17

Modelling in Forest Management

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17.1 THE ISSUE

Forest management has traditionally been considered management of trees for timber. It really includes vegetation management and land management and people management as multiple objectives. As such, forest management is intimately linked with other topics in this volume, most especially those chapters on ecological modelling and human dimensions. The key to responsible forest management is to understand both how forest ecosystems work and how to use this understanding to satisfy society's expectations and values. The key to forest modelling is to portray accurately the dynamics of forests. Successful forest-management modelling finds a means to improve management through accurate representation of all parts of the system. In this chapter I will review both modelling approaches and the types of applications that various modelling techniques have been used to address.

The complexity of forest management does not stop with the intricate details of the biological system found in a forest. Because all forest management is by people to meet goals or objectives desired by people, forestry is at its core a social activity. Thus, it demands that we understand the relationships among land owners, professional forest managers, forest-dependent communities and other stakeholders if we are to model the results of decisions regarding forest management. Individuals and communities have broad interests in the physical, biological and social goods and services that forest ecosystems provide. To meet the challenges of today we need to know as much about the people as about the physical and biological conditions, and to deepen our understanding of the social goods and services that we expect our forest ecosystems to supply.

Models used to assist in forest management consist of several types. First and most prevalent are growth and yield models, which predict the development of stands of trees through time. Initially, these models focused on single species, single age stands, such as one would find in plantations. Little wonder, because in plantations were the highest investments of forest managers who primarily sought timber value from the forest. As modelling sophistication increased, so did the models. Multiple species and multiple age and size classes in an individual stand have been included in growth models with varying success. Further developments along a different track have seen modelling techniques used to help schedule activities, such as harvesting or thinning in forests. Linear programming and other techniques that allow a modeller to specify constraints on resources have allowed models to find solutions to allocation problems, again primarily for those interested in extracting timber value from forests.

As various public and private groups have come to recognize the importance of forests for values beyond timber and focused research into those topics, further modelling efforts have begun to characterize these resources. Wildlife habitat, recreation opportunities and watershed protection are just a few of the benefits that now must be modelled and presented to decision-makers for their evaluation of alternative forest management strategies. These efforts face many challenges due to the inherent complexities of the systems they attempt to model and the lack of good quantitative date for many of the factors involved. In addition, the most complex and fuzziest of the factors is that of the role of humans in the forest. Models capable of predicting human needs and desires, and their implications for the state of forested ecosystems, are a great need that is still largely unmet.

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Managers need to predict effects of implementing different alternatives. Although a large body of scientific knowledge exists on relations between forest structure and pattern and ecosystem attributes, this information is frequently difficult to interpret and apply. To have and to use models that both incorporate the best knowledge available about the biological system and present the results in an interpretable and useful fashion is a significant challenge. Some such integrated models have been developed, and more are in various stages of design. Further, the incorporation of stakeholders' knowledge and goals, and the integration of social disciplines, theories and measurement techniques are difficult for many traditionally trained resource managers. One of today's greatest challenges is the development and testing of new theories and tools that describe the multiple ramifications of management decisions and that provide a practical, understandable decision process. Developing, evaluating and adapting new decision processes and their supporting software tools is a critically important endeavour in forest management and elsewhere.

17.2 THE APPROACHES

17.2.1 The empirical approach

Traditionally, simulation models of tree growth have been developed to enable projection of future timber production. Economic values drove the effort, and the models were built to do a good job of estimating growth of trees that have already reached moderate size. Limitations include the fact that these models were built from measurements on stands that have intentionally included only 'undisturbed, fully stocked' stands, rendering them of questionable use when trying to predict responses to disturbances such as thinnings or windstorms.

In a review of the earliest forest yield studies, Assmann (1970) describes several eighteenth- and nineteenth-century efforts to predict expected yields in German forests of beech and other important species. In North America, forest growth and yield prediction models began as simple estimates of standing volume (Pinchot, 1898) and progressed to estimates using increment cores (Fenska and Lauderburn, 1924). These studies and others led to stand table projection systems still in use as a basic form of empirical forest-growth modelling. Other reviews of the development of this type of modelling can be found in Chapman and Meyer (1949), Spurr (1952) and Clutter *et al.* (1983). See also http://sres.anu.edu.au/associated/mensuration/xref.htm.

17.2.2 The mechanistic approach

Models based on presumed or observed mechanisms of growth, theoretical controlling factors, and interactions among elements of a system are what I refer to here as mechanistic models. JABOWA (Botkin *et al.*, 1972) is among the earliest of these models used to simulate forest growth, which it predicts for individual trees based on available light, nutrients, temperature and other parameters. Successors to the JABOWA model include Fortnite (Aber and Melillo, 1982) and Zelig (Urban and Shugart, 1992), among others, all of which use basic ecological principles to predict the response of an individual tree to its surroundings and grow a forest by accumulating the sum of the individuals. Sortie (Pacala *et al.*, 1993, 1996) is a spatially explicit model developed using similar ecological variables to the earlier gap models. The stochastic element added to gap models complicates their use in management applications because of the need to run many simulations and average their outcomes. On the other hand, because of their reliance on basic principles, these models do a better job of predicting multiple generations of forest development than empirical models based on growth within the lifetime of an existing stand of trees, and thus are more useful for modelling long-term succession under existing or changing conditions.

