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Growth and yield models for uneven-aged stands: past, present and future

Changhui Peng*

Ministry of Natural Resources, Ontario Forest Research Institute, 1235 Queen Street East, Sault Ste. Marie, Ont., Canada P6A 2E5

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Abstract

Growth and yield modeling has a long history in forestry. Methods of measuring the growth of uneven-aged forest stands have evolved from those developed in France and Switzerland during the last century. Furthermore, uneven-aged growth and yield modeling has progressed rapidly since the first models were pioneered by Moser and Hall (1969) (Moser Jr., J.W., Hall, O.F., 1969. For. Sci. 15, 183–188). Over the years, a variety of models have been developed for predicting the growth and yield of uneven-aged stands using both individual and stand-level approaches. Modeling methodology not only has moved from an empirical approach to a more ecological process-based mechanistic approach, but also has incorporated a variety of techniques, such as, (1) systems of equations, (2) nonlinear stand table projections, (3) Markov chains, (4) matrix models, and (5) artificial neural network models. However, modeling the growth and yield of uneven-aged stands has received much less attention than that of even-aged stands. This paper reviews the current literature regarding growth and yield models for uneven-aged stands, discusses basic types of models and their merits, and reports recent progress in modeling the growth and dynamics of uneven-aged stands. Furthermore, future trends involving integration of new computer technologies (object-oriented programming and user-friendly interfaces), tree visualization techniques, and the spatially explicit application of Geographical Information Systems (GIS) into uneven-aged modeling strategies are discussed.

Keywords: Empirical models; Forest management; Mechanistic models; Simulation

1. Introduction

Forests are long-lived dynamic biological systems that are continuously changing. It is often necessary to project these changes in order to obtain relevant information for sound decision making. Forest management decisions are made based on information about both current and future resource conditions. Inventories taken at one instant in time provide information on current wood volumes and related statistics. Growth and yield models describe forest dynamics (i.e., the growth, mortality, reproduction, and associated changes in the stand) over time and hence have been widely used in forest management because of their ability to update inventories, predict future yield, and to explore management alternatives and

* Tel.: +1-705-946-2981/119; fax: +1-705-946-2030.
E-mail address: changhui.peng@mnr.gov.on.ca (C. Peng)

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silvicultural options, thus providing information for decision-making (Burkhart, 1990; Vanclay, 1994). Consequently, predicting future forest growth and yield under different management scenarios is a key element of sustainable forest management (Kimmins, 1990, 1997).

Growth and yield modeling has a long history in forestry. As early as the early 1850s, central European foresters used graphical methods to model the growth and production of forests. Yield tables, based on complete observations of yield throughout entire rotations, were constructed for important tree species in Europe (Vuokila, 1965). In contrast, American yield tables from the 1920s–1940s were based on guide curve assumptions (Spurr, 1952; Monserud, 1984). These basic yield tables persisted as the status quo for growth and yield modeling until the 1950s. The breadth and complexity of modeling efforts increased with advances in information technology. It is now 25 years since the first IUFRO meetings on forest growth and yield modeling (Fries, 1974) and 35 years since compatible growth and yield models were developed (Bucnman, 1962; Clutter, 1963). Furthermore the proceedings of Ek et al. (1988) documented worldwide efforts in these areas through the 70s and 80s. During the last two decades, along with advanced mathematical statistics and rapidly developed computing technology, growth and yield modeling methodology and technology for uneven-aged stands have moved forward significantly, and many computer-based growth and yield models, such as FOREST (Ek and Monserud, 1974), PROGNOSIS (Stage, 1973; Wykoff et al., 1982), FREP (Hahn and Leary, 1979) and its successors STEM (Belcher et al., 1982) and TWIGS (Miner et al., 1988), PP-MASAM (O'Hara, 1996), Forest Vegetation Simulator (FVS) (Teck et al., 1996) based on PROGNOSIS and uses STEM/TWIGS model architecture, and PROGNAUS (Monserud and Sterba, 1996; Sterba and Monserud, 1997), have been developed and used in forest management (Table 1). Moreover, the forest gap dynamic model (or succession model) has been developed for simulating tree growth and dynamics of mixed-species and mixed-age stands (Shugart and West, 1980; Shugart, 1984; Botkin, 1993).The first such model was the JABOWA model (Botkin et al., 1972), developed for forests in New England. Over the past 20 years, gap models have been developed for a wide variety of forest ecosystems (Shugart and West, 1980; Shugart, 1984; Botkin, 1993; Shugart and Smith, 1996).

In these models, the unit of scale ranges from the whole stand to the individual tree, and the objective extends from stand yield prediction to ecological process description. Moreover, most of these models continue to evolve as new data are acquired, design objectives are modified, or advances in mathematical and computational procedures are made. Despite this heritage, growth and yield modeling and management of uneven-aged stands remains in the early stage of development (Hann and Bare, 1979; Vanclay, 1995). Furthermore, the first comprehensive summary of research trends and modeling approaches for uneven-aged management is now 20 years old (Hann and Bare, 1979). Limited reviews, such as that by Rayner and Turner (1990) for uneven-aged eucalypt stands in Australia and by Vanclay (1995) for uneven-aged mixed species stands in tropical forests, suggest that a more recent broad-based review is warranted. Consequently, our primary objectives are to review published growth and yield models for uneven-aged stands, and to illustrate the historical development, recent progress, and future direction of alternative modeling approaches for growth and dynamics of uneven-aged stands. The author focuses on research on uneven-aged modeling rather than uneven-aged management.

2. Features of uneven-aged stands

2.1. Uneven-aged and even-aged stands

There are two typical stand structures — even-aged and uneven-aged — in silvicultural systems, although under natural forest conditions there are gradations between the two (Smith et al., 1996). An even-aged stand is a group of trees composed of a single age class, and thus originated within a short period of time. Diameters at breast height (DBH) in an even-aged stand show some variation, although most trees cluster near the average diameter, with decreasing frequencies at large and small diameters.

