23 Forest-Management Modelling

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23.1 The issue

Forests are complex and dynamic ecosystems comprising individual trees that can vary in both size and species. In comparison to other organisms, trees are relatively long lived (40–2000 years), quite plastic in terms of their morphology and ecological niche, and adapted to a wide variety of habitats, which can make predicting their behaviour exceedingly difficult. Forests are widely managed for a variety of objectives including biodiversity, wildlife habitat, products, and recreation. Consequently, forest managers need tools that can aid them during the decision-making process.

Both conceptual and quantitative models are used in forest management. Conceptual models are built from the extensive scientific literature that describes forest response to management (e.g. Moores *et al.*, 2007). Often conceptual models are difficult to apply because each forest is unique due to its location and past management history. In addition, one major objective of sustainable forest management is the ability to compare multiple alternative management activities. Thus, quantitative models are widely used because they can be used to update and project forest inventories, compare alternative management regimes, estimate sustainable harvests, and test important hypotheses regarding forest growth and development (Vanclay, 1994). Quantitative models attempt to represent forests with mathematical equations that describe their behaviour over time.

Various quantitative models are used in forest management. These models differ in terms of their temporal resolution (daily versus annual versus decadal), spatial scale (stand versus individual tree) (see also Chapter 5), reliance on data (empirical versus mechanistic) (see also Chapter 7), representation of competitive processes (distance-independent versus distance-dependent) (see also Chapter 13), and degree of stochasticity (see also Chapter 8). These differences have important implications for how useful they are for forest management planning process. Understanding these tradeoffs is important.

Forest-management activities range from the selective removal of certain individuals (thinning) to altering soil nutrient availability (fertilization). Ascertaining the long-term effects of these management activities is difficult because of the dynamic nature of trees and high variability in the response of forests to management. In addition, new questions on the effective management of forests are emerging like the impacts of climate change, broader ecosystem-management objectives, and increased demands for forest-resource products. Thus, models will continue to be an important component of the forest-planning process.

The objective of this chapter is to explore various modelling approaches used for forest management, provide a brief description of some example models, explore the ways that they have been used to aid the decision-making process, and make suggestions for future improvements.

23.2 The approaches

The modelling approaches used in forest management differ widely in their general frameworks as previously described. One of the most significant distinctions is the way that the models treat forest processes. *Empirical*

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models describe the development of a forest based on regression equations parameterized from extensive datasets, while *mechanistic* models represent the key physiological processes such as light interception, photosynthesis, and respiration to predict growth. *Hybrid* models combine features of both empirical and mechanistic models to take advantage of strengths offered by each approach. *Knowledge-based* models use rule-based systems and may not rely on data in the same way as the previous approaches. Each approach is described below.

23.2.1 Empirical Models

Empirical models depict trends observed in measurement plots that are established in forests. Consequently, empirical models are usually only as good as the data used to develop them. To be effective for modelling purposes, the data must cover the extremes of the population they are intended to represent, be extensive, and include measurements that likely describe the inherent variability of the observations. Due to regional differences, resolution of datasets, and the statistical approaches used, a vast number of empirical models currently exist. Most empirical models operate on five- to ten-year time steps, but annualized models exist too (Weiskittel *et al.*, 2007). In addition, most empirical models rely on site index, average dominant height at a certain base age (generally 50 years), as a measure of potential site productivity (Skovsgaard and Vanclay, 2008). Therefore, the largest differences in empirical models are their spatial resolution and treatment of competition.

Most empirical models are developed to operate at the stand level, which is a relatively uniform collection of trees that