A different approach to modelling tree growth mechanistically is to model individual trees primarily based on inherent physiological characteristics. For example, the pipe-model theory presumes that a given unit of foliage requires a given unit of sapwood area to supply water (Shinozaki *et al.*, 1964; Waring *et al.*, 1982). One such model, TREGRO (Weinstein and Yanai, 1994), predicts growth and carbon allocation patterns based on various levels of ozone, nutrient stress and water availability. Hybrid (Friend *et al.*, 1997) is a growth model using a combination of techniques, including competition between plants that is modelled with a gap model approach, while physiological knowledge is used to predict plant growth. Pipestem*[1] (Valentine *et al.*, 1997) is a pipe-model-based stand growth model that projects even-aged, single-species stands using production and loss rates of leaves, stems and roots.

17.2.3 The knowledge-based approach

Knowledge-based or rule-based systems are a special case of modelling in which the components being modelled and the interactions between them are not necessarily represented mathematically. Approaches such as these use a symbolic representation of information to model systems by effectively simulating the

logical processes of human experts (Reynolds *et al*., 1999). Knowledge-based systems have the advantages that they do not necessarily require the specific, detailed data that many simulation models do, and they can be adapted to situations in which some information may be lacking entirely. As such, they can be very useful in providing assistance to decision-makers who must analyse situations and choose actions without complete knowledge. Schmoldt and Rauscher (1996) point out that knowledge-based systems also prove useful as agents to codify institutional memory, manage the collection and delivery of scientific knowledge, and train managers through their ability to provide explanations of their reasoning processes. All these characteristics make knowledge-based models extremely useful in forest management.

17.3 THE CONTRIBUTION OF MODELLING

17.3.1 Models of the forest system

17.3.1.1 Growth and yield models

Predicting growth and yield has long been at the heart of simulating the future of forests. Growth and yield models were classified by Clutter *et al*. (1983) as for natural forests (either even-aged or uneven-aged) or plantations (either thinned or unthinned). Early modelling efforts, restricted by lack of computational power, typically resulted in the publication of yield tables that presented basal area or volume of a stand at regular intervals of development. See Hann and Riitters (1982) for a summary of such models in the western United States or Schumacher and Coile (1960) for an example from the southeastern United States. Assmann (1970) presents a comprehensive description of the history of European forest-yield modelling. Often, such yield tables are still adequate for managers interested primarily in timber-volume production and who have only extensive data on size class and basal area in their stands. Without more detailed data to run computer-based simulation models, yield tables still prove useful.

Computer-based simulation models now dominate the field. Simulators may be divided between stand-level models that project stand-level summary variables such as basal area and number of stems, or individual tree models that project individual trees from a tree list or by species and size class. Individual tree models can be further classified as distance-independent or distance-dependent. Clutter (1983) provides a detailed review of the various techniques. Ritchie (1999) has compiled an exhaustive description of the numerous growth and yield simulators available for the western United States and an extensive bibliography of publications using the various simulators. Ritchie (1999)* describes some newer techniques in individual tree modelling, including disaggregative techniques in which stands grown as a whole are disaggregated among trees in a list, which is maintained to allow more detailed stand parameters needed in predicting other variables. His analysis includes an evaluation of the suitability of the models for management planning. Pretzsch (2001) reviews forest growth modelling from a European perspective, including recently developed simulators of growth and visualization such as SILVA.

Examples of growth models in use in the eastern United States include FIBER, SILVAH and TWIGS. FIBER* (Solomon *et al*., 1995) is a two-stage matrix model using dynamic transition probabilities for different ecological classifications to obtain the growth of trees between diameter classes. These transition probabilities are a function of diameter, initial and residual stand basal area, proportion of hardwoods, and elevation. SILVAH* (Marquis and Ernst, 1992) is an expert system for making silvicultural decisions in hardwood stands of the Allegheny Plateau and Allegheny Mountain region that recommends appropriate treatments based on user objectives and overstorey, understorey and site data provided by the user. SILVAH also contains a forest-stand growth simulator, provides the ability to test alternative cuts, enables development of a forest-wide inventory database, and facilitates other forest management planning functions. TWIGS* (Miner *et al*., 1988) is a computer program used to simulate growth and yield for forests in the North Central region of the United States. It grows individual tree lists, has a regeneration component, and also includes management and economic analyses. Two variants are available: Central States (Indiana, Illinois, and Missouri) and Lake States (Michigan, Minnesota, and Wisconsin).

17.3.1.2 Regeneration models

Models of forest regeneration that provide reasonable estimates of tree species composition and density after a disturbance have been difficult to develop. Gap-dynamics models in the JABOWA family tend to use an approach of generating many small individuals in a predetermined proportion based on their prevalence in the seed bank or in the overstorey before disturbance and letting them die in early steps of the simulation. Empirical stand models typically have no regeneration function or a crude one that applies ingrowth to the

smaller size classes based on proportions of a previous stand (e.g. Solomon *et al*., 1995).

Recent developments using knowledge-based models to predict the composition of understorey after a minor disturbance or a newly regenerated stand after a major disturbance show some promise. Rauscher *et al*. (1997a) have developed a rule-based regeneration-prediction program for the southern Appalachians. Yaussy *et al*. (1996) describe their efforts to catalogue ecological characteristics of various species of the central hardwood forest of the United States and the individual-tree regeneration model developed from those characteristics. Ribbens (1996) developed a spatially explicit, data-intensive regeneration model called RECRUITS, which calculates the production and spatial dispersion of recruited seedlings in reference to the adults and uses maximum likelihood analysis to calibrate functions of recruitment. Because this program requires map data of adults and transect sampling of seedlings, it is unlikely to be useful in management applications.