A stand consisting of trees of many ages is said to be uneven-aged. In an uneven-aged forest, the trees in the crown canopy vary in height, resulting in an irregular stand profile in the vertical dimension. The diameter

Table 1
Simplified chronology of selected growth and yield models for uneven-age stands

Periods	Authors	Model description	Model levels[a]
Pre-1960	De Liocourt (1898)	balanced diameter distribution (a constant *q* value)	S
	Duerr and Gevorkiantz (1938)	yield table	S
	Meyer (1952)	balanced diameter distribution (*q* ratio)	S
	Knuchel (1953)	Method du Control	S
1960–1980			S
	Leak (1964)	diameter distribution (*q* ratio)	S
	Moser and Hall (1969)	stand-level models	
	Moser (1972)	system of equations	S
	Botkin et al. (1972)	JABOWA: gap model	T
	Stage (1973)	PROGNOSIS	S
	Bruner and Moser (1973)	Markov chains	S
	Cassell and Moser (1974)	Markov chains	S
	Ek (1974)	Nonlinear stand table projection	S
	Adams and Ek (1974)	Nonlinear stand table projection	S
	Ek and Monserud (1974)	FOREST: distance-dependent model	T
	Shugart and West (1977)	FORET: gap model	T
	Frazier (1978)	Markov chains	S
	Hahn and Leary (1979)	FREP: growth projection system	S
Post-1980	Buongiorno and Michie (1980)	matrix model	S
	Wykoff et al. (1982)	PROGNOSIS version 4.0	S
	Belcher et al. (1982)	STEM model	T
	Murphy and Farrar (1982, 1983)	stand-level models	S
	Hyink and Moser (1983)	diameter distribution models	S
	Wykoff (1986)	PROGNOSIS version 5.0	S
	Farrar et al. (1984)	stand-level models	S
	Murphy and Farrar (1985)	stand-level models	S
	Murphy and Farrar (1988)	system of difference equations	S
	Pukkala and Kolström (1988)	transition matrix model.	S
	Miner et al. (1988)	TWIGS model	T
	Crookston et al. (1990); Crookston and Stage (1991)	PROGNOSIS version 6.0	S
	Kolström (1993)	transition matrix model.	S
	Guan and Gertner (1991a, b)	artificial neural network model	T
	McTague and Stansfield (1994)	system of difference equations	S
	Buongiorno et al. (1995)	nonlinear matrix model	S
	O'Hara (1996)	PP-MASAM	S
	Teck et al. (1996)	Forest Vegetation Simulator (FVS)	S
	Hasenauer and Monserud (1997)	height increment model	T
	Monserud and Sterba (1996)	PROGNAUS (basal Area increment model)	T
	Sterba and Monserud (1997)	PROGNAUS	T
	Gölser and Hasenauer (1997).	distance-dependent regeneration model	T
	Hasenauer and Merkl (1997)	artificial neural network model	T
	Favrichon (1998)	matrix model	S
	Lin et al. (1998)	density-dependent matrix model	S
	Hökkä and Groot (1999)	individual-tree basal area growth model	T

[a] S: Stand level model; T: Individual tree level model.

distribution for small areas of uneven-aged forests may show considerably greater irregularity. As the area of the uneven-aged stand or forest increases, the irregularities tend to even out and the typical reverse, J-shaped diameter distribution becomes apparent. Uneven-aged stands are commonly characterized by three variables: (1) maximum diameter, (2) density (usually expressed in units of basal area) and (3) the ratio (or factor) q-which is the ratio of the numbers of trees in adjacent diameter classes (Murphy and Farrar, 1982).

2.2. Difficulties in modeling uneven-aged stands

There are a numbers of reasons that modeling of growth and yield in uneven-aged stands has not been as widespread as for even-aged stands in forest management.

2.2.1. Lack of concentration and research efforts in uneven-aged management

The philosophy of uneven-aged management stemmed from France and Switzerland after even-aged management was well developed in Germany and Austria (Knuchel, 1953; Vuokila, 1965). Although, the pioneer uneven-aged silvicutural system of loblolly-shortleaf pine stands in southern Arkansas had been developed by R.R. Reynolds and his colleagues in the early 1930s (Reynolds, 1980) and the work by Eyre and Zillgitt (1950, 1953) in northern hardwoods of the Lake State, in North America today, uneven-aged forest management has simply followed the even-aged management philosophy (Hann and Bare, 1979; Baker et al., 1996). Consequently, development of systems unique to uneven-aged stands has been limited for some ecosystems.

2.2.2. Scarcity of suitable data and experiments

Given that growth and yield models are used to project the present forest stock and to evaluate alternative silvicultural treatment effects, both inventory data (which describe operational stands of interest) and experimental or research data (which describe responses to treatment) are needed. However, historically, data available for modeling uneven-aged stands has been limited for certain forest types (Murphy and Farrar, 1983). Although forest gap models have already been used for more than two decades (Botkin et al., 1972; Shugart and West, 1977; Shugart and Smith, 1996), they have rarely been validated with observation, mainly because appropriate data are difficult to obtain. The lack of experiments is mainly due to the fact that we also lack a temporal reference system in uneven-aged stands (neither stand age, nor tree age have any significance) and a canonical way for describing the structure of such stands, especially when they are mixed; also there is a lack of empirical rules (such as those derived from the long-term permanent plots and experiments which were used to build yield tables). Nevertheless, recent improvements in data collection and sampling design procedures for uneven-aged stands will no doubt facilitate improved future model developments, calibration, and validation (Baker et al., 1996).

2.2.3. Different modeling philosophy

Some variables such as age and site index used in even-aged models are not directly applicable to uneven-aged stands. Since uneven-aged stands are composed of trees that differ markedly in age, stand age cannot be used to predict growth and yield. Furthermore, site quality assessment using site index, an age-dependent variable, is questionable because of initial suppression of advance reproduction, especially for tolerant species. A number of growth and yield models, using neither age as a variable, or site index for assessing site quality, have been proposed for uneven-aged stands in the Unite States (e.g., PROGNOSIS: Stage, 1973; Wykoff et al., 1982, FREP: Hahn and Leary, 1979, STEM: Belcher et al., 1982, TWIGS: Miner et al., 1988, PP-MASAM: O'Hara, 1996) and in Austria (e.g., PROGNAUS: Monserud and Sterba, 1996; Sterba and Monserud, 1997). In fact, modeling techniques developed for uneven-aged stand may be applied to even-aged conditions.

3. Types of models

Growth and yield models may consist of a single equation or a series of interrelated sub-models, which together comprise of a simulation system. Although the data requirements, design, and output variables of these models may vary, they can be classified according to their purpose as well as their level of focus. The following different classifications are traditionally used to identify different modeling philosophies that have developed over the past 50 years.

3.1. Whole stand and individual tree models

Growth and yield models are traditionally classified by the variables used to define the growth process. Munro (1974); Burkhart (1990) classified growth and

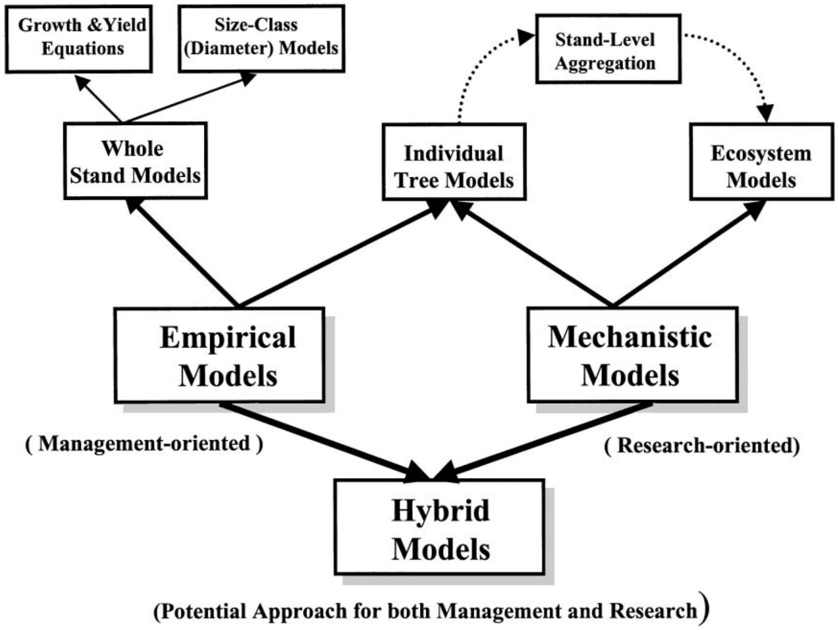

Fig. 1. Classification of forest growth and yield models for uneven-aged stands.

yield models into two major categories: whole stand and individual tree models (Fig. 1).

