2006). LandClim is a spatially explicit, stochastic landscape model, based on the well-established LANDIS model (He *et al.*, 1999). It operates on long time scales (hundreds to thousands of years) and large spatial extents (>100 ha) at a relatively fine scale (grid cells of 25 × 25 m). The state of the forest at each grid cell (stand scale) is represented by the number and biomass of trees in cohorts (individuals of the same age and species). Processes at the stand scale, i.e. growth and mortality, operate on annual time steps, whereas landscape-scale processes, i.e. fire, wind, harvesting and seed dispersal, are simulated in decadal time steps. The fire regime is an emergent property of the system. The spread of fires depends on climate and topography; it is independent of tree species composition. Fire effects, i.e. tree mortality, however, are species-specific.

Long-term simulations with LandClim serve a different purpose than applications of the two previously discussed models, SILVA and BALANCE. The simulations do not aim to provide reliable forecasts or specific transformation knowledge, given the uncertainty about key drivers, particularly in areas with a strong direct human influence, and in the context of climate change, which will probably combine long-term trends (e.g. warmer and drier conditions), with increased inter-annual variability. Rather, the role of these long-term simulations is to help gain a better understanding of the potentially intricate relationship between landscape structure and dynamics. They assist in envisaging long-term consequences of alternative management options, by rigorously and transparently translating scenarios, formulated in terms of land-use and climate change, to changes of the forest landscape structure. In this context, links from these models to visualization tools such L-VIS promise to be highly beneficial (see following section).

LandClim has comparatively modest input requirements. It needs a digital elevation model at approx. 25 m resolution and a map of soil depths. The essential climate inputs are mean monthly precipitation sums and temperature means at a reference elevation, together with altitudinal lapse rates.



Current climate

Climate scenario

FIG. 10. Distributions of dominant tree species in the Dischma valley simulated with LandClim for (A) current climate conditions (3·2 °C mean annual temperature, 900 mm mean annual precipitation) and (B) a climate warming scenario (6·2 °C mean annual temperature, 700 mm mean annual precipitation).

Wind disturbance is characterized by mean disturbance size and return interval. Harvest rates can be differentiated with respect to size class, species and spatial position (Gustafson *et al.*, 2000; Schumacher *et al.*, 2004). Simulations can be started from bare ground or from an initial spatial distribution of tree cohorts.

LandClim provides aggregated output on biomass and stem numbers per species along elevation bands, or complete information on the state of individual cells. In addition, information on the harvest and disturbance regimes is reported, e.g. records of fire dates and sizes as well as maps of fire events.

The following example illustrates the impact of direct (via increased species pool) and indirect (via altered fire regime) effects of climate change on forest biomass and species diversity at the landscape scale. We focus on differential effects in the landscape with respect to elevation and exposition. Dischma valley is located near Davos (Grisons) in the eastern part of the Swiss Alps. It covers an area of 16·7 km^2, with an altitudinal range of 1550–2800 m; mean annual temperature is 3·2 °C, and mean annual precipitation is approx. 900 mm. Current climatic conditions are simulated using data from the climate station Davos-Platz (elevation 1560 m a.s.l.). A climate warming scenario with mean annual temperature of 6·2 °C and mean annual precipitation of 700 mm is simulated using data from a climate scenario based on the SRES A2 transient greenhouse-gas scenario (Schär *et al.*, 2004).

A fire suppression scenario is compared with a scenario that includes forest fires. Simulations using only the current species pool (13 species) are compared with an enriched pool that includes oak, beech and sycamore maple. Current harvest regimes in the area are extensive, and harvesting was excluded in these simulations. Simulations start from the current forest cover, and run for a period of 300 years. Twenty-five replicate simulations were performed for each scenario.

At the landscape scale, the diversity of (potential natural) forest types is increased after 300 years in the climate change scenario compared with current climatic conditions. In the valley bottom, stands dominated by *Picea abies* are replaced by *Pinus silvestris*, *Fagus silvatica*, *Acer pseudoplatanus* and *Abies alba*. There is an overall upward shift in tree species composition, and the upper treeline formed by *Pinus cembra* increases from 2250 m a.s.l. to elevations of 2650 m a.s.l.

At the stand scale, diversity is likewise increased under climate warming (Fig. 10). Under both simulated climate regimes, diversity decreases with altitude. Diversity is largest at disturbed sites, because of reduced dominance by a single or few species. The fire regime is substantially differentiated in the landscape, with a strong decrease in fire activity with increasing altitude (cf. Schumacher and Bugmann, 2006). South-facing slopes exhibit higher fire activity, and the effect of aspect increases with altitude. However, fire activity has only limited effect on species composition in the model. Differences are most pronounced at lower elevation with highest fire activity, where *Pinus cembra* is simulated to profit from fire exclusion against *Pinus silvestris* (results not shown).

TREEVIEW and L-VIS, visualization tools

This sub-section discusses two tools for forest visualization. The first is TREEVIEW, software optimized for fast and spatially explicit interactive rendering of forest stands. The second is L-VIS, a forest landscape visualization software.

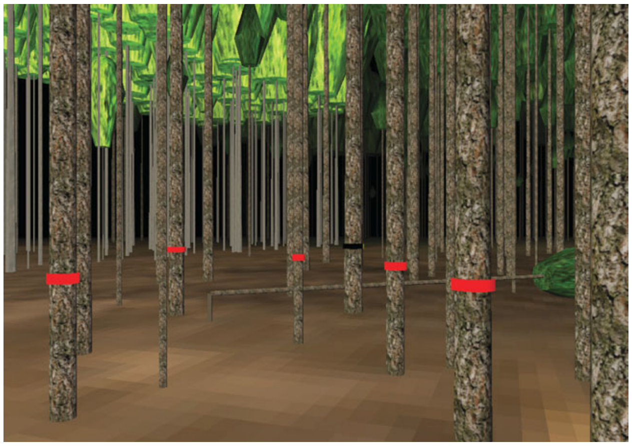


FIG. 11. An example of TREEVIEW output, with interactively selected trees for thinning and selected future trees.

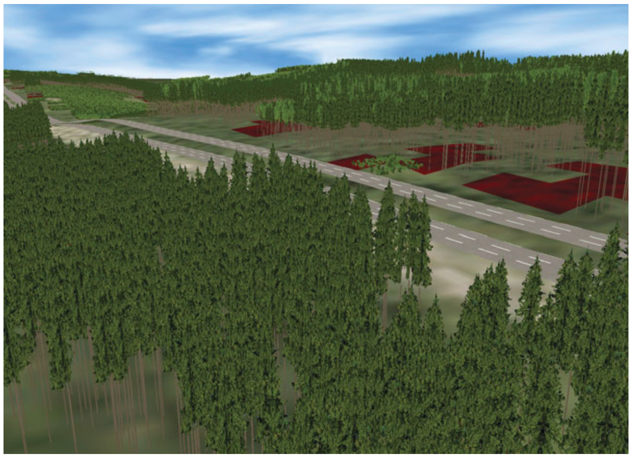


FIG. 13. Example of the use of L-VIS for displaying landscape planning of a street project. Parcells with high risk from wind are coloured in red.

TREEVIEW is designed for realistic and thematic visualization at the stand level. It is a data-driven, interactive visualization tool. One design goal was to display directly the outputs of the simulators SILVA and BALANCE while staying on the same level of resolution as simulation models, i.e. the single tree and tree compartment level. With TREEVIEW it is possible to display interactively the simulation results of SILVA, perform fly-through in the stands and manually select future trees or trees for interactive thinning via a mouse click (Fig. 11). It is possible to visualize the stand structure for teaching purposes or to support the dissemination of simulation results at the stand level. The software also supports thematic visualization such as false colouring of crowns, e.g. to display the biomass density distribution calculated by BALANCE (Fig. 12). While BALANCE is connected offline to TREEVIEW, the connection to SILVA is realized online to enable the interactive features. TREEVIEW displays geometric modelled trees which have the same geometry as the virtual objects in the simulation. To create a more realistic appearance, species-specific textures are applied to the tree models.