17.3.1.3 Mortality models

Mortality of trees is an important process in forest development. Empirical simulation models usually calculate mortality through generating probabilities based on species and relative sizes, densities and ages of trees measured in the data sets used to generate the model parameters. Mechanistic models typically set a minimum level of growth parameters for survival, and a tree dies if it does not reach the minimum level. Mortality has been important to forest-management models as an indication of timber loss, so typically trees that die are removed from the model in further projections. A comprehensive review of the state of mortality models can be found in Hawkes (2000).

In recent years, dead trees, both standing and fallen, have become more widely recognized as important parts of the forest in their own right, and models are being developed to simulate creation, duration and decomposition of standing snags, fallen logs and coarse woody debris in general. Forest-fire models have recognized that dead wood within the forest is an important factor as fuel for potential fires, but forest managers are seeing the need to estimate dead wood in its various forms to feed wildlife habitat, visual quality and water quality models as well. Models to predict the longevity of dead wood include systems as diverse as subalpine Colorado (Brown *et al*., 1998), and coastal Oregon (Spies *et al*., 1988). The subject is well addressed by Parminter at http://www.for.gov.bc.ca/hre/deadwood/. Other references can be found at http://www.tws-west.org/deadwoodabstracts.html, a summary of a symposium sponsored by the Wildlife Society in 1999.

17.3.1.4 Habitat models

Providing wildlife habitat has long been one of the objectives of forest management. Often the availability of habitat that has been assumed in the forest is managed to maximize timber. Recent controversies such as those over the spotted owl and salmon habitat in the Pacific Northwest have shown that sometimes forest practices need to be altered to meet multiple objectives, and sometimes objectives other than timber are of overriding importance. Habitat-suitability models have been a common technique for formulating descriptions of the conditions needed to provide habitat for individual species. These models typically are generated from expert knowledge and expressed in terms of ranges and thresholds of suitability for several important habitat characteristics. Models that use such techniques lend themselves to adaptation to the use of fuzzy logic in a knowledge-based computer system.

Recent developments using general habitat information in a Geographic Information System (GIS) coupled with other techniques have produced a number of promising approaches to integrating timber and wildlife habitat modelling in a spatially explicit context. Hof and Joyce (1992, 1993) describe the use of mixed linear and integer programming techniques to optimize wildlife habitat and timber in the context of the Rocky Mountain region of the western United States. Ortigosa *et al*. (2000) present a software tool called VVF, which accomplishes an integration of habitat suitability models into a GIS to evaluate territories as habitat for particular species.

17.3.2 Models of human responses and interactions

17.3.2.1 Harvest-scheduling models

Large-scale analyses are necessary for policy and for including ecosystem processes that include a greater area than a stand. Spatially explicit techniques are important and valuable because we know that patterns and arrangements affect the interactions of components.

Forest managers need to plan activities across a landscape in part to maintain a reasonable allocation of their resources, but also to include considerations of maintenance of wildlife habitat and to minimize negative effects on the aesthetic senses of people who see the management activities. Gustafson (1999) has developed such a model, HARVEST*, to enable analysis of

such activities across a landscape, including an educational version, HARVEST Lite. The model has now been combined with LANDIS* (Mladenoff *et al*., 1996) to integrate analyses of timber harvesting, forest succession and landscape patterns (Gustafson and Crow, 1999; Gustafson *et al*., 2000). Hof and Bevers (1998) take a mathematical optimization approach to a similar problem, to maximize or minimize a management objective using spatial optimization given constraints of limited area, finite resources and spatial relationships in an ecosystem.

17.3.2.2 Recreation-opportunity models

Providing recreation opportunities is an important part of forest management, especially on public lands. Indeed, the total value generated from recreation on National Forests in the United States competes with that from timber sales, and may well surpass it soon (USDA Forest Service, 1995). Forest managers have long used the concept of a 'recreation opportunity spectrum' (Driver and Brown, 1978) to describe the range of recreation activities that might be feasible in a particular area, with the intention of characterizing the experience and evaluating the compatibility of recreation with other activities and goals in a particular forest or other property.

RBSim* (Gimblett *et al*., 1995, 1996) is a computer program that simulates the behaviour of human recreationists in high-use natural environments using GIS to represent the environment and autonomous human agents to simulate human behaviour within geographic space. In RBSim, combinations of hikers, mountain bikers and jeep tours are assigned individual characteristics and set loose to roam mountain roads and trails. The behaviours and interactions of the various agents are compiled and analysed to provide managers with evaluations of the likely success of an assortment of management options.

17.3.2.3 Visualization

Many people tend to respond to visual images, leading to the adage, 'a picture is worth a thousand words'. Much information generated by forest models is in the form of data tables, which are intelligible to the well initiated, but meaningless to many, including public stakeholders and many forest managers. Photographs of a forest may be nearly as good at conveying an image of the conditions as actually visiting a site, but models are used to project conditions that do not yet exist. The best available means of providing an image of potential future conditions is a computer representation of the data. One such system, the Stand Visualization System (SVS*) (McGaughey, 1997), generates graphic images depicting stand conditions represented by a list of individual stand components, e.g., trees, shrubs and down material. It is in wide use as a secondary tool, connected to growth models such as FVS* (Stage, 1973, 1997), LMS (McCarter *et al*., 1998) and NED (Twery *et al*., 2000). UTOOLS* and UVIEW are geographic analysis and visualization software for watershed-level planning (Ager and McGaughey, 1997). The system uses a Paradox database to store spatial information and displays landscape conditions of a forested watershed in a flexible framework. Another similar visualization tool is SmartForest* (Orland, 1995), which is also an interactive program to display forest data for the purposes of visualizing the effects of various alternative treatments before actually implementing them. Different versions have been developed on a variety of platforms, many of them requiring more data or computer power than is practical for management activities, but SmartForest II (Orland *et al*., 1999) is designed to run on a PC and display either stand-level or landscape data. Recently, McGaughey has developed an advanced landscape-scale visualization program addressing the same issues, entitled EnVision*.