Whole stand models use stand parameters such as basal area, volume density, and parameters characterizing the underlying diameter distribution to simulate the stand growth and yield. Avery and Burhart (1994) and Vanclay (1994) schematically classify whole stand models into growth and yield equations and size-class (diameter) distribution categories (Fig. 1). Most whole stand models are usually simple and robust, and require relatively little information to simulate stand growth and development. However, they provide little or no detail about individual trees within a stand. They have been very useful for modeling plantations, but are of limited use in mixed forests, where the number of species and the size distributions are difficult to describe using a few stand-level variables (Vanclay, 1994). Size class models provide some information relating to stand structure. One size-class distribution model widely applied in uneven-aged stands uses the stand table projection method (Ek, 1974). Individual tree models simulate each individual tree as a basic unit with respect to establishment, growth and mortality, and sum the resulting individual tree estimates to produce stand-level values. Individual tree models can be further classified into distance independent, where tree spatial locations are not required (e.g., the JABOWA model, Botkin et al., 1972; Botkin, 1993, the FORET model, Shugart and West, 1977; Shugart, 1984) and dependent models, where inter-tree spatial locations are required (e.g., FOREST, Ek and Monserud, 1974). Table 2 shows a simple comparison of these models type (e.g., growth and yield equation, size-class distribution model and individual tree model).

3.2. Empirical growth and yield and mechanistic process models

Depending on the structure and description process of their simulation system, Landsberg (1986); Kimmins (1990); Mohren et al. (1994) categorize growth and yield models into empirical, process (mechanistic), or hybrid classes (Fig. 1). Empirical models are derived from large amounts of field data, and describe growth rate as a regression function of variables such as site index, age, tree density, and basal area. Empirical models rely on the process of production, in which a set of simulation system inputs and outputs are observed, recorded, and measured, and some or all

Table 2
Comparison of three types of models for uneven-aged stands

	Growth and yield equations	Size-class distribution models	Individual tree models
Example	Moser and Hall (1969)	Ek (1974)	Ek and Monserud (1974)
Approach	volume growth-rate equation	stand table projection model	FOREST: a distance-dependent model
Driving Variables	initial basal area, elapsed time interval	stand basal area, number of trees and basal area in specified diameter class, site index (height)	tree coordinates, height, diameter, clear bole length, species
Equations	$V = [V_0\ (8.3348\mathrm{BA}_0 - 1.3175)] \times [0.9348 - (0.9348 - 1.0203\mathrm{BA}_0{}^{-0.0125}) \times \exp(-0.0062\ T)]^{-105.4}$ Note (1)[a]	$Y_{\mathrm{in}} = 15.123N^{0.38753} \times \exp(-0.32908\mathrm{BA}^{1.58011}\mathrm{N}^{-1})$ $Y_{\mathrm{m}} = 0.03443n[(\mathrm{BA}/N)/(\mathrm{ba}/n)]^{0.54748}$ $Y_{\mathrm{up}} = 0.0107n^{0.81433}S \times [(\mathrm{ba}/n)/(\mathrm{BA}/N)]^{0.14611} \times \exp(-0.00160\mathrm{BA})$ $\Delta n = Y_{\mathrm{in}} - Y_{\mathrm{m}} - Y_{\mathrm{up}} + Y_{\mathrm{i}}$ Note (2)[b]	$\mathrm{HIN} = \mathrm{PHIN} \times \mathrm{HMULT} + \mathrm{PHIN} \times \mathrm{HMULT} \times \mathrm{WNOISE}$ (1) $\mathrm{DIN} = \mathrm{PDIN} \times \mathrm{DMULT} + \mathrm{PDIN} \times \mathrm{DMULT} \times \mathrm{WNOISE}$ (2) $\mathrm{PLIVE} = \mathrm{PLIVE} + \mathrm{PLIVE} \times \mathrm{WNOISE}$ (3) $\mathrm{CIU}_i = \Sigma_j[(O_{\mathrm{ij}}/A_i) \times (S_j/S_i)]$ $\mathrm{CIA}_i = \mathrm{CIU}_i\ (\mathrm{TOL}_i)$ Note (3)[c]
Advantage	can be applied with existing inventory data, and is computation efficient	requires only overall stand values as input, but provide detailed size-class information as output	provides maximum detail and flexibility for evaluating alternative utilization options and stand treatments
Disadvantage	does not provide size-class information needed to evaluate various utilization options, and cannot be used to analyze a wide range of stand treatments	not flexible enough to evaluate a broad range of stand treatments	more expensive to develop, require a more detailed database to implement

[a] Note (1): V is predicted volume (cu ft); V_0 initial volume (cu ft per acre); BA_0 initial basal area (sq. ft per acre); and T is the elapsed time interval, years from initial conditions.

[b] Note (2): Y_{in} is stand ingrowth, merchantable trees at t_1 that were nonmerchantable at t_0; Y_{m} mortality, trees present in a diameter class at t_0 but dead at t_1; Y_{up} upgrowth, trees present in a diameter class at t_0 that grow into next larger diameter class at t_1; N number of trees per acre in stand; n number of trees in specified diameter class; BA stand basal area (sq. ft per acre); ba basal area in specified diameter class; S site index (height, ft, at age 50 years); Δn net 5 year change in the number of trees in a diameter class; and Y_{i} is ingrowth, upgrowth from next lower measured diameter class.