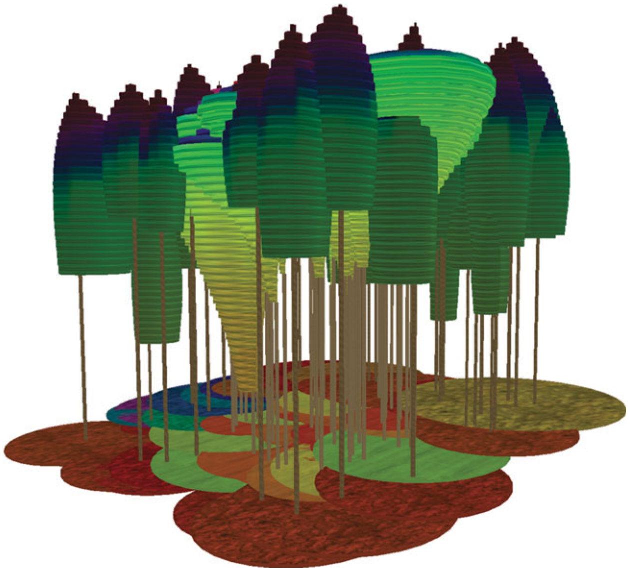


FIG. 12. TREEVIEW can visualize the output of BALANCE and display various tree compartment attributes as false colours. Here the biomass density is used for colouration.

The landscape visualization system L-VIS was developed to create realistic views of forest landscapes up to an area of 5×5 km^2. It uses the simulation results of SILVA to show the visual changes of such landscapes according to defined management or climate scenarios. It can be used in participative planning and dissemination of scientific results on landscape change to the public. Examples of applications are the visual impacts of insect outbreaks, power plants or motorways (Fig. 13).

One design goal of L-VIS is to preserve the single tree as the structural element in forest landscapes. In central Europe, with its long tradition in continuous cover forestry and selective thinning, the most important decision basis at stand level provides the species mixture, single tree distances, spatial groupings and tree dimensions. At the same time, these aspects strongly determine the visual impression of a forest landscape. For this reason L-VIS uses the single-tree dimensions, tree positions and regeneration densities of the simulation results of SILVA. One important feature of SILVA is that it is possible to simulate the development of the whole landscape based on inventory data. This provides the data for landscape-scale visualization. More specifically, the surroundings of inventory sample points are represented according to the exact simulation result of SILVA. Between the sample points, structural interpolation routines are employed to generate the remaining forests.

To display single trees, species-specific textures from photographs are scaled to the individual tree dimensions. Additional methods are incorporated directly in the visualization system to provide high visual realism of the images. These methods generate additional tree properties such as crown radius variation and stem declination.

To aid the user in gaining an impression of the scenario displayed, he or she can not only go interactively through

FIG. 14. An output of L-VIS on landscape level at various time steps. The integrated interplation routines offer time to the user as a real dimension in which he or she can continuously navigate.

the forest but is also able to follow the forest change in time. This is realized using a method based on pre-generated time slices from SILVA results, which are displayed on the fly (Fig. 14). The single tree dimensions are interpolated between two time steps. Tree growth, regeneration and decay are plausibly calculated between the time steps from SILVA. This offers a real four-dimensional fly-through in the simulated scenario to visualize not only static landscapes but also the dynamic changes.

DISCUSSION

In order to assess and control the development of forests with respect to sustainability, European countries agreed on a list of criteria and indicators for ecological, economic and social sustainability (Table 3). These criteria reflect and manifest the scope of European ecosystem managers and are not just a political issue (MCPFE, 2000). The variables of interest should be produced by models along with scenarios of forest development in order to make the results more understandable for practical managers and supply the most relevant information for decision support. In addition, the list of criteria and indicators are suitable to enhance participation of the public or forest management in the decision-making process.

TABLE 3. *Pan-European criteria 1–6 and examples for corresponding indicators for sustainable forest development (adapted from MCPFE, 2000)*

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; . . .

Excerpt for stand of Norway spruce for age 20 to 59. Yield is displayed in saxonian cubic feet per saxonina acre (1 saxonian cubic foot/1saxonian acre = $0{\cdot}04$ m^3 ha^{-1}) for the worst up to the best site fertility (I up to X).

Normal yield tables model the development of fully stocked stands on the basis of mean stand variables, e.g. number of trees per acre, mean diameter at breast height or basal area per acre [uses traditional (Imperial) measures].

This review of the existing model categories and current line of research reveals a split into two different approaches. On the one hand are models with rather coarse input requirements (such as age and relative site condition) but accurate predictions for wood production. These models are built on regression relations based on measurements of the required output variables from long-term trials or sample plots. As the same variables are required for model construction and produced as output, they are generally classified as 'empirical' (Constable and Friend, 2000). On the other hand, models have been introduced that explain various forest developments from underlying physiological and ecological principles. Although the mathematical description of these principles may also be derived from sample measurements, the inherent linkage between two or more scales has led to the classification of this approach as 'mechanistic' or 'process-based' (Constable and Friend, 2000; Mäkelä *et al.*, 2000). As several important processes at the physiological and individual scale influence the developments of the stand, a balanced model requires a more extensive set of input variables. Because these are often not available or have to be roughly estimated, but also due to incomplete process knowledge, mechanistic models are often rather unreliable with respect to yield management. However, process-based models are becoming increasingly important because they deliver a broad set of output variables for managers that are concerned with forest development under long-term environmental changes (Landsberg, 2003; Monserud, 2003).

The use of empirical approaches may be acceptable for short-term intensive wood production in plantations, representing the dominant use paradigm. However, with respect to European forests, where ecosystem management follows the concept of integration, models are needed that consider and provide ecological, economic and social aspects alike. Planning and decision-making in the multi-functional European forests requires production and analyses of long-term scenarios of various forest aspects (e.g. growth and yield, water supply, wood quality, recreation or aesthetic value) based on environmental change assumptions and different treatment options (such as thinning, species selection, regeneration techniques). The set of available models should therefore include a range of approaches that is able to support any decision formulated under the paradigms outlined above, enabling the consideration of trade-offs between different aims.

In the following, the important role of inventory measurements is first highlighted, this being independent of the approach taken to fulfil this task. Secondly, two different strategies are discussed that seem suitable to introduce various model developments into the process of forest planning. Thereafter, we discuss this process itself and include the role that visualization can play for different interest groups. Finally, we summarize current developments with respect to sustainable multiple-use forestry aims, and point out lines of research that could lead to a better representation of these criteria.

Link between 'mechanistic' models and inventory measurements

The outlined European forestry concept requires a concentration on process-based approaches. This, however, does not mean that the measurements at the tree and stand level are becoming less important. On the one hand, hybrid models (see above and 'Future model development' below) require knowledge about growth potentials for the species and sites to which they are going to be applied. On the other hand, forest inventories can improve information supply for ecosystem management considerably.

First, current inventories are designed to provide variables that are suitable for initialization of simulation runs. They provide detailed information about standing volume, diameter distribution and sometimes even spatially explicit information about stand structure such as stem coordinates, crown base height or crown length. As stand dynamics are closely related to initial stand structure, utilization of this information can increase the accuracy of predictions. If necessary, stand structure generators that are developed from these inventory data can provide the necessary initial values if data sets are incomplete and thus serve as flexible linkage between models and inventory data (Nagel, 1996; Pretzsch, 1997).

Secondly, successive inventories at permanent investigation plots can be used to evaluate and parameterize the simulation of stand development and tree growth in process-based models (Valentine and Mäkelä, 2005). When only basic information about environmental conditions is available, these data are also suitable to parameterize the relationship between site fertility and productivity. Compared with experimental plots, large-scale inventories cover a much broader range of site conditions and stand structures and are thus much more representative (von Gadow, 2005). It is also possible to use rule-based systems that assign the correct height growth pattern to each stratum dependent upon simple classification variables if growth measurements are not available (Klemmt, 2007).