17.3.3 Integrating techniques

17.3.3.1 Decision-support systems

Adaptive management has recently been viewed as a very promising and intuitively useful conceptual strategic framework for defining ecosystem management (Rauscher, 1999). Adaptive management is a continuing cycle of four activities: planning, implementation, monitoring and evaluation (Walters and Holling, 1990; Bormann *et al*., 1993). Planning is the process of deciding what to do. Implementation is deciding how to do it and then doing it. Monitoring and evaluation incorporate analysing whether the state of the managed system was moved closer to the desired goal state or not. After each cycle, the results of evaluation are provided to the planning activity to produce adaptive learning. Unfortunately, this general theory of decision analysis is not specific enough to be operational. Further, different decision-making environments typically require different, operationally specific decision processes. Decision-support systems are combinations of tools designed to facilitate operation of the decision process (Oliver and Twery, 1999).

Mowrer *et al*. (1997) surveyed 24 of the leading ecosystem-management decision-support systems

(EM-DSS) developed in the government, academic and private sectors in the United States. Their report identified five general trends: (1) while at least one EM-DSS fulfilled each criterion in the questionnaire used, no single system successfully addressed all important considerations; (2) ecological and management interactions across multiple scales were not comprehensively addressed by any of the systems evaluated; (3) the ability of the current generation EM-DSS to address social and economic issues lags far behind biophysical issues; (4) the ability to simultaneously consider social, economic and biophysical issues is entirely missing from current systems; (5) group consensus-building support was missing from all but one system – a system which was highly dependent upon trained facilitation personnel (Mowrer *et al*., 1997). In addition, systems that did offer explicit support for choosing among alternatives provided decision-makers with only one choice of methodology.

There are few full-service DSSs for ecosystem management (Table 17.1). At each operational scale, competing full-service EM-DSSs implement very different decision processes because the decision-making environment they are meant to serve is very different. For example, at the management-unit level, EM-DSSs can be separated into those that use a goal-driven approach and those that use a data-driven approach to the decision support problem. NED (Rauscher *et al*., 1997a; Twery *et al*., 2000) is an example of a goal-driven EM-DSS where goals are selected by the user(s). In fact, NED is the only goal-driven, full-service EM-DSS operating at the management-unit level. These goals define the desired future conditions, which define the future state of the forest. Management actions should be chosen that move the current state of the forest closer to the desired future conditions. In contrast, INFORMS (Williams *et al*., 1995) is a data-driven system that begins with a list of actions and searches the

Table 17.1 A representative sample of existing ecosystem management decision-support software for forest conditions of the United States arranged by operational scale and function

Full service EM-DSS		Functional service modules	
Operational scale	Models	Function	Models
Regional Assessments	EMDS	Group negotiations	AR/GIS
	LUCAS *		IBIS *
		Vegetation dynamics	FVS
	RELM		LANDIS
Forest-level planning	SPECTRUM		CRBSUM
	WOODSTOCK		SIMPPLLE
	ARCFOREST		
	SARA	Disturbance simulations	FIREBGC
	TERRA VISION		GYPSES
	EZ-IMPACT *		UPEST
	DECISION PLUS *		
	DEFINITE *		UTOOLS/UVIEW
		Spatial visualization	SVS *
	NED		SMARTFOREST *
	INFORMS		
Management-unit-level planning	MAGIS		LOKI
	KLEMS	Interoperable system architecture	CORBA *
	TEAMS		
	LMS *		IMPLAN
		Economic impact analysis	SNAP
		Activity scheduling	

Note: * References for models not described in Mowrer *et al*. (1997): EZ-IMPACT (Behan, 1994); DECISION PLUS (Sygenex, 1994); IBIS (Hashim, 1990); DEFINITE (Janssen and van Herwijnen, 1994); SMARTFOREST (Orland, 1995); CORBA (Otte *et al*., 1996); SVS (McGaughey, 1997); LMS (Oliver and McCarter, 1996); LUCAS (Berry *et al*., 1996).

existing conditions to find possible locations to implement those management actions.

Group decision-making tools are a special category of decision support, designed to facilitate negotiation and further progress toward a decision in a situation in which there are multiple stakeholders with varied perspectives and opinions of both the preferred outcomes and the means to proceed. Schmoldt and Peterson (2000) describe a methodology using the analytic hierarchy process (Saaty, 1980) to facilitate group decision-making in the context of a fire-disturbance workshop, in which the objective was to plan and prioritize research activities. Faber *et al*. (1997) developed an 'Active Response GIS' that uses networked computers to display proposed options and as intermediaries to facilitate idea generation and negotiation of alternative solutions for management of US national forests.