[c] Note (3): HIN is height increment; PHIN potential height increment; HMULT derivation of height increment realization multiplier which is estimated as a function of competition index (CIA); WNOISE(1–2) correlated random variable $N(0, \sigma^2)$ where $\sigma = (1/y_{\mathrm{mean}}) \times$ (standard error of residuals) and y_{mean} is the mean of the dependent variable; DIN diameter increment; PDIN potential diameter increment; DMULT derivation of diameter increment realization multiplier which is estimated as a function of CIA; PLIVE tree survival probability; WNOISE(3) generated random variable $N(0, \sigma^2)$ where σ is derived from residual variation obtained in model fitting process. A_i is the zone of influence of the ith tree defined as the area of a circle of radius equal to that of an open grown tree of the same height; O_{ij} area of zone of influence overlap between the ith tree and its jth competitor; S_i size of ith tree (height × crown radius); S_j size of jth competitor (height × crown radius); TOL_i shade tolerance value between 0 and 1 expressed as a function of tree size and species; and CIU_i is the unadjusted (by tolerance) competition index.

of the mathematical models are inferred. These empirical models are based on massive experimentation or inventory where the available input and output data are accepted as the most appropriate. The major strength of the empirical approach is in describing the best relationship between the measured data and the growth-determining variables using a specified mathematical function or curve. In implementation, empirical models require only simple inputs, and are easily constructed. They are also easily incorporated into diversified management analyses and silvicultural treatments, and are able to achieve greater efficiency and accuracy in providing quantitative information for forest management. They may be an appropriate method for predicting short-term yield for time scales over which historical growth conditions are not expected to change significantly. Empirical growth and yield models may not be used, for example, to analyze the consequences of climatic changes or environmental stress (Kimmins, 1990; Shugart et al., 1992).

Unlike empirical models, process models generally are developed after a certain amount of knowledge has

Table 3
Comparison major features of growth and yield models (empirical vs. mechanistic) used for forest management and research

Users	Empirical models	Mechanistic (Process) models
	Foresters and forest managers	Research scientists and university researchers
Forest management	high	low
Research	intermediate	high
Extension service	high	low
Prediction time	short-term	long-term
Complexity	low to high	high
Flexibility	intermediate	low
Model parameters	few to many	many
Field measurements plots	many	none to few
Environmental measured factors	site index, site characteristics	temperature, light, water, nutrients and disturbance

been accumulated using empirical models, and may describe a key ecosystem process or simulate the dependence of growth on a number of interacting processes, such as photosynthesis, respiration, decomposition, and nutrient cycling. These models offer a framework for testing and generating alternative hypotheses and have the potential to help us to accurately describe how these processes will interact under given environmental change (Landsberg and Gower, 1997). Consequently, their main contributions include the use of eco-physiological principles in deriving model development and specification, and long-term forecasting applicability within changing environments. A number of process-based growth and yield models have been developed to help predict forest growth and yield under changing conditions (e.g., Bossel and Schäfer, 1989; Dixon et al., 1990; Amateis, 1994; Mohren et al., 1994). An example of this class of model is TREE-BGC (Korol et al., 1994, 1996), which simulates the flux of carbon, water and nutrients through a plant-soil system in response to environmental conditions. West (1987) provides an example of a typical process-based model designed to simulate silvicultural treatment response. The application of process-based forest productivity models in forest management was recently reviewed by Battaglia and Sands (1998). They include that a change in the questions being asked in forest management, for example in relation to sustainability, biodiversity, and climate change, has increased the potential use of mechanistic process models. However, process-based models will need to be at least as accurate as empirical models across the decade to rotation length time periods commonly considered in forest management.

Table 3 briefly lists the advantages and disadvantages of empirical and process models. Generally, a weakness of the growth and yield model is a strength of the process model, and vice versa. It is almost always possible to find an empirical model that provides a better fit for a given set of data due to the constraints imposed by the assumptions of process models (Landsberg and Gower, 1997). Nevertheless, empirical and process approaches (models) can be married into hybrid models in which the shortcomings of both component approaches can be overcome to some extent. This is the rationale behind the hybrid simulation approach to growth and yield modeling (Kimmins, 1993). Specifically, incorporating the key elements of empirical and process approaches into a hybrid ecosystem modeling approach can result in a model to predict forest growth and production in both the short and long term. Kimmins (1990) developed a framework for hybrid simulation yield modeling that uses the historical growth pattern as a baseline estimate of future forest growth under unchanged conditions, and then simulates changes in future forest growth modified by the expected changes in growth-determining processes.

4. Historical development of models

4.1. Early work

Methods of measuring the growth of uneven-aged forest stands have evolved from those developed in France and Switzerland during the last century. A famous Swiss forester, M. Henri Billey, introduced his Méthode du Contrôle (control or check method), which is well documented by Knuchel (1953). He established a successive inventory system that measured all small, medium, and large trees. These data were then used in planning the fellings over the next period. The stand prediction method created by Meyer (1953) was similar to the Méthode du Contrôle, but predicted future structure of a stand either from the increment measured from successive inventories, in sample plots, or by increment borings. Mortality and regeneration were normally taken into account.

The demand for more detailed information, the stand table, to determine harvest and siliviculture treatments dates back to 1898 when De Liocourt (1898) first observed the tendency of many uneven-aged stands to exhibit a reverse J-shaped diameter distribution that could be described by geometric progression. This progression is defined by q-the constant ratio of the numbers of trees in a given diameter class to the number of trees in the next larger diameter class. This relationship has been quantitatively described in the equation of Murphy and Farrar (1982). What de Liocourt found was that a balanced, or sustainable, diameter distribution was characterized by a constant 'q' (Meyer, 1953). Since then, the constant 'q' has been central to the discussion concerning uneven-aged silviculture given its relationship to sustainable yield management.

Meyer (1952) defined a balanced, uneven-aged forest structure as one where constant yield can be removed periodically while maintaining the structure and volume of the forest. His work showed that reverse J-shaped distribution could be a useful form for uneven-aged stands. The balanced concept has been referred to as a sustainable, equilibrium, or steady-state structure in uneven-aged modeling studies (Adams and Ek, 1974; Adams, 1976; Lorimer and Frelich, 1984; Hansen and Nyland, 1987; Chapman and Blatner, 1991; Gove and Fairweather, 1992). The implication is that the diameter distribution and density will be maintained over time in a natural stand through mortality, or that the distribution and density can be maintained forestwide through cutting and mortality (Leak, 1996).

Much progress in uneven-aged growth and yield modeling has occurred since the first prediction models were pioneered by Moser and Hall (1969). Since then, a wide variety of models has been developed for predicting the growth and yield of uneven-aged stands at both the individual tree and stand levels. Over time, the general level of sophistication of these models has grown owing to many factors, including more refined statistical estimation techniques, expanding databases, and the burgeoning power and availability of computers. Growth and yield methodology for uneven-aged (age-indeterminate) and mixed-species stands has incorporated a variety of techniques (see Table 1): (1) Stand-level models (Leak, 1964; Moser and Hall, 1969; Murphy and Farrar, 1982, 1983, 1985; Farrar et al., 1984); (2) Systems of equations (Moser, 1972, 1974; Leary et al., 1979; McTague and Stansfield, 1994); (3) Nonlinear stand table projection (Adams and Ek, 1974; Ek, 1974); (4) Markov chains (Bruner and Moser, 1973; Cassell and Moser, 1974; Frazier, 1978); (5) Matrix models (Buongiorno and Michie, 1980; Mendoza and Setyarso, 1986; Solomon et al., 1986; Pukkala and Kolström, 1988; Kolström, 1993; Solomon et al., 1995; Virgilietti and Buongiorno, 1997; Favrichon, 1998); and (6) Artificial neural network techniques (Guan and Gertner, 1991a,b, 1995; Hasenauer and Merkl, 1997; Keller et al., 1997). An overview of growth and yield developments can be found in Knoebel et al. (1986); Kimmins (1993).