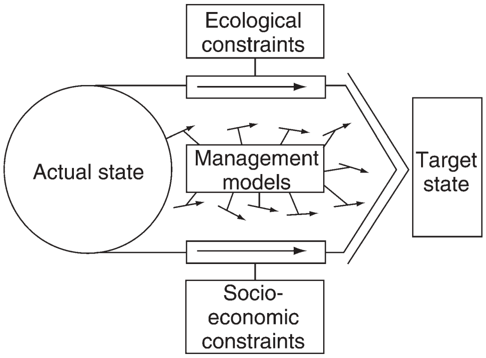


FIG. 15. Management models support decisions within a given decision corridor (framed arrows) by prognosticating the long-term consequences of treatment variants (mobile arrows). The corridor can be explored by application of mechanistic model approaches on stand and landscape levels.

Future model development

The following solutions for further model research are considered. A first option would be the coexistence of various model approaches, including empirical and mechanistic ones (Fig. 15). In this case, matter-balance models would be used to derive a broad spectrum of environmental variables that indicate the sustainability of socio-economic services at the stand scale (e.g. carbon sequestration, nitrogen retention from groundwater, biodiversity). These indications are complemented by information from landscape models about management risks by means of sudden events such as fire, storm or insect attacks. Taken together, long-term leading 'planks' for management and the corridor for successive management decisions could be provided. For operational purposes, strategic planning and optimization of wood production within this given corridor, conventional growth simulators could still be used, although an occasional re-parameterization has to be considered. Such a co-application would enable the forester to respond to long-term developments (e.g. climate change, nitrogen deposition) without losing the necessary accuracy for operational decision-making.

A more innovative option is the hybrid model approach, which has been pointed out as one of the most promising developments for future forestry decision support (Battaglia and Sands, 1998; Landsberg, 2003; Monserud, 2003). This aims at an estimation of stand primary production considering the dependencies of physiological processes on environmental conditions, 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 provide a quite extensive list of variables for sustainable management. In return, they require information about the vegetation and soil processes (such as net carbon gain, allocation and turnover) that are – despite their sometimes strong site dependence – generally derived from a small number of extensive long-term experimental plots.

However, integration of mechanistic and empirical model elements is still at an early stage, and the most advanced approaches are focused on the dominant use paradigm only (e.g. Robinson and Ek, 2003; Waterworth *et al.*, 2007). Various problems connected with a balanced process integration, initialization and evaluation are presenting considerable hurdles for this approach, particularly under European management considerations. We suggest that future developments concentrate on simple hybrid approaches that include well-balanced physiologically based process descriptions and on extensive evaluation on the basis of existing experimental plots, including variables that are not directly connected to timber yield.

Tailoring models for users

With respect to presentation of model scenario results, it should be noted that 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, considering that completely different user-groups exist. According to our experiences, three user groups have to be distinguished that prefer different user interfaces. A rather unproblematic user group comprises scientists at universities and research stations, and other scientific experts. This group familiarizes conscientiously with new demanding tools, adapts existing software easily for their special purpose, and requires the lowest software adjustment, introduction and training. A second group consists of lecturers, trainers, teachers, and consultants for private and public forests. These have to be supplied with specifically approved model versions for particular purposes. They require a rather intensive phase of introduction in which scenarios and management options had to be worked out together with the user, but due to the relatively narrow range of applications further maintenance effort is relatively small. Finally, forest managers require a more transparent and user-friendly interface, and occasionally the implementation of enterprise-specific algorithms, for example modules for stratification of inventory data, thinning options, assortment rules or harvesting techniques. As new models compete to some degree with well-established simpler methods, general scepticism for new software tools is often high. As remedies for these hurdles, training courses, team work, continuous technical support and guarantees for confidential treatment of results may be required. Although these difficulties currently to some degree prevent new methods from application to European forestry, we are confident that an early introduction into models during student education will overcome the scepticism and ease future progress.

CONCLUSIONS AND PROSPECTS

Recent literature introduces a number of models that offer considerably more than the conventional growth and yield output variables to forest management. Particular emphasis is put on combined yield and carbon stock estimation using evaluated matter balance (e.g. Peng *et al.*, 2002; Deckmyn *et al.*, 2003; Battaglia *et al.*, 2004; Garcia-Gonzalo *et al.*, 2007) or hybrid models (Waterworth *et al.*, 2007). Rarely, other forest services such as recreational value or groundwater recharge are also considered with matter-balance models (Lasch *et al.*, 2005; Fürstenau *et al.*, 2007) or sophisticated growth simulators (Pretzsch *et al.*, 2002). It seems that the currently most accepted means of progress is a convergence of empirical and mechanistic model approaches. Many relevant components for building such hybrid models are already available. Model development is therefore rather a question of simplification, integration, standardization, programming and, last but not least, improved evaluation (e.g. Robinson and Ek, 2003; Almeida *et al.*, 2004; Seidl *et al.*, 2005; Schmid *et al.*, 2006). Without doubt, a commitment to standardized initial variables, driving variables and evaluation variables would foster their development, linkage with inventory data, and integration into the data flow of forest management and planning. Nevertheless, the results are still far from covering all relevant criteria and indicators for sustainable ecosystem management under various paradigms (Table 1).

One of the key problems in linking different models directly together is the balanced and consistent representation of processes. The combination of various processes at one scale affects processes at higher levels, and the higher level processes feedback to the scales below by changing boundary conditions (Ulrich, 1999). For example, self-thinning at the stand level is a result of single tree mortality, which is caused by a negative long-term net carbon gain resulting from various physiological processes. The process is so complex that it is still difficult to describe mechanistically (Reynolds and Ford, 2005). Mortality is therefore generally derived from empirically determined stand-level processes ('self-thinning law'). However, mortality affects resource availability and thus the driving forces for physiological processes. Despite the realistic description of physiological processes, the whole simulation thus depends very much on the accuracy of the empirical relation, which is by no means as generally applicable as assumed (Pretzsch, 2006). This applies to an even higher degree to the use of empirically determined stand growth equations, which are also derived from a limited number of experimental stations. In particular, studies of the effect of species mixture on growth, yield, stability and disturbances are at a very early stage. Thus, forest management may benefit from hybrid approaches by gaining a wealth of additional variables but these approaches still rely very much on local parameterization.

These difficulties allow us to emphasize the usefulness of the toolbox approach outlined above. It includes empirical forest knowledge explicitly but separately and enables the stepwise introduction of process-based knowledge as soon as appropriate specific models are available. Furthermore, new results from different disciplines can be integrated more easily and fitted into the concept and data flow of the planning procedure according to the needs of the user. It should be noted, however, that environmental change requires empirically based yield knowledge to be updated in short time periods and that this requires maintaining a sound basis of long-term experimental plots. This toolbox could also include the important links to the landscape level, i.e. quantitative connections with grassland systems, arable land and urban landscapes. Model application here does not aim to explain stand-level processes but

(1) gives boundary information for long-term sustainable management by quantification of risks in a larger landscape, (2) enables the determination of exchange processes between rural and urban regions (water availability and water quality, air pollution).

We are aware of increasingly detailed and scattered system knowledge on the one hand, and increasing information demand about stand-level dynamics on the other. Models can help to bridge this gap by supporting (not dictating) decisions and training. Their value lies in the provision of scenario-based lines of forest development. However, it is not necessarily one model that should be used for various management targets. Although further research will increase the predictive potential for each group of targets, it is also the integration and joint application of models that should be specified in the course of an ongoing process.