17.4 LESSONS AND IMPLICATIONS

17.4.1 Models can be useful

Models of various kinds have been very useful to forest management for a long time. The most basic models provide at least an estimate of how much timber is available and what it may be worth on the market, so that managers can determine the economic feasibility of timber cutting. More sophisticated modelling techniques provide better estimates of timber, include other forest characteristics, and project likely developments into the future. Reliability of empirical models tends to be restricted to the current generation of trees, for which they are very good.

Other forest-growth models use ecological and physiological principles to make projections of growth. Theoretical, mechanistically based models tend to be better for general pictures of forest characteristics in a more distant future projection, but may be less reliable for near-term forecasts. They tend to require more data than managers are capable of collecting for extensive tracts, and thus are often restricted to use in scientific research contexts, rather than management decisions directly. Still, such research-oriented models are still very useful in the long term, as they help increase understanding of the system and direct further investigations.

With greater and greater computing power in recent years, modelling techniques have expanded to include spatially explicit models of landscape-level change. These models now help provide the context in which a stand-level forest management decision is made, giving a manager a better understanding of the implications one action has on other areas. Positive effects are being seen in wildlife management, fire management, watershed management, land-use changes and recreation opportunities.

Other improvements in computing power and collaboration between forestry and landscape architecture have resulted in greatly enhanced capabilities to display potential conditions under alternative management scenarios before they are implemented. This capability enhances the quality of planning and management decisions by allowing more of the stakeholders and decision-makers to understand the implications of choosing one option over another. As computing power increases and digital renderings improve, care must be taken to ensure that viewers of the renderings do not equate the pictures they see with absolute certainty that such conditions will occur. We are still subject to considerable uncertainty in the forest system itself, and there is considerable danger that people will believe whatever they see on a computer screen simply because the computer produced it.

17.4.2 Goals matter

Forestry practice in general and silviculture in particular are based on the premise that any activity in the forest is intended to meet the goals of the land owner. Indeed, identification of the landowner's objectives is the first step taught to silviculturists in forestry schools (Smith, 1986). However, there has always been societal pressure for management practices, even on private lands, to recognize that actions on any particular private tract influence and are influenced by conditions on surrounding lands, including nearby communities and society at large. This implies that decision-makers need to be cognizant of the social components and context of their actions. Forest-management models intended to help land owners or managers determine appropriate actions must focus on meeting the goals defined by the user if they are to be used. Models that predetermine goals or constrain options too severely are unlikely to be useful to managers.

17.4.3 People need to understand trade-offs

There are substantial and well-developed theory and methodological tools of the social sciences to increase our understanding of the human element of forest ecosystem management (Burch and Grove, 1999; Cortner and Moote, 1999; Parker *et al*., 1999). Models of human behaviour, social organizations and institutional functions need to be applied to forest planning, policy and management. Existing laws, tax incentives and best management practices provide some context for delivering social goods, benefits and services from

forest management (Cortner and Moote, 1999). In addition, recent forest initiatives such as sustainable forestry certification through the forest industry's Sustainable Forestry Initiative (SFI) and the independent Forest Stewardship Council's (FSC) 'Green Certification' programmes include explicit, albeit modest, social considerations (Vogt *et al*., 1999). Unfortunately, these sideboards to forest management fail to deal with the complexity of forest ecosystem management. Indeed, new modelling approaches are needed to identify effectively, collect and relate the social context and components of forest ecosystem management in order to enhance and guide management decisions (Burch and Grove, 1999; Villa and Costanza, 2000). One of today's greatest challenges is the development and testing of new theories and tools that describe the multiple ramifications of management decisions and that provide a practical, understandable decision process. Developing, evaluating and adapting new decision processes and their supporting software tools are critically important endeavours.

NOTE

[1] Models with an asterisk next to their name have URLs given in the list at the end of the chapter.

REFERENCES

Ager, A.A. and McGaughey, R.J. (1997) *UTOOLS: Microcomputer Software for Spatial Analysis and Landscape Visualization*. Gen. Tech. Rep. PNW-GTR-397. Portland, OR: Pacific Northwest Research Station, Forest Service, US Department of Agriculture, Washington, DC.

Assmann, E. (1970) *The Principles of Forest Yield Study*, (translated by S.H. Gardner), Pergamon Press, Oxford.

Behan, R.W. (1994) Multiresource management and planning with EZ-IMPACT, *Journal of Forestry* **92** (2), 32–36.

Berry, M.W., Flamm, R.O., Hazen, B.C. and MacIntyre, R.M. (1996) The land-use change and analysis (LUCAS) for evaluating landscape management decisions, *IEEE Computational Science and Engineering* **3**, 24–35.

Bormann, B.T., Brooks, M.H., Ford, E.D., Kiester, A.R., Oliver, C.D. and Weigand, J.F. (1993) *A Framework for Sustainable Ecosystem Management*, USDA Forest Service Gen. Tech. Rep. PNW-331, Portland, OR.

Botkin, D.B., Janak, J.F. and Wallis, J.R. (1972) Some ecological consequences of a computer model of forest growth, *Journal of Ecology* **60**, 849–872.

Brown, P.M., Shepperd, W.D., Mata, S.A. and McClain, D.L. (1998) Longevity of windthrown logs in a subalpine forest of central Colorado, *Canadian Journal of Research* **28**, 1–5.

Burch, W.R. and Morgan Grove, J. (1999) Ecosystem management – some social and operational guidelines for practitioners, in W.T. Sexton, A.J. Malk, R.C. Szaro and N.C. Johnson (eds) *Ecological Stewardship: A Common Reference for Ecosystem Management*, Oxford: Elsevier Science, Vol. 3, 279–295.