4.2. Growth and yield equations

Moser and Hall (1969) developed a volume growth rate equation for uneven-aged stands of mixed northern hardwoods. The resulting equation expresses yield as a function of time, initial volume, and basal area. Integrating and substituting for volume leads to compatible growth and yield equations for both basal area and volume. In a later version, Moser (1974) used a set of first-order, ordinary differential equations to express gross growth, mortality, and ingrowth rates for all trees 7 in. (17.8 cm) or greater.

Khatouri and Dennis (1990) have developed a stand-level model to predict growth and yield in uneven-aged cedar (*Cedrus atlantica Manetti*) stands in the Ajdir Forest in Morocco. Based on temporary plots, they used a system of 11 first-order nonlinear differential equations relating the rates of change of ingrowth, mortality, and survivor growth to stand conditions and predicted yield from different model and diameter distributions. A method for obtaining compatible estimates between stand-level project equations and individual-tree growth and mortality for uneven-aged ponderosa pine was reported by McTague and Stansfield (1994). They used a system of algebraic difference equations to predict several stand attributes including number of pole trees, surviving number of merchantable trees, and survivor basal area. Ingrowth is indirectly derived from projected equations that model the total changes in the number of pole trees. Ingrowth diameter distribution is estimated with a parameter recovery method for an uniform distribution. The individual tree growth and mortality equations are consistent with the stand-level projection equation.

4.3. Size-class (diameter) distribution models

Leak (1964) reported methods for determining stand structure when stand density is measured by basal area. Moser (1976) has presented a unified technique in which reverse J-shaped diameter distributions can be discretely specified by an exponential function with density expressed as basal area, tree-area ratio, or crown competition factor.

$$\text{density} = f(\text{basal area, tree-area ratio, or crown competition factor})$$

Murphy and Farrar (1982) provided a good example of a diameter distribution model in which the underlying diameter distribution was expressed as a function of basal area and tree-area ratio.

Another approach to size-class distribution modeling in uneven-aged stands is the use of the stand-table projection model developed by Ek (1974). He reported equations to predict periodic ingrowth, mortality, and survivor growth by 2 in. (5 cm) diameter classes, in northern hardwood stands. Net 5 year change in the number of trees in a diameter class (Δn) was defined as

$$\Delta n = \text{stand ingrowth} - \text{mortality} - \text{upgrowth} + \text{ingrowth}$$

Stand ingrowth and mortality are estimated as a function of basal area and number of trees per acre in the stand. Upgrowth is calculated as a function of basal area, site index and number of trees per acre in the stand. Ingrowth is the upgrowth from next lower measured diameter class and estimated as a function of stand basal area and number of trees per acre in the stand.

4.4. Individual-tree models

4.4.1. Distance-independent models

Most distance-independent tree-level models require stand table data as inputs in addition to such stand-level information as age and index. Typical examples are the pine growth model of New Zealand Monterey developed by Clutter and Allison (1974) and the growth model developed by Alder (1979) for thinned conifer plantations in East Africa. A number of distance-independent models have been used to optimize rotation, growing-stock level, thinning type, species mixture, and planting density (e.g., Bullard et al., 1985; Roise, 1986; Bare and Opalach, 1987; Haight and Monserud, 1990a,b; Yoshimoto et al., 1990; Solberg and Haight, 1991; Valsta, 1992a,b; Carlsson, 1995). One of the few distance-independent stand models that does not need site index and age, and has the potential for adaptation to uneven-aged stands is the widely used Prognosis model originally developed by Stage (1973) and Wykoff et al. (1982), The latest version is now called Forest Vegetation Simulator (FVS) (Teck et al., 1996), which is a framework that contains about 20 geographic variants across United States (Teck et al., 1997) and links a number of previously existing models, including GENGYM (Edminster et al., 1991), Lake State TWIGS (USDA Forest Service, 1979), Central States TWIGS (Shifley, 1987) and Northeast TWIGS (Hilt and Teck, 1989), into one software package, with a common interface of SUPPOSE (Crookston, 1997). The Prognosis model is a set of computer programs that predict the growth and development of forest stands in North Idaho. An important feature of this model is that it is able to predict the growth and development of forest stands with any composition, from pure even-aged to mixed-species uneven-aged structures. The basic modeling unit is the individual tree. Prognosis consists of 4 major submodels: (1) diameter increment, (2) height increment, (3) crown ratio development, and (4) mortality. Its growth equations are a function of tree size, vigor, and dominance, not age; site productivity is described by site characteristics, not tree characteristics (e.g., site index), and it has a proven track record of 20 years of reliable use, in North America (Teck et al., 1996). Wykoff and Monserud (1988) demonstrated that the Prognosis model for representing site quality performs as well as approaches using traditional site index information. One of the obvious advantages of distance-independent models (such as Prognosis) is that they do not require tree coordinates (tree spatial information), which are usually not available in forest inventory and permanent sample plots. In addition, Stage's approach does not require the complete enumeration of the plots to be 'prognosticated'. Instead, it is based on samples drawn from throughout the stand. This lessens the amount of data required to run the model and makes it possible to apply to uneven-aged stands, which are often large in size. However, individual tree distance-independent models are limited in their ability to provide accurate individual tree development information.

Another typical example of a distance-independent model is the forest gap model, which incorporates explicit representation of key ecological processes including establishment, tree growth, competition, death, and nutrient cycling. All other gap models were eventually derived from the parental models of JABOWA (Botkin et al., 1972) and FORET (Shugart and West, 1977; Shugart, 1984). They have similar rationale and basic structure. More recently, a number of different forest gap models have been used to evaluate forest sustainability and the effect of harvesting regimes (Aber et al., 1978, 1979, 1982; Botkin, 1993; Pausas and Austin, 1998), to analyze wildlife habitats and biodiversity (Botkin et al., 1991; Pausas et al., 1997; Kolström, 1998), and to simulate potential effect of climate change on tree species composition (e.g., Pastor and Post, 1988; Overpeck et al., 1990; Solomon and Bartlein, 1992; Prentice et al., 1993; Price and Apps, 1996; Shugart and Smith, 1996) and ecosystem structure and function (Pastor and Post, 1986; Smith and Urban, 1988; Friend et al., 1993; Bugmann and Solomon, 1995; Jiang et al., 1999; Price et al., 1999).