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LITERATURE CITED

Aber JD, Federer CA. 1992. A generalized, lumped parameter model of photosynthesis, evaporation and net primary production in temperate and boreal forest ecosystems. *Oecologia* **92**: 463–474.

Aber JD, Ollinger SV, Federer CA, Reich PB, Goulden ML, Kicklighter DW, *et al*. 1995. Predicting the effects of climate change on water yield and forest production in the northeastern United States. *Climate Research* **5**: 207–222.

Aber JD, Ollinger SV, Driscoll CT, Likens GE, Holmes RT, Freuder RJ, Goodale CL. 2002. Inorganic nitrogen losses from a forested ecosystem in response to physical, chemical, biotic,and climatic perturbations. *Ecosystems* **5**: 648–658.

Almeida AC, Landsberg JJ, Sands PJ, Ambrogi MS, Fonseca S, Barddal SM, Bertolucci FL. 2004. Needs and opportunities for using a process-based productivity model as a practical tool in *Eucalyptus* plantations. *Forest Ecology and Management* **193**: 167–177.

Alveteg M. 2004. Projecting regional patterns of future soil chemistry status in Swedish forests using SAFE. *Water, Air, and Soil Pollution: Focus* **4**: 49–59.

Ancelin P, Courbaud B, Fourcaud TY. 2004. Development of an individual tree-based mechanical model to predict wind damage within forest stands. *Forest Ecology and Management* **203**: 101–121.

Arheimer B, Andreasson J, Fogelberg S, Johnsson H, Pers BC, Persson K. 2005. Climate change impact on water quality: model results from southern Sweden. *Ambio* **34**: 559–566.

Arney JD. 1972. *Computer simulation of Douglas-fir tree and stand growth*. PhD thesis, Oregon State University.

Assmann E, Franz F. 1963. *Vorläufige Fichten-Ertragstafel für Bayern*. München: Institut für Ertragskunde der Forstlichen Forschungsanstalt München.

Bailey IE. 1973. *Development of unthinned stands of Pinus radiata in New Zealand*. PhD thesis, University of Georgia, USA.

Baldwin VC Jr, Burkhart HE, Westfall JA, Peterson KD. 2001. Linking growth and yield and process models to estimate impact of environmental changes on growth of loblolly pine. *Forest Science* **47**: 77–82.

Baron JS, Hartman M, Band LE, Lammers R. 2000. Sensitivity of a high-elevation Rocky Mountain watershed to altered climate and CO_2. *Water Resources Research* **36**: 89–100.

Barton C. 2001. The role of allocation in modelling NEE. In: Kirschbaum MUF, Mueller R, eds. *Proceedings of CRC-workshop on Net Ecosystem Exchange*. Canberra: CRC for Greenhouse Publications, 43–49.

Battaglia M, Sands PJ. 1998. Process-based forest productivity models and their application in forest management. *Forest Ecology and Management* **102**: 13–32.

Battaglia M, Sands P, White D, Mummery D. 2004. CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. *Forest Ecology and Management* **193**: 251–282.

Bell S. 2001. Can a fresh look at the psychology of perception and the philosophy of aesthetics contribute to a better management of forest landscapes. In: Sheppard SRJ, Harshaw HW, eds. *Forests and landscapes: Linking ecology, sustainability and aesthetics*, CABI Publishing, 125–148.

Bella E. 1970. *Simulation of growth, yield and management of aspen*. PhD thesis, Faculty of Forestry, University of British Columbia.

Bergh J, Freeman M, Sigurdsson BD, Kellomäki S, Laitinen K, Niinistö S, *et al*. 2003. Modelling the short-term effects of climate change on the productivity of selected tree species in Nordic countries. *Forest Ecology and Management* **183**: 327–340.

Bishop ID. 2005. Visualization for participation: the advantages of real-time? In: Buhmann E, Paar P, Bishop ID, Lange E, eds. *Trends in Real-Time Landscape Visualization and Participation*. Berlin: Wichmann, 2–15.

Blaise F, Saint-André L, Leban JM, Gégout JC, Hervé JC. 2004. Connection between forest inventory data and geographic information systems for assessing timber value at the stand level. In: Nepveu G, ed. *Proceedings of the 4th IUFRO Conference on: Connection between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software*, Harrison Hot Springs (BC Canada 2002), INRA, Nancy, 583–594.

Bonnemann A. 1939. Der gleichaltrige Mischbestand von Kiefer und Buche. *Mitteilungen aus Forstwirtschaft und Forstwissenschaft* **10**[4].

Bossel H. 1996. TREEDYN3 forest simulation model. *Ecological Modelling* **90**: 187–227.

Botkin DB, Janak JF, Wallis JR. 1972. Some ecological consequences of a computer model of forest growth. *Journal of Ecology* **60**: 849–872.

Bradley RT, Christie JM, Johnston DR. 1966. *Forest management tables*. Forestry Commission (ed.), booklet 16, 212 pp.

Bruce D, De Mars DJ, Reukema DC. 1977. *Douglas-fir managed yield simulator: DFIT User's Guide*. PNW-57, USDA, Forest Service Gen. Technical Report. Portland, OR: PNW Forest and Range Exp. Station.

Bruner HD, Moser JW. 1973. A Markov chain approach to the prediction of diameter distributions in uneven-aged forest stands. *Canadian Journal of Forest Research* **3**: 409–417.

Buckman RE. 1961. Growth and yield of red pine in Minesota. *USDA Technical Bulletin*. Washington, DC, 1272, 50.

Bugmann H. 2001. A review of forest gap models. *Climatic Change* **51**: 259–305.

Bugmann H, Grote R, Lasch P, Lindner M, Suckow F. 1997. A new forest gap model to study the effects of environmental change on forest structure and functioning. In: Mohren GMJ, Kramer K, Sabaté S, eds. *Impacts of global change on tree physiology and forest ecosystems*. Wageningen, The Netherlands: Kluwer Academic Publishers, 255–261.

von Carlowitz HC. 1713. *Sylvicultura oeconomica. Anweisung zur wilden Baumzucht*. Leipzig: Verlag Braun.

Clutter JL. 1963. Compatible growth and yield models for loblolly pine. *Forestry Chronical* **9**: 354–371.

Clutter JL, Bennett FA. 1965. Diameter distributions in old-field slash pine plantations. *Georgia Forest Research Council Reports* **13**.

Constable JVH, Friend AL. 2000. Suitability of process-based tree-growth models for adressing tree response to climate change. *Environmental Pollution* **110**: 47–59.

Cucchi V, Meredieu C, Stokes A, de Coligny F, Suarez J, Gardiner BA. 2005. Modelling the windthrow risk for simulated forest stands of Maritime pine (*Pinus pinaster* Ait.). *Forest Ecology and Management* **213**: 184–196.

Cui J, Li C, Sun G, Trettin C. 2005. Linkage of MIKE SHE to Wetland-DNDC for carbon budgeting and anaerobic biogeochemistry simulation. *Biochemistry* **42**: 147–167.

Curtis RO, Clendenen GW, De Mars DJ. 1981. *A new stand simulator for coast Douglas-fir: User's Guide*. General Technical Report. PNW-128. Portland, OR: USDA, Forest and Range Experimental Station.

Curtis RO, Clendenen GW, Reukema DC, De Mars DJ. 1982. *Yield tables for managed stands of coast Douglas-fir*. General Technical Report. PNW-135. Portland, OR: USDA, Forest and Range Experimental Station.

Decaudin P, Nayret F. 2004. Rendering forest scenes in real-time. In: Hansmann W, Purgathofer W, Sillion D, eds. *Eurographics Symposium on Rendering*. Aire-la-Ville, Switzerland: The Eurographics Association, 93–102.

Deckmyn G, Ceulemans R, Rasse D, Sampson DA, Garcia J, Muys B. 2003. Modelling the carbon sequestration of a mixed, uneven-aged, managed forest using the process model SECRETS. In: Amaro A, Reed D, Soares P, eds. *Modelling forest systems*. Wallingford: CAB International, 143–155.