Chapman, H.H. and Meyer, W.H. (1949) *Forest Mensuration*, McGraw-Hill, New York.

Clutter, J.L., Fortson, J.C., Pienaar, L.V., Brister, G.H. and Bailey, R.L. (1983) *Timber Management: A Quantitative Approach*, John Wiley & Sons, Chichester.

Cortner, H. and Moote, M.A. (1999) *The Politics of Ecosystem Management*, Island Press, New York.

Driver, B.L. and Brown, P.J. (1978) The opportunity spectrum concept and behavioral information in outdoor recreation resource supply inventories: a rationale, in *Integrated Inventories of Renewable Natural Resources*, USDA Forest Service General Technical Report RM-55, Fort Collins, CO, 24–31.

Faber, B.G., Wallace, W., Croteau, K., Thomas, V. and Small, L. (1997) Active response GIS: an architecture for interactive resource modeling, in *Proceedings of GIS '97 Annual Symposium*, GIS World, Inc., Vancouver, 296–301.

Fenska, R.R. and Lauderburn, D.E. (1924) Cruise and yield study for management, *Journal of Forestry* **22** (1), 75–80.

Friend, A.D., Stevens, A.K., Knox, R.G. and Cannell, M.G.R. (1997) A process-based, biogeochemical, terrestrial biosphere model of ecosystem dynamics (Hybrid v3.0), *Ecological Modelling* **95**, 249–287.

Gimblett, H.R., Durnota, B. and Itami, R.M. (1996) *Spatially-Explicit Autonomous Agents for Modelling Recreation Use in Wilderness: Complexity International*, Vol. 3, http://www.csu.edu.au/ci/vol03/ci3.html

Gimblett, H.R., Richards, M., Itami, R.M. and Rawlings, R. (1995) Using interactive, GIS-based models of recreation opportunities for multi-level forest recreation planning, *Geomatics 1995*, Ottawa, Ontario, Canada, June 1995.

Gustafson, E.J. (1999) Harvest: a timber harvest allocation model for simulating management alternatives, in J.M. Klopatek and R.H. Gardner (eds) *Landscape Ecological Analysis Issues and Applications*, Springer-Verlag, New York, 109–124.

Gustafson, E.J. and Crow, T.R. (1999) HARVEST: linking timber harvesting strategies to landscape patterns, in D.J. Mladenoff and W.L. Baker (eds) *Spatial Modeling of Forest Landscapes: Approaches and Applications*, Cambridge University Press, Cambridge, 309–332.

Gustafson, E.J., Shifley, S.R., Mladenoff, D.J., He, H.S. and Nimerfro, K.K. (2000) Spatial simulation of forest succession and timber harvesting using LANDIS, *Canadian Journal of Forest Research* **30**, 32–43.

Hann, D.W. and Riitters, K. (1982) *A Key to the Literature of Forest Growth and Yield in the Pacific Northwest: 1910–1981: Research Bulletin 39*, Oregon State University, Forest Research Laboratory, Corvallis, OR.

Hashim, S.H. (1990) *Exploring Hypertext Programming*, Windcrest Books, Blue Ridge Summit, PA.

Hawkes, C. (2000) Woody plant mortality algorithms: description, problems, and progress, *Ecological Modelling* **126**, 225–248.

Hof, J. and Bevers, M. (1998) *Spatial Optimization for Managed Ecosystems*, Columbia University Press, New York.

Hof, J. and Joyce, L. (1992) Spatial optimization for wildlife and timber in managed forest ecosystems, *Forest Science* **38** (3), 489–508.

Hof, J. and Joyce, L. (1993) A mixed integer linear programming approach for spatially optimizing wildlife and timber in managed forest ecosystems, *Forest Science* **39** (4), 816–834.

Janssen, R. and van Herwijnen, M. (1994) *DEFINITE: Decisions on a Finite Set of Alternatives*, Institute for Environmental Studies, Free University Amsterdam, The Netherlands, Kluwer Academic Publishers, software on 2 disks.

Marquis, D.A. and Ernst, R.L. (1992) *User's Guide to SILVAH: Stand Analysis, Prescription, and Management Simulator Program for Hardwood Stands of the Alleghenies*, Gen. Tech. Rep. NE-162, US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA.

McCarter, J.B., Wilson, J.S., Baker, P.J., Moffett, J.L. and Oliver, C.D. (1998) Landscape management through integration of existing tools and emerging technologies, *Journal of Forestry*, June, 17–23 (also at http://lms.cfr.washington.edu/lms.html).

McGaughey, R.J. (1997) Visualizing forest stand dynamics using the stand visualization system, in *Proceedings of the 1997 ACSM/ASPRS Annual Convention and Exposition*, April, 7–10, American Society for Photogrammetry and Remote Sensing, Seattle, WA, **4**, 248–257.

Miner *et al*. (1988) *A Guide to the TWIGS program for the North Central United States*, Gen. Tech. Rep. NC-125, USDA Forest Service, North Central Forest Experiment Station, St Paul, MN.

Mladenoff, D.J., Host, G.E., Boeder, J. and Crow, T.R. (1996) Landis: a spatial model of forest landscape disturbance, succession, and management, in M.F. Goodchild, L.T. Steyaert, B.O. Parks, C.A. Johnston, D.R. Maidment and M.P. Crane (eds) *GIS and Environmental Modeling: Progress and Research Issues*, Fort Collins, CO, 175–179.