4.4.2. Distance-dependent model

Unlike distance-independent models, distance-dependent models typically require a pair of X–Y coordinates that specify the tree's location within the area. All trees for which growth is being predicted are included in the growth projection plot. Information provided for each tree includes DBH, height, crown ratio, or crown diameter. The fundamental assumption of the distance-dependent model is that individual tree growth can be predicted if location and sizes of neighboring competitors are known. Distance-dependent models are generally developed to describe the effect of competition on the growth of a single tree. Competition indices, particularly in mixed forests, are useful tools for quantifing the variation in stand structure so that the development of a single tree can be predicted more precisely (e.g. Newnham and Smith, 1964; Bella, 1971; Mitchell, 1975; Daniels et al., 1986; Pukkala, 1989; Pukkala and Kolström, 1991; Biging and Doppertin, 1992, 1995). Another typical example is FOREST (Ek and Monserud, 1974), an individual-tree-based stand model designed to simulate the growth and reproduction of even-or uneven-aged mixed species stands of northern hardwoods. It consists of separate component models for overstory tree diameter growth, height growth, and survival, as well as reproduction, establishment, understory tree height growth, and survival. In FOREST, all of the above component processes are affected by the spatial location of trees on the study plot. Spatial information is summarized by a competition index, which is calculated for every tree at the start of each growth period. The competition index is based on the area of overlap of the hypothetical open-grown crowns of all potential competitors and is weighted by the relative sizes of the competitors to account for availability of light, moisture, and nutrients to the tree. Mortality occurs when the probability of survival for a stem falls below a threshold value, which is depends on the competitive status of a tree. Usual input for FOREST is a set of tree coordinates and associated tree characteristics (e.g., height, diameter, age, clear bole length, and species). Tree coordinates and tree characteristics may also be generated by the program. Model outputs consist of periodic stand tables with product yields and mortality information.

This type of simulator can provide more detailed information about tree and stand development and incorporate relationships expressing biological and ecological interactions at a more fundamental level than is possible with other models. Some argue that most distance-dependent models are able to reliably predict growth in stand types for which little or no empirical data are available (Clutter et al., 1983; Vanclay, 1994). There are two major inconveniences when using individual tree distance-dependent models to answer uneven-aged management questions: (1) these models are expensive to develop because data with individual tree coordinates are not common; and (2) the plots generated by distance-dependent models may not be large enough to represent uneven-aged stands accurately.

4.4.3. Individual-tree basal area growth models

Individual tree growth may be expressed as basal area increment or as diameter increment (Vanclay, 1994). There is growing interest in developing tree basal area growth models (or basal area increment models) (Lemmon and Schumacher, 1962; West, 1980; Burkhart and Sprinz, 1984; Pienaar and Shiver, 1984; Pienaar et al., 1985), because basal area is directly related to silvicultural practices. Consequently, modeling diameter or basal area growth and its response to stand and site variables has been intensively studied (Wykoff, 1990; Hann and Larsen, 1991; Quicke et al., 1994; Monserud and Sterba, 1996; Murphy and Shelton, 1996; Sterba and Monserud, 1997; Hökkä et al., 1997; Hökkä and Groot, 1999). As Murphy and Shelton (1996) pointed out, there have been two basic approaches used to predict the growth of uneven-aged stands.

One approach is to develop a single equation (which is a function of tree, stand, and site variables) to describe growth and estimate all parameters simultaneously. The Prognosis model (Stage, 1973; Wykoff, 1990) is a good example. This approach generally relies on the formulation of linear equations. Competition and vigor are used to explain deviations about a mean growth rate, instead of deviation from potential growth (Wykoff, 1990). Recent examples are found in Hann and Larsen (1991), Monserud and Sterba (1996), and Sterba and Monserud (1997).

An alternative approach to modeling diameter increment is to predict tree growth from a potential growth function multiplied by a modifier function (Ek and Monserud, 1974; Quicke et al., 1994; Vanclay, 1994):

$$\text{GROWTH} = (\text{Potential Growth}) \times (\text{Modifier Function})$$

Potential growth represents the maximum growth attainable for a tree. The modifier function represents deviation from the potential due to competition or other limiting factors. Potential growth is generally estimated separately from the modifier function. Teck and Hilt (1991) selected the top 10% of trees in each group to develop the potential growth function. Similar samples can be found in Hahn and Leary (1979); Leary and Holdaway, (1979); Quicke et al. (1994). Murphy and Shelton (1996) listed two techniques that have been used to derive a potential growth function. One is to select a subset of the growth data that represents trees unaffected by the competing influence of other trees. This idea was used to develop tree growth simulators such as FREP (Hahn and Leary, 1979) for Lake State forests, and its successors STEMS (Belcher et al., 1982) and TWIGS (Miner et al., 1988). The second technique involves using open-grown tree data to derive the coefficients for the potential function. A good example using this technique is given in Smith et al. (1992).

Some argue that modeling basal area increment is preferable to diameter increment given that basal area increment correlates with volume growth. The decision to use diameter or basal area increment in growth modeling seems to be arbitrary. West (1980) concluded that no a priori reason exists for expressing growth as diameter increment or basal area increment in tree growth studies.

5. Recent progress

More recently, a new variant of Prognosis-PROGNAUS (PROGNosis for Austria), has been developed by Monserud and Sterba (1996) for predicting the development of both pure even-aged and mixed-species uneven-aged stands in Austria using distance-independent individual tree methods. It was validated in the Bohemian Massif of Austria using independent permanent plot data (Sterba and Monserud, 1997). Another variant of Prognosis (Prognosis^{BC}) is reported on the Internet (http://www.for.gov.bc.ca/resinv/homepage.htm) by the BC Ministry of Forests, Resources Inventory Program (Victoria, March, 1997).

O'Hara (1996) developed PP-MASAM (Ponderosa Pine Multi-Aged Stocking Assessment Model) to predict gross and recoverable stand volume increment with different stocking assumptions over one cutting cycle. Based on an average tree approach, PP-MASAM used four parameters to predict stand increment: (1) total stand leaf area index (LAI), (2) trees per ha in a cohort, (3) total leaf area per cohort, and (4) tree growth per unit leaf area. This model suggests that residual age structures with large numbers of young trees are less productive, given young trees have lower absolute growth rates than smaller size trees. They may incur mortality, and hence not all will become merchantable. In additional, residual size structures defined by the *q*-factor are no more sustainable than other structures that provide linearly increasing growing space to each older age class.

Based on 240 sample plots consisting of Norway spruce (*Picea abies* L. Karst), fir (*Abies alba* Mill.), and common beech (*Fagus silvatica* L.), Gölser and Hasenauer (1997) developed a distance-dependent tree height growth model to predict juvenile tree height growth in uneven-aged mixed species stands in Austria. The model predicts the periodic 5 year height increment by adjusting the corresponding potential height increment using: (1) the competition from the remaining overstory, (2) the intra-and inter-species competition among the regeneration, and (3) a modifier for light incidence edge effects. The results suggested that the edge affected incidence of light is important for spruce and beech regeneration, while no effects were evident in fir regeneration. Moreover, several distance-dependent growth models in Finland have been developed for optimizing thinning regimes and rotation of mixed stands (Miina, 1996; Pukkala and Miina, 1998; Pukkala et al., 1998; Vettenranta and Miina, 1999), and for predicting the development of mixed coniferous forests (Vettenranta, 1999). These studies showed that a spatially-based distance-dependent model accounts for variation in tree growth better than a non-spatial model.