Derognat C, Beekmann M, Baeumle M, Martin D, Schmidt H. 2003. Effect of biogenic volatile organic compound emissions on tropospheric chemistry during the Atmospheric Pollution Over the Paris Area (ESQUIF) campaign in the Ile-de-France region. *Journal of Geophysical Research-Atmospheres* **108**: 8560.

Deussen O, Colditz C, Stamminger M, Rettakis G. 2002. Interactive visualization of complex plant ecosystems. In: Moorhead R, Gross M, Joy KI, eds. *Proceedings of IEEE Visualization*. IEEE, 219–226.

Ek AR, Dudek A. 1980. *Development of individual tree based stand growth simulators: progress and applications*. Staff Paper 20. College of Forestry, Department of Resource, University of Minnesota.

Ek AR, Monserud RA. 1974. Trials with program FOREST: growth and reproduction simulation for mixed species even- or uneven-aged forest stands. In: Fries J, ed. *Growth models for tree and stand simulation*. Royal College of Forestry, Uppsala, Sweden, Research Note **30**: 56–73.

Farquhar GD, Von Caemmerer S, Berry JA. 2001. Models of photosynthesis. *Plant Physiology* **125**: 42–45.

Feduccia DP, Dell TR, Mann WF, Pomer BH. 1979. *Yields of unthinned loblolly pine plantations on cutover sites in the West Gulf region*. USDA Research Paper SO-148.

Fürstenau C, Badeck F, Lasch P, Lexer M, Lindner M, Mohr P, Suckow F. 2007. Multiple-use forest management in consideration of climate change and the interests of stakeholder groups. *European Journal of Forest Research* **126**: 225–239.

von Gadow K. 1987. *Untersuchungen zur Konstruktion von Wuchsmodellen für schnellwüchsige Plantagenbaumarten*. München: Ludwig-Maximilian Universität München.

von Gadow K. 2005. *Forsteinrichtung. Analyse und Entwurf der Waldentwicklung*. Göttingen: Universitätsverlag Göttingen.

Garcia-Gonzalo J, Peltola H, Zubizarreta Gerendiain A, Kellomäki S. 2007. Impacts of forest landscape structure and management on timber production and carbon stocks in the boreal forest ecosystem under changing climate. *Forest Ecology and Management* **241**: 243–257.

Gehrhardt E. 1909. Über Bestandes-Wachstumsgesetze und ihre Anwendung zur Aufstellung von Ertragstafeln. *Allgemeine Forst- und Jagdzeitung* **85**: 117–128.

Gehrhardt E. 1923. *Ertragstafeln für Eiche, Buche, Tanne Fichte und Kiefer*. Berlin: Springer-Verlag.

Gilet G, Meyer A, Neyret F. 2005. Point-based rendering of trees. In: Galin E, Poulin P, eds. *Proceedings of the Eurographics Workshop on Natural Phenomena*. Aire-la-Ville, Switzerland: The Eurographics Association, 67–72.

Grote R, Pretzsch H. 2002. A model for individual tree development based on physiological processes. *Plant Biology* **4**: 167–180.

Grundner F. 1913. *Normalertragstafeln für Fichtenbestände*. Berlin: Springer-Verlag.

Gustafson EJ, Shifley SR, Mladenoff DJ, Nimerfro KK, He HS. 2000. Spatial simulation of forest succession and timber harvesting using LANDIS. *Canadian Journal of Forest Research* **30**: 32–43.

von Guttenberg A. 1915. *Wachstum und Ertrag der Fichte im Hochgebirge*. Wien, Leipzig: Verlag Franz Deuticke.

Hamilton GJ, Christie JM. 1973. Construction and application of stand yield tables. Paper 96. British Forest Commission Research and Development.

Hamilton GJ, Christie JM. 1974. Construction and application of stand yield models. In: Fries J, ed. *Growth models for tree and stand simulation*. Royal College of Forestry, 222–239.

Hanewinkel M. 2001. Neuausrichtung der Forsteinrichtung als strategisches Managementinstrument. *Allgemeine Forst- und Jagdzeitung* **172**: 203–211.

Hartig GL. 1795. *Anweisung zu Taxation der Forsten oder zur Bestimmung des Holzertrages der Wälder*. Gießen: Heyer Verlag.

Hartig R. 1868. *Die Rentabilität der Fichtennutzholz- und Buchenbrennholzwirtschaft im Harze und im Wesergebirge*. Stuttgart: Cotta Verlag.

Hartig Th. 1847. *Vergleichende Untersuchungen über den Ertrag der Rotbuche*. Berlin: Förster Verlag.

Hartman MD, Baron JS, Ojima DS. 2006. Application of a coupled ecosystem-chemical equilibrium model, DayCent-Chem, to stream and soil chemistry in a Rocky Mountain watershed. *Ecological Modelling* **200**: 493–510.

Hauhs M, Kastner-Maresch A, Rost-Sieber K. 1995. A model relating forest growth to ecosystem-scale budgets of energy and nutrients. *Ecological Modelling* **83**: 229–243.

He HS, Mladenoff DJ, Boeder J. 1999. An object-oriented forest landscape model and its representation of tree species. *Ecological Modelling* **119**: 1–19.

He HS, Shang BZ, Crow TR, Gustafson EJ, Shifley SR. 2004. Simulating forest fuel and fire risk dynamics across landscapes – LANDIS fuel module design. *Ecological Modelling* **180**: 135–151.

Heyer G. 1852. *Über die Ermittlung der Masse, des Alters und des Zuwachses der Holzbestände*. Dessau: Verlag Katz.

Hickler T, Smith B, Sykes MT, Davis MB, Sugita S, Walker K. 2004. Using a generalized vegetation model to simulate vegetation dynamics in northeastern USA. *Ecology* **85**: 519–530.

Hong B, Swaney DP, Weinstein DA. 2006. Simulating spatial nitrogen dynamics in a forested reference watershed, Hubbard Brook Watershed 6, New Hampshire, USA. *Landscape Ecology* **21**: 195–211.

Hoyer GE. 1975. *Measuring and interpreting Douglas-fir management practices*. Report 26. Olympia, WA: State Dept. of Nat. Resources.

Hradetzky J. 1972. *Modell eines integrierten Ertragstafel-Systems in modularer Form*. PhD thesis, Universität Freiburg.

Hundeshagen JC. 1825. *Beiträge zur gesamten Forstwirtschaft*. Tübingen: Verlag Laupp.

Huth A, Ditzer Th, Bossel H. 1998. *The Rain Forest Growth Model FORMIX3*. [124] Göttingen: Verlag Erich Goltze. Göttinger Beiträge zur Land- und Forstwirtschaft in den Tropen und Subtropen. Seifert Horst S. H, Vlek Paul L. G., Weidelt H.-J.

Johnsen K, Samuelson L, Teskey R, McNulty S, Fox T. 2001. Process models as tools in forestry research and management. *Forest Science* **47**: 2–8.

Judeich F. 1871. *Die Forsteinrichtung*. Dresden: Schönfeld Verlag.

Kahn M. 1994. *Modellierung der Höhenentwicklung ausgewählter Baumarten in Abhängigkeit vom Standort*. München: Universität München. Forstliche Forschungsberichte München.

Kahn M. 1995. Die Fuzzy Logik basierte Modellierung von Durchforstungseingriffen. *Allgemeine Forst- und Jagdzeitung* **168**: 115–123.

Kahn M, Pretzsch H. 1997. Das Wuchsmodell SILVA – Parametrisierung für Rein- und Mischbestände aus Fichte und Buche. *Allgemeine Forst- und Jagdzeitung* **168**: 115–123.

Kellomäki S, Väisänen H. 1997. Modelling the dynamics of the forest ecosystem for climate change studies in the boreal conditions. *Ecological Modelling* **97**: 121–140.