Mowrer, H.T., Barber, K., Campbell, J., Crookston, N., Dahms, C., Day, J., Laacke, J., Merzenich, J., Mighton, S., Rauscher, M., Reynolds, K., Thompson, J., Trenchi, P. and Twery, M. (1997) *Decision Support Systems for Ecosystem Management: An Evaluation of Existing Systems*, USDA Forest Service, Interregional Ecosystem Management Coordination Group, Decision Support System Task Team, Rocky Mountain Forest and Range Experiment Station, RM-GTR-296, Fort Collins, CO.

Oliver, C.D. and McCarter, J.B. (1996) Developments in decision support for landscape management, in M. Heit, H.D. Parker and A. Shortreid (eds) *GIS Applications in Natural Resource Management 2*, Proceedings of the 9th American Symposium on Geographic Information Systems, Vancouver, BC, 501–509.

Oliver, C.D. and Twery, M.J. (1999) Decision support systems/models and analyses, in W.T. Sexton, A.J. Malk, R.C. Szaro and N.C. Johnson (eds) *Ecological Stewardship: A Common Reference for Ecosystem Management*, Oxford: Elsevier Science, Vol. III, 661–685.

Orland, B. (1995) SMARTFOREST: a 3-D interactive forest visualization and analysis system, in J.M. Power, M. Strome and T.C. Daniel (eds) *Proceedings of the Decision Support-2001 Conference*, 12–16 September 1994, Toronto, Ontario, 181–190.

Orland, B., Liu, X., Kim, Y. and Zheng, W. (1999) *Smart-Forest-II: Dynamic forest visualization*, software release to US Forest Service, Imaging Systems Laboratory, University of Illinois, Urbana (http://www.imlab.psu.edu/smartforest/)

Ortigosa, G.R., de Leo, G.A. and Gatto, M. (2000) VVF: integrating modelling and GIS in a software tool for habitat suitability assessment, *Environmental Modelling & Software* **15** (1), 1–12.

Otte, R., Patrick, P. and Roy, M. (1996) *Understanding CORBA: The Common Object Request Broker Architecture*, Prentice-Hall, Englewood Cliffs, NJ.

Pacala, S.W., Canham, C.D. and Silander, J.A.J. (1993) Forest models defined by field measurements: I. the design of a northeastern forest simulator, *Canadian Journal of Forest Research* **23**, 1980–1988.

Pacala, S.W., Canham, C.D., Silander, J.A.J., Kobe, R.K. and Ribbens, E. (1996) Forest models defined by field measurements: Estimation, error analysis and dynamics, *Ecological Monographs* **66**, 1–43.

Parker, J.K. *et al*. (1999) Some contributions of social theory to ecosystem management, in N.C. Johnson, A.J. Malk, W.T. Sexton and R. Szaro (eds) *Ecological Stewardship: A Common Reference for Ecosystem Management*, Elsevier Science, Oxford, 245–277.

Pinchot, G. (1898) *The Adirondack Spruce*. Critic Co, New York.

Pretzsch, H. (2001) *Modelling Forest Growth*, Blackwell Verlag, Berlin.

Rauscher, H.M. (1999) Ecosystem management decision support for federal forests of the United States: a review, *Forest Ecology and Management* **114**, 173–197.

Rauscher, H.M., Kollasch, R.P., Thomasma, S.A., Nute, D.E., Chen, N., Twery, M.J., Bennett, D.J. and Cleveland, H. (1997b) NED-1: a goal-driven ecosystem management decision support system: technical description, in *Proceedings of GIS World '97: Integrating Spatial Information Technologies for Tomorrow*, 17–20 February, Vancouver, BC, 324–332.

Rauscher, H.M., Loftis, D.L., McGee, C.E. and Worth, C.V. (1997a) Oak regeneration: a knowledge synthesis, *The COMPILER* **15**, 52 + 3 disks.

Reynolds, K., Bjork, J., Riemann Hershey, R., Schmoldt, D., Payne, J., King, S., DeCola, L., Twery, M. and Cunningham, P. (1999) Decision support for ecosystem management, in W.T. Sexton, A.J. Malk, R.C. Szaro and N.C. Johnson (eds) *Ecological Stewardship: A Common Reference for Ecosystem Management*. Oxford: Elsevier Science, Vol. III, 687–721.

Ribbens, E. (1996) Spatial modelling of forest regeneration: how can recruitment be calibrated?, in J.P. Skovsgaard and V.K. Johannsen (eds) *IUFRO Conference on Forest Regeneration and Modelling*, Danish Forest and Landscape Research Institute, Hoersholm, 112–120.

Ritchie, M.W. (1999) *A Compendium of Forest Growth and Yield Simulators for the Pacific Coast States*, Gen. Tech. Rep. PSW-GTR-174, Pacific Southwest Research Station, Forest Service, S Department of Agriculture, Albany, CA.

Saaty, T.L. (1980) *The Analytic Hierarchy Process*, McGraw-Hill, New York.

Schmoldt, D.T. and Peterson, D.L. (2000) Analytical group decision making in natural resources: methodology and application, *Forest Science* **46** (1), 62–75.

Schmoldt, D.T. and Rauscher, H.M. (1996) *Building Knowledge-Based Systems For Resource Management*, Chapman & Hall, New York.

Schumacher, F.X. and Coile, T.S. (1960) *Growth and Yield of Natural Stands of the Southern Pines*, T.S. Coile, Durham, NC.