Following the approach of Solomon et al. (1986), Favrichon (1998) has recently developed a management-oriented demographic matrix model describing the combined effects of ingrowth, mortality, and growth for tropical mixed species uneven-aged natural stands in French Guiana. This model has two main features: (1) species are grouped into ecological guilds, and (2) the ingrowth and transition probabilities are dependent on the relative distance of the stand from its initial pristine conditions. The model was validated with both short-and medium-term projections. This model provides a tool to simulate stand dynamics and species composition after logging or other systematic silviculture treatments. It is still in the first stage of development, and needs to be improved to analyze the cutting cycles and economic implications of management decision or policies. Lin et al. (1998) also reported a density-dependent matrix growth model of uneven-aged loblolly pine stands developed with data from 991 permanent plots in the southern United States. The growth model is an extension of earlier matrix models of Buongiorno and Michie (1980); Lu and Buongiorn (1993). The elements of the growth matrix vary with residual stand basal area and site productivity (Solomon et al., 1986). The model predicts the number of pine, soft hardwood, and hard hardwood trees in 13 classes based on tree diameter at breast height. The results from the post-sample forestcasts suggested that predictions of 6–10 years were accurate.

6. Future direction

Traditional forestry objectives aimed at sustainable yield management are being replaced with those of sustainable ecosystem management (Kimmins, 1997). This paradigm shift in forest management requires an effective transfer of results from researchers to forest managers. The key to growth and yield modeling for forest planning and management in the 21st century is the extent to which the ecosystem is treated holistically. Future growth and yield efforts will face the challenges of including an increased number of silvicultural alternatives, providing expanded information on tree quality and product yields, and predicting long-term forest response to environmental stresses such as climate change, land-use, and fire disturbance at landscape levels. As Burkhart (1990) pointed out, progress in growth and yield modeling for the 21st century centers around data collection, analysis techniques, and computing technology. Since growth and yield models are primarily tools for forest management, the author focuses on technological aspects rather than science issues in the following discussions.

6.1. Hybrid models

Considering the challenges for forest research such as prediction of growth and dynamics of mixed-species, uneven-aged stands, and the analysis of forest response to future environment changes, a hybrid approach coupling an empirical growth and yield model with a process-based model may be useful. In the hybrid approach, physical and physiological mechanics are used to derive model forms that are conditioned to fit common remeasurement data. Some hybrid growth and yield models have recently been developed (Kimmins, 1990, 1993; Korol et al., 1994, 1996). Basic growth and yield models have started to be coupled with rapidly emerging tree process models whose dynamics are determined by physiological processes (Friend et al., 1993, 1997; Bossel, 1996; Landsberg and Waring, 1997).

6.1.1. Tree-level

The hybrid model TREE-BGC (Korol et al., 1994, 1996), a variant of the landscape process model FOREST-BGC (Running and Coughlan, 1988; Running and Gower, 1991), calculates the cycling of carbon, water, and nitrogen in and through trees. The model uses disaggregation logic to allocate stand-level estimates of carbon gain and respiration costs to individual trees. Increments in height and diameter are estimated so as to maintain their allometric relationship. Mortality is simulated when the maintenance respiration of the tree exceeds the carbon allocated to the tree. Stand variables are derived from a tree list. TREE-BGC was successfully used to simulate the growth and yield of 998 trees in uneven-aged stands near Kamloops, BC, Canada.

6.1.2. Stand-level

FORCYTE-11 (FORest nutrient Cycling and Yield Trend Evaluator) (Kimmins, 1993) and FORECAST (FORestry and Environmental Change ASsessmenT) (the successor to FORCYTE-11) (Kimmins et al., 1995) are hybrid forest simulation models that combine an empirical bioassay modeling approach with process-based simulation modeling. Yield predictions from a historical-bioassay model are modified based on simulation of the temporal variation in competition for both light and nutrient availability. These models provide a method of predicting biomass yield of aspen and white spruce mixedwoods in northeastern BC, Canada (Wang et al., 1995), and soil organic matter and nitrogen for Vancouver Island Douglas-fir sites (Morris et al., 1997) under various management regimes.

6.2. Three-dimension models and tree visualization

Arcadia (named for an idealized landscape), an individual-tree-based forest stand model that simulates the establishment, growth, and mortality of hardwood and coniferous species over century time scales, has been recently developed by William (1994). The model includes a fine-scaled three-dimensional framework within which spatial relationships, including three-dimensional leaf area distributions, are explicitly simulated to define competitive interactions. Productivity is modeled through a carbon allocation approach, and linked to a unique light environment within each of the 300 000 cells in the framework. Arcadia has been used to simulate the development of old-growth forests in the northeastern US, and alternatively predicts stand structure and productivity relationships derived from tree rings (William, 1996). Another new three-dimensional individual-tree-based tree growth model, (3D-FOREST) is being developed by Dr. Oleg Kisliuk at the European Forest Institute (EFI News, 1997). 3D-FOREST can calculate the energy balance of each branch in a tree, assess the impacts of shadow and the position of the tree in the stand, and describe the interaction between trees and branches. This has not been possible with other existing models. Similarly, a three-dimensional tree growth model, LIGNUM, coupling structure and function of trees, has been recently reported by researchers from the Finnish Forest Research Institute (Perttunen et al., 1996, 1998). Additional example of a three-dimensional architectural plant simulation model has been developed by P. de Reffye and his colleagues in France (Reffye et al., 1988; Jaeger and Reffye, 1992; Bouchon et al., 1997).

The advent of high-speed computing has greatly facilitated the modeling of forest growth. Models are now able to explicitly represent the complex interplay between the local environment and each individual tree in the stand. Complexity becomes a major liability as models become increasingly difficult to understand. Visualizing complex interactions of model simulations has become a key part of model exploration. SORTIE, originally developed by Pacala et al. (1993), is a spatially explicit, stochastic, and mechanistic model of forest growth for the northeastern United States. The model describes local competition among nine species of trees in terms of empirically derived responses of individuals. It uses species-specific information on growth rates, mortality, and seed dispersal distance, as well as detailed, spatially explicit information about local light regimes, that are linked to changing disturbance patterns. Deutschman et al. (1997) and Levin et al. (1997) demonstrated the power of three-dimensional visualization to illustrate how interactions drive SORTIE.