Kesik M, Ambus P, Baritz R, Brüggemann N, Butterbach-Bahl K, Damm M, *et al.* 2005. Inventories of N_2O and NO emissions from European forest soils. *Biogeosciences* **2**: 353–375.

Kesik M, Brüggemann N, Forkel R, Kiese R, Knoche R, Li C, *et al.* 2006. Future scenarios of N_2O and NO emissions from European forest soils. *Journal of Geophysical Research* **111**: G02018, doi: 10·1029/2005JG000115.

Kimmins JP. 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.

Klemmt H-J. 2007. *Anwendung von Entscheidungsbaumverfahren und Regressionsanalysen zur semiautomatischen Feinkalibrierung des Wuchsmodells SILVA mit Hilfe von Forstinventurdaten*. Dissertation, Technische Universität München.

Kolström T. 1993. Modelling the development of uneven aged stand of *Picea abies*. *Scandinavian Journal of Forest Research* **8**: 373–383.

Komarov A, Chertov O, Zudin S, Nadporozhskaya M, Mikhailov A, Bykhovets S, *et al.* 2003. EFIMOD2 – a model of growth and cycling of elements in boreal forest ecosystems. *Ecological Modelling* **170**: 373–392.

Korol RL, Milner KS, Running SW. 1996. Testing a mechanistic model for predicting stand and tree growth. *Forest Science* **42**: 139–153.

Kouba J. 1973. Markov chains and definition of normal forest (in Russian). *Doklady TSChA Moscow* **194**: 185–191.

Köhler P, Huth A. 1998. An individual based rain forest model – concepts and simulation results. In: Kastner-Maresch A, Kurth W, Sonntag M, Breckling B, eds. *Individual-bsed structural and functional models in ecology*. Bayreuth: Bayreuther Institut für Terrestrische Ökosystemforschung, 35–52.

Krenn K. 1946. *Ertragstafeln für Fichte*. 3. Freiburg i. Br. Schriftenr. d. Bad. Forstl. Versuchsanst.

Kulakowski D, Rixen C, Bebi P. 2006. Changes in forest structure and in the relative importance of climatic stress as a result of suppression of avalanche disturbances. *Forest Ecology and Management* **223**: 66–74.

Lacointe A. 2000. Carbon allocation among tree organs: a review of basic processes and representation in functional-structural tree models. *Annals of Forest Science* **57**: 521–533.

Landsberg J. 2003. Modelling forest ecosystems: state of the art, challenges, and future directions. *Canadian Journal of Forest Research* **33**: 385–397.

Landsberg J, Johnsen K, Albaugh T, Allen H, McKeand S. 2001. Applying 3-PG, a simple process-based model designed to produce practical results to data from loblolly pine experiments. *Forest Science* **47**: 43–51.

Landsberg JJ, Waring RH, Coops NC. 2003. Performance of the forest productivity model 3-PG applied to a wide range of forest types. *Forest Ecology and Management* **172**: 199–214.

Lasch P, Lindner M, Erhard M, Suckow F, Wenzel A. 2002. Regional impact assessment on forest structure and functions under climate change – the Brandenburg case study. *Forest Ecology and Management* **162**: 73–86.

Lasch P, Badeck F-W, Suckow F, Lindner M, Mohr P. 2005. Model-based analysis of management alternatives at stand and regional level in Brandenburg (Germany). *Forest Ecology and Management* **207**: 59–74.

Laurence JA, Retzlaf WA, Kern JS, Lee EH, Hogsett WE, Weinstein DA. 2001. Predicting the regional impact of ozone and precipitation on the growth of loblolly pine and yellow-poplar using linked TREGRO and ZELIG models. *Forest Ecology and Management* **146**: 247–263.

Le Roux X, Lacointe A, Escobar-Gutierrez A, Le Dizes S. 2001. Carbon-based models of individual tree growth: a critical appraisal. *Annals of Forest Science* **58**: 469–506.

Leary RA. 1970. *System identification principles in studies of forest dynamics*. Research paper NC45. USDA, North Central For. Exp. Station.

Leemans R, Prentice IC. 1989. FORSKA, a general forest succession model. Uppsala: Inst. Ecol. Bot., Univ. Meddelanden fran Växtbiologiska Institutionen.

Lembcke G, Knapp E, Dittmar O. 1975. Die neue DDR-Kiefernertragstafel 1975. *Beiträge für die Forstwirtschaft* **15**: 55–64.

Lexer MJ, Hönninger K. 1998. Simulated effects of bark beetle infestations on stand dynamics in *Picea abies* stands: coupling a patch model an a stand risk model. In: Beniston M, Innes J, Wengen CH, eds. *Lecture Notes in Earth Sciences: The impacts of climate change on forests*. Berlin: Springer, 289–308.

Lexer MJ, Hönninger K. 2001. A modified 3D-patch model for spatially explicit simulation of vegetation composition in heterogeneous landscapes. *Forest Ecology and Management* **144**: 43–65.

Li C, Aber J, Stange F, Butterbach-Bahl K, Papen H. 2000. A process-oriented model of N_2O and NO emissions from forest soils: 1, Model development. *Journal of Geophysical Research* **105**: 4369–4384.

Lo E, Wang ZM, Lechowicz M, Messier C, Nikinmaa E, Perttunen J, Sievänen R. 2001. Adaptation of the LIGNUM model for simulation of growth and light response in Jack pine. *Forest Ecology and Management* **150**: 279–291.

Lu L, Pielke RA, Liston GE, Parton WJ, Ojima DS, Hartman M. 2001. Implementation of a two-way interactive atmospheric and ecological model and its application to the central United States. *Journal of Climate* **14**: 900–919.

Matala J, Hynynen J, Miina J, Ojansuu R, Peltola H, Sievänen R, *et al.* 2003. Comparison of a physiological model and a statistical model for prediction of growth and yield in boreal forests. *Ecological Modelling* **161**: 95–116.

Matjicek L, Benesova L, Tonika J. 2003. Ecological modelling of nitrate pollution in small river basins by spreadsheets and GIS. *Ecological Modelling* **170**: 245–263.

Mäkelä A, Landsberg J, Ek AR, Burk TE, Ter-Mikaelian M, Ågren GI, *et al.* 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. *Tree Physiology* **20**: 289–298.

McGaughey RJ. 2006. *EnVision – Environmental Visualization System*. University of Washington, http://forsys.cfr.washington.edu/envision.html.

McGee CE, Della-Bianca L. 1967. Diameter distributions in natural Yellow-poplar stands. Research Paper SE-25. USDA, South East Forest Experimental Station.

MCPFE. 2000. General declarations and resolutions adopted at the Ministerial conference on the protection of forests in Europe. Strasbourg 1990, Helsinki 1993, Lisbon 1998. Ministerial conference on the protection of forests in Europe. Liaison Unit, Vienna, 88.

Meiner MJ, Gandy R, Sheppard SRJ. 2005. Reviewing the role of visualization in communicating and understanding forest complexity. In: *Proceedings of the Ninth International Conference on Information Visualisation* (IV'05), IEEE, doi: 10·1109/IV.2005·114, 121–128.

Menard A, Dube P, Bouchard A, Canham CD, Marceau DJ. 2002. Evaluating the potential of the SORTIE forest succession model for spatio-tmporal analysis of small-scale disturbances. *Ecological Modelling* **153**: 81–96.

Mitchell KJ. 1969. Simulation of the growth of even-aged stands of white spruce. *Yale University, School of Forestry, Bulletin* **75**.

Mitchell KJ. 1975. Dynamics and simulated yield of douglas-fir. *Forest Science Monograph* **17**.

Mohren GMJ. 1987. *Simulation of forest growth, applied to Douglas Fir stands in the Netherlands*. Wageningen, The Netherlands: Agricultural University.

Mohren GMJ, Van de Veen JR. 1995. Forest growth in relation to site conditions. Application of the model FORGRO to the Solling spruce site. *Ecological Modelling* **83**: 173–183.

Monserud RA. 2003. Evaluating forest models in a sustainable forest management context. *Forest Biometry, Modelling and Information Sciences* **1**: 35–47.

Moser JW. 1972. Dynamics of an uneven-aged forest stand. *Forest Science* **18**: 184–191.

Moser JW. 1974. A system of equations for the components of forest growth. In: Fries J, ed. *Growth models for tree and stand simulation*. London: Royal College of Forestry, 260–287.

Mouillot F, Rambal S, Lavorel S. 2001. A generic process-based SImulator for meditERRanean landscApes (SIERRA): design and validation exercises. *Forest Ecology and Management* **147**: 75–97.

Mouillot F, Rambal S, Joffre R. 2002. Simulating climate change impacts on fire frequency and vegetation dynamics in a Mediterranean-type ecosystem. *Global Change Biology* **8**: 423–437.

Nagel J. 1996. Anwendungsprogramm zur Bestandesbewertung und zur Prognose der Bestandesentwicklung. *Forst und Holz* **51**: 76–78.

Newnham RM. 1964. *The development of a stand model for Douglas-fir*. Vancouver: Faculty of Forestry, University of British Columbia.

Nuutinen T, Matala J, Hirvelä H, Härkönen K, Peltola H, Väisänen H, Kellomäki S. 2006. Regionally optimized forest management under changing climate. *Climatic Change* **79**: 315–333.

Pacala SW, Canham CD, Silander JA Jr. 1993. Forest models defined by field measurements: 1. The design of a northeastern forest simulator. *Canadian Journal of Forest Research* **23**: 1980–1988.

Paivio A. 1971. *Imagery and verbal processes*. New York: Holt, Rinehart and Winston.

Parra R, Gasso S, Baldasano JM. 2004. Estimating the biogenic emissions of non-methane volatile organic compounds from the North Western Mediterranean vegetation of Catalonia, Spain. *Science of the Total Environment* **329**: 241–259.

Paulsen JC. 1795. *Kurze praktische Anleitung zum Forstwesen*. Verfaßt von einem Forstmanne. Detmold: von Kammerrat G. F. Führer.

Peng C, Liu J, Dang Q, Apps MJ, Jiang H. 2002. TRIPLEX: a generic hybrid model for predicting forest growth and carbon and nitrogen dynamics. *Ecological Modelling* **153**: 109–130.

Perttunen J, Sievänen R, Nikinmaa E. 1998. LIGNUM: a model combining the structure and the functioning of trees. *Ecological Modelling* **108**: 189–198.

Petritsch R, Hasenauer H, Pietsch SA. 2007. Incorporating forest growth response to thinning within biome-BGC. *Forest Ecology and Management* **242**: 324–336.

Pienaar LV, Turnbull KJ. 1973. The Chapman-Richards generalization of von Bertalanffy's growth model for basal area growth and yield in even-aged stands. *Forest Science* **19**: 2–22.

Poorter H, Nagel O. 2000. The role of biomass allocation in the growth response of plants to different levels of light, CO_2, nutrients and water: a quantitative review. *Australian Journal of Plant Physiology* **27**: 595–607.

Pretzsch H. 1992. *Konzeption und Konstruktion von Wuchsmodellen für Rein- und Mischbestände*. [115]. München: Forstwissenschaftliche Fakultät der Universität München und Bayerische Forstliche Versuchs- und Forschungsanstalt. Forstliche Forschungsberichte.

Pretzsch H. 1997. Analysis and modeling 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*. Stuttgart: Ulmer.

Pretzsch H. 2003. Strategische Planung der Nachhaltigkeit auf Forstbetriebsebene. *Forstwissenschaftliches Centralblatt* **122**: 231–249.

Pretzsch H. 2004. *Wuchsmodelle für die Planung auf Betriebsebene*. 50. Berichte Freiburger Forstliche Forschung.

Pretzsch H. 2006. Wissen nutzbar machen für das Management von Waldökosystemen. *Allgemeine Forstzeitschrift/Der Wald* **61**: 1158–1159.

Pretzsch H, Kahn M. 1996. Wuchsmodelle für die Unterstützung der Writschaftsplanung im Forstbetrieb, Anwendungsbeispiel: Variantenstudie Fichtenreinbestand versus Fichten/Buchen-Mischbestand. *Allgemeine Forstzeitschrift* **51**: 1414–1419.

Pretzsch H, Kahn M, Grote R. 1998. Die Fichten-Buchen-Mischbestände des Sonderforschungsbereiches 'Wachstum oder Parasitenabwehr?' im Kranzberger Forst. *Forstwissenschaftliches Centralblatt* **117**: 241–257.

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

Pretzsch H, Utschig H, Sodtke R. 2006. Applications of tree growth modelling in decision support for sustainable forest management. In: Hasenauer H, ed. *Sustainable forest management*. Berlin: Springer, 131–149.

Prodan M. 1965. *Holzmesslehre*. Frankfurt am Main: J.D. Sauerländer Verlag.

Pukkala T. 1987. Simulation model for natural regeneration *Pinus sylvestris*, *Picea abies*, *Betula pendula* and *Betula pubescens*. *Silva Fennica* **21**: 37–53.

Reynolds JH, Ford ED. 2005. Improving competition representation in theoretical models of self-thinning: a critical review. *Journal of Ecology* **93**: 362–372.

Robinson AP, Ek AR. 2003. Description and validation of a hybrid model of forest growth and stand dynamics for the Great Lakes region. *Ecological Modelling* **170**: 73–104.

Rötzer T, Grote R, Pretzsch H. 2004. The timing of bud burst and its effect on tree growth. *International Journal of Biometeorology* **48**: 109–118.

Rötzer T, Grote R, Pretzsch H. 2005. Effects of environmental changes on the vitality of forest stands. *European Journal of Forest Research* **124**: 349–362.

Running SW, Gower ST. 1991. FOREST-BGC, A general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. *Tree Physiology* **9**: 147–160.

Schaab G, Steinbrecher R, Lacaze B, Lenz R. 2000. Assessment of long-term vegetation changes on potential isoprenoid emission for a Mediterranean-type ecosystem in France. *Journal of Geophysical Research* **105**: 28863–28876.

Schär C, Vidale PL, Lüthi D, Frei C, Häberli C, Liniger MA, Appenzeller C. 2004. The role of increasing temperature variability in European summer heatwaves. *Nature* **427**: 332–336.

Schmid S, Zingg A, Biber P, Bugmann H. 2006. Evaluation of the forest growth model SILVA along an elevational gradient in Switzerland. *European Journal of Forest Research* **125**: 43–55.

Schmidt A. 1971. *Wachstum und Ertrag der Kiefer auf wirtschaftlich wichtigen Standorteinheiten der Oberpfalz*. 1. München: Universität München. Forstliche Forschungsberichte München.

Schober R. 1972. Buchen-Ertragstafel für mäßige und starke Durchforstung. In: Schober R ed. *Die Rotbuche 1971*. Frankfurt am Main: J. D. Sauerländer's Verlag, 333.

Schumacher S, Bugmann H. 2006. The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps. *Global Change Biology* **12**: 1435–1450.

Schumacher S, Bugmann H, Mladenoff DJ. 2004. Improving the formulation of tree growth and succession in a spatially explicit landscape model. *Ecological Modelling* **180**: 175–194.

Schumacher S, Reineking B, Sibold J, Bugmann H. 2006. Modeling the impact of climate and vegetation on fire regimes in mountain landscapes. *Landscape Ecology* **21**: 539–554.

Schwalm CR, Ek AR. 2004. A process-based model of forest ecosystems driven by meteorology. *Ecological Modelling* **179**: 317–348.

Schwappach A. 1893. *Wachstum und Ertrag normaler Rotbuchenbestände*. Berlin: Julius Springer.

Seidl R, Lexer MJ, Jäger D, Hönninger K. 2005. Evaluating the accuracy and generality of a hybrid patch model. *Tree Physiology* **25**: 939–951.

Seifert S. 2006. Visualisierung von Waldlandschaften. *Allgemeine Forstzeitschrift/Der Wald* **61**: 1170–1171.

Sheppard SRJ, Harshaw HW. 2001. *Forests and Landscapes: linking ecology, sustainability and aesthetics*. Wallingford: CABI Publishing. IUFRO research series.

Shugart HH. 1984. *A theory of forest dynamics. The ecological implications of forest succession models*. New York: Springer Verlag.

Sloboda B. 1976. *Mathematische und stochastische Modelle zur Beschreibung der Statik und Dynamik von Bäumen und Beständen – insbesondere das bestandesspezifische Wachstum als stochastischer Prozess. Habilitation*. Freiburg: University of Freiburg.

Solmon F, Sarrat C, Serca D, Tulet P, Rosset R. 2004. Isoprene and monoterpenes biogenic emissions in France: modeling and impact during a regional pollution episode. *Atmospheric Environment* **38**: 3853–3865.

Song C, Woodcock CE. 2003. A regional forest ecosystem carbon budget model: impacts of forest age structure and landuse history. *Ecological Modelling* **164**: 33–47.

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

Stephens GR, Waggoner PE. 1970. The forests anticipated from 40 years of natural transitions in mixed hardwoods. *Agricultural Experimental Station, Connecticut Bulletin* **707**.

Sterba H, Moser M, Monserud R. 1995. Prognaus – Ein Waldwachstumssimulator für Rein- und Mischbestände. *Österreichische Forstzeitung* **5**: 1–2.

Strasser U, Etchevers P. 2005. Simulation of daily discharges for the upper Durance catchment (French Alps) using subgrid parameterization for topography and a forest canopy climate model. *Hydrological Processes* **19**: 2361–2373.

Sturtevant BR, Gustafson EJ, Li W, He HS. 2004. Modeling biological disturbances in LANDIS: a module description and demonstration using spruce budworm. *Ecological Modelling* **180**: 153–174.

Suzuki T. 1971. *Forest transition as a stochastic process*. Wien: Bundesversuchsanstalt Wien. Mitteilungen der Forstl. Bundesversuchsanstalt Wien. 137–150.

Suzuki T. 1983. Übergang des Waldbestandes als ein stochastischer Prozess. In: *Schriften aus der Forstlichen Fakultät der Universität Göttingen und de Niedersächsischen Forstlichen Versuchsanstalt*. Göttingen: Beiträge zur biometrischen Modellbildung in der Forstwirtschaft, **74**: 23–58.

Thornley JHM. 1991. A transport-resistance model of forest growth and partitioning. *Annals of Botany* **68**: 211–226.

Thornley JHM, Cannell MGR. 2000. Modelling the components of plant respiration: representation and realism. *Annals of Botany* **85**: 55–67.

Ulrich B. 1999. Entwicklungsprognosen für Waldökosysteme aus der Sicht der Hierarchietätstheorie. *Forstwissenschaftliches Centralblatt* **118**: 118–126.

Valentine HT, Mäkelä A. 2005. Bridging process-based and empirical approaches to modeling tree growth. *Tree Physiology* **25**: 769–779.

Van Deusen PC, Biging GS. 1985. *STAG A Stand Generator for mixed species stands*. Version 2·0. Department of Forest and Reseasrch Management, University of California. North. Calif. Forest Yield Cooper, Res. Note.

Vanclay JK. 1994. *Modelling forest growth and yield, applications to mixed tropical forests*. Wallingford: CAB International.

Vanselow K. 1951. Fichtenertragstafel für Südbayern. *Forstwissenschaftliches Centralblatt* **70**: 409–445.

Von Cotta H. 1821. *Hülfstafeln für Forstwirte und Forsttaxatoren*. Dresden: Arnoldische Buchhandlung.

Vuokila Y. 1966. Functions for variable density yield tables of pine based on temporary sample plots. Comm. Inst. Forestalsi Fenniae **60/4**.

Walko RL, Band LE, Baron J, Kittel TGF, Lammers R, Lee TJ, *et al.* 2000. Coupled atmosphere–biophysics–hydrology models for environmental modeling. *Journal of Applied Meteorology* **39**: 931–944.

Wallman P, Svensson MGE, Sverdrup H, Belyazid S. 2005. ForSAFE – an integrated process-oriented forest model for long-term sustainability assessments. *Forest Ecology and Management* **207**: 19–36.

Wang X, Song B, Chen J, Crow TR, LaCroix JJ. 2006. Challenges in visualizing forests and landscapes. *Journal of Forestry* **104**: 316–319.

Waterworth RM, Richards GP, Brack CL, Evans DMW. 2007. A generalised hybrid process-empirical model for predicting plantation forest growth. *Forest Ecology and Management* **238**: 231–243.

Wattenbach M, Hattermann F, Weng R, Wechsung F, Krysanova V, Badeck F. 2005. A simplified approach to implement forest eco-hydrological properties in regional hydrological modelling. *Ecological Modelling* **187**: 40–59.

Weinstein DA, Laurence JA, Retzlaff WA, Kern JS, Lee EH, Hogsett WE, Weber J. 2005. Predicting the effects of tropospheric ozone on regional productivity of ponderosa pine and white fir. *Forest Ecology and Management* **205**: 73–89.

Weise W. 1880. *Ertragstafeln für die Kiefer*. Berlin: Springer.

Wensel LC, Koehler JR. 1985. *A tree growth projection system for Northern California coniferous forests*. Research Note 12. University of California, Department of Forest and Research Management, North. Calif. Forest Yield Cooper.

Werner A, Deussen O, Döllner J, Hege HC, Paar P, Rekitte J. 2005. Lenné3D – Walking through Landscape Plans. In: Buhmann E, Paar P, Bishop ID, Lange E, eds. *Trends in real-time landscape visualization and participation*. Berlin: Wichmann. 48–59.

White MA, Thornton PE, Running SW, Nemani RR. 2000. Parameterization and Sensitivity Analysis of the BIOME–BGC Terrestrial Ecosystem Model: Net Primary Production Controls. *Earth Interactions* **4**, 1–85.

Wiedemann E. 1932. Die Rotbuche 1931. *Mitteilungen aus Forstwirtschaft und Forstwissenschaft* **3/1**.

Wiedemann E. 1939. Ertragskundliche Fragen des gleichaltrigen Mischbestandes aus der Preußischen Versuchsanstalt. *Der deutsche Forstwirt*. **51**.

Wiedemann E. 1942. Der gleichaltrige Fichten-Buchen-Mischbestand. *Mitteilungen aus Forstwirtschaft und Forstwissenschaft* **13/1**.

Wolf J, Hack-ten Broeke MJD, Rötter R. 2005. Simulation of nitrogen leaching in sandy soils in The Netherlands with the ANIMO model and the integrated modelling system STONE. *Agricultural and Forest Meteorology* **105**: 523–540.

Wykoff WR, Crookston NL, Stage AR. 1982. *User's Guide to the stand prognosis model*. General Technical Report INT-133. Ogden, UT: US Forest Service.

Yaffee SL. 1999. Three faces of ecosystem management. *Conservation Biology* **13**: 713–725.

Zeng H, Peltola H, Talkkari A, Strandman H, Venalainen A, Kellomäki S. 2007. Simulations of the influence of clear-cutting on the risk of wind damage on a regional scale over a 20-year period. *Canadian Journal of Forest Research* **36**: 2247–2258.

Zimmerle H. 1952. *Ertragszahlen für Grüne Douglasie, Japaner Lärche und Roteiche in Baden-Württemberg*. Stuttgart: Ulmer.