Shinozaki, K., Yoda, K., Hozumi, K. and Kiro, T. (1964) A quantitative analysis of plant form – the pipe model theory, I. Basic analysis, *Japanese Journal of Ecology* **14**, 97–105.

Smith, D.M. (1986) *The Practice of Silviculture*, 8th edn, John Wiley & Sons, New York.

Solomon, D.S., Herman, D.A. and Leak, W.B. (1995) *FIBER 3.0: An Ecological Growth Model for Northeastern Forest Types*, USDA Forest Service Northeastern Forest Experiment Station, GTR-NE-204, Radnor, PA.

Solomon, D.S., Hosmer, R.A. and Hayslett, Jr. H.T. (1987) A two-stage matrix model for predicting growth of forest stands in the Northeast, *Canadian Journal of Forest Research* **16** (3), 521–528.

Spies, T.A., Franklin, J.F. and Thomas, T.B. (1988) Coarse woody debris in Douglas-fir forests of western Oregon and Washington, *Ecology* **69**, 1689–1702.

Spurr, S.H. (1952) *Forest Inventory*, Roland Press, New York.

Stage, A.R. (1973) *Prognosis Model for Stand Development*. Research Paper INT-137, US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Stage, A.R. (1997) Using FVS to provide structural class attributes to a forest succession model (CRBSUM), in R. Teck, M. Moeur and J. Adams (eds) *Proceedings of Forest Vegetation Simulator Conference, February 3–7 1997*, Fort Collins, CO, Gen. Tech. Rep. INT-GTR-373, Ogden, UT: US Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, 139–147.

Sygenex (1994) *Criterium Decision Plus: The Complete Decision Formulation, Analysis, and Presentation for Windows: User's Guide*, Sygenex Inc., 15446 Bel-Red Road, Redmond, WA 98052.

Twery, M.J., Rauscher, H.M., Bennett, D., Thomasma, S., Stout, S., Palmer, J., Hoffman, R., DeCalesta, D.S., Gustafson, E., Cleveland, H., Grove, J.M., Nute, D., Kim, G. and Kollasch, R.P. (2000) NED-1: integrated analyses for forest stewardship decisions, *Computers and Electronics in Agriculture* **27**, 167–193.

Urban, D.L. and Shugart, H.H. (1992) Individual-based models of forest succession, in D.C. Glenn-Lewin, R.K. Peet and T.T. Veblen (eds) *Plant Succession*, Chapman & Hall, New York, 249–292.

USDA Forest Service. (1995) *The Forest Service Program for Forest and Rangeland Resources: A Long-Term Strategic Plan*, Washington: US Department of Agriculture, Forest Service.

Valentine, H.T., Gregoire, T.G., Burkhart, H.E. and Hollinger, D.Y. (1997) A stand-level model of carbon allocation and growth, calibrated for loblolly pine, *Canadian Journal of Forest Research* **27**, 817–830.

Villa, F. and Costanza, R. (2000) Design of multi-paradigm integrating modelling tools for ecological research, *Environmental Modelling & Software* **15** (2), 169–177.

Vogt, K.A., Larson, B.C., Gordon, J.C., Vogt, D.J. and Franzeres, A. (1999) *Forest Certification: Roots, Issues, Challenges, and Benefits*, CRC Press, New York.

Walters, C.J. and Holling, C.S. (1990) Large-scale management experiments and learning by doing, *Ecology* **71**, 2060–2068.

Waring, R.H., Schroeder, P.E. and Oren, R. (1982) Application of the pipe model theory to predict canopy leaf area, *Canadian Journal of Forest Research* **12**, 556–560.

Weinstein, D.A. and Yanai, R.D. (1994) Integrating the effects of simultaneous multiple stresses on plants using the simulation model TREGRO, *Journal of Environmental Quality* **23**, 418–428.

Williams, S.B., Roschke, D.J. and Holtfrerich, D.R. (1995) Designing configurable decision-support software: lessons learned. *AI Applications* **9** (3), 103–114.

Yaussy, D.A., Sutherland, E.K. and Hale, B.J. (1996) Rule-based individual-tree regeneration model for forest simulators, in J.P. Skovsgaard and V.K. Johannsen (eds) *Modelling Regeneration Success and Early Growth of Forest Stands: Proceedings from the IUFRO Conference*, Copenhagen, 10–13 June 1996, Danish Landscape Research Institute, Horsholm, 176–182.

Models available on the Web

EnVision – http://forsys.cfr.washington.edu/envision.html
FIBER – http://www.fs.fed.us/ne/durham/4104/products/fiber.shtml
FVS – http://www.fs.fed.us/fmsc/fvs/index.php
HARVEST – http://www.ncrs.fs.fed.us/products/Software.htm
LANDIS – http://landscape.forest.wisc.edu/Projects/LANDIS_overview/landis_overview.html
NED – http://www.fs.fed.us/ne/burlington/ned
Pipestem – http://www.fs.fed.us/ne/durham/4104/products/pipestem.html
RBSim – http://www.srnr.arizona.edu/~gimblett/rbsim.html
Ritchie – http://www.snr.missouri.edu/silviculture/tools/index.html for numerous useful links to models of various kinds that are available for downloading
SILVAH – http://www.fs.fed.us/ne/warren/silvah.html
SmartForest – http://www.imlab.psu.edu/smartforest/
SVS – http://forsys.cfr.washington.edu/svs.html
TWIGS – http://www.ncrs.fs.fed.us/products/Software.htm (this site also contains other related models)
UTOOLS – http://faculty.washington.edu/mcgoy/utools.html