The Landscape Management System (LMS) is able to integrate forest inventory, growth and yield models, computer visualization, and analysis software into a landscape-level analysis tool (McCarter, 1997; McCarter et al., 1998). Forest Vegetation Simulator (FVS) (Teck et al., 1996) is one of the growth and yield models integrated with LMS that is being modified to allow FVS to be used for silviculture and disturbance simulation (McCarter, 1997). Recently, the Stand Visualization System (McGaughey, 1997, 1998) was linked to FVS. The Pacific Southwest Region of the US Forest Service is now using it to communicate fire hazard stand structure relationships, spatial variation, treatment comparisons, and stand development for forest managers (Landram, 1997).

6.3. User-friendly models and education tools

Most existing growth and yield models were developed using procedural or structural languages such as FORTRAN (e.g., Prognosis: Stage, 1973), Pascal (e.g. TREEDYN3: Bossel, 1996) and C (e.g., SORTIE: Pacala et al., 1993; SYMFOR: Young and Muetzelfeldt, 1998). More advanced programming languages like object-oriented C++ (e.g., Liu, 1993; Congleton et al., 1997; Koesmarno, 1997) and Visual Basic 5.0 (MacLean et al., 1997a,b) help to build user-friendly modeling interfaces and will enhance the flexibility and efficiency of forest growth and yield models. For example, SUPPOSE 1.0, developed by Crookston (1997) using the C++ programming language and running under Windows 3.1, Windows 95 and Unix, is a graphical user interface for FVS (Teck et al., 1996). It is designed to simplify the task of simulating changes in forest vegetation over the long-term (100–400 years) and at a landscape spatial scale between one and about 1000 stands. The current version of SUPPOSE provides flexibility in input data, output results, and analysis of the simulation results, making it easier for forest managers to use.

Forest modeling is being extended from the realm of research and academia to a broader management, policy, and education audience or user-group. Forest simulation models (particularly process-based models) now contain important environmental factors (both abiotic and biotic) and key ecological, physiological, and physical processes controlling tree growth and forest stand development. They have potential educational value, not only for students but also for forest managers and policy-makers concerned with forests (Landsberg, 1998). Students or managers can better understand individual processes and their role in the dynamics of forest systems by studying model structure and behavior, by simulating experiments, or even by playing games. An example is FORECAST-FORTOON (Kimmins and Scoullar, 1995; Kimmins et al., 1995). Specifically, FORECAST-FORTOON includes the following software packages.

6.3.1. Game

An educational forest management computer game based on the FORECAST model. This is designed for high school applications in which students can examine changes in ecosystem function and response to various management treatments/regimes, and assess the trade-off between various social and environmental values that occur as they make different choices about forest management.

6.3.2. Classroom

Classroom learning environments with libraries of text and pictures are provided to help the students understand forestry, and the science and technical background behind the games.

6.3.3. Management example

A management gaming environment for university/college applications. Using graphical and pictorial outputs from FORECAST, the user can explore the effects of 64 different combinations of management decisions.

The influence of Internet technology is becoming widespread in the research and education system and the benefits of integrating growth and yield models with Internet technology will certainly increase the use and accessibility of models. The Active-X technology, which is a set of diverse technologies developed by Microsoft to support the creation of sophisticated interactive applications for the World Wide Web (Eddon and Eddon, 1997), can bring models alive on Internet web pages. The use of these technologies is becoming easier. A nice example was given by MacLean et al. (1997a,b) who developed the Forester's Yield Curve designer (FYCD) software. It can be downloaded from 'http://atl.cfs.nrcan.gc.ca/lmn/FYCDWEB.HTM'. FYCD uses a mouse-driven graphical user interface that facilitates the import and display of results from stand growth models, and is aimed at helping forest management planners and field foresters to develop and validate timber volume yield curves. It was developed using Visual Basic, and runs on a PC in a Microsoft Windows environment.

6.4. Integrating with geographical information system (GIS)

Linkage of forest growth models within a GIS is presently receiving a great deal of attention (Osborne, 1989; Buckley et al., 1994; Oliver and McCarter, 1995). GIS is a powerful tool for integrating different spatially referenced databases as multiple layers of driving variables. These linked multiple layers can be used to model the responses of ecosystems to different perturbations. GIS technology enables the investigation of large scale environmental issues by facilitating the analysis of the heterogeneous patterns and processes that are present at lower (finer) spatial scales. GIS systems, however, deal only with spatial scaling issues. They cannot, on their own, deal with issues of temporal scale or provide spatially explicit development patterns of ecosystem structure and function. The obvious solution to this limitation has been to link GIS and stand-level models. In forestry, this generally has involved traditional growth and yield models (e.g., Oliver and McCarter, 1995).

Berry et al. (1997) developed FVS*ARC, which is a powerful GIS tool linking ARC/INFO to a FVS. The FVS*ARC program applies user-friendly graphical menus to control the selection of maps, access ARC/INFO data, selection of program indices, program execution; and links them to results stored in database tables, or ARC/INFO maps; and displayed in a variety of tables, charts, and maps used in forest growth and yield modeling and landscape analysis. Bateman and Lovett (1998) showed a case study using GIS and large area databases to predict yield class of Sitka spruce in Wales. Peng and Apps (1997) reported the basic framework to link CENTURY 4.0, which is a point-based ecosystem process model and is not spatially oriented, into a GIS, taking advantage of both the temporal dynamics of CENTURY 4.0 and the spatial integration powers of the GIS. This makes it possible to examine the potential effects of future global climate change on growth and dynamics of Canadian boreal forests and to link this information to spatial characteristics at the landscape level.

7. Summary

- Growth and yield modeling has a long history in forestry. Methods of measuring the growth of uneven-aged forest stands have evolved from those developed in France and Switzerland during the last century. Quantification of more detailed stand table information dates back to 1898 when de Liocourt (Meyer, 1953) first noted the tendency of uneven-aged stands to exhibit a reverse J-shaped diameter distribution that could be described by geometric progression.
- Much progress in uneven-aged growth and yield has occurred since the first models were pioneered by Moser and Hall (1969). Over time, a wide variety of models have been developed to predict the growth and yield of uneven-aged stands at both the individual tree and stand level. Growth and yield methodology for uneven-aged stands not only has moved from an empirical approach to a process-based mechanistic approach, but also has incorporated a variety of techniques such as (1) systems of equations, (2) nonlinear stand table projection, (3) Markov chains, (4) matrix models, and (5) artificial neural network techniques.
- Growth and yield model development has not yet been fully integrated with uneven-aged management regulation techniques. Forest management for uneven-aged stands is hampered by a lack of adequate growth and yield information, likely due to (1) lack of interest in uneven-aged management in the past; (2) scarcity of suitable data for research efforts; and (3) difficulties in developing modeling strategies.
- An improved understanding of the growth and dynamics of uneven-aged stands and improved

modeling approaches, such as hybrid modeling, as well as the integration of new computer technologies (object-oriented programming with user-friendly interfaces), tree visualization, and spatially-explicit application of GIS, will certainly facilitate our ability to project the future growth and yield of uneven-aged stands at large scales. This will assist modellers and researchers to meet the information needs of future forest managers, and help to answer the diverse questions about sustainable forest management in the next millennium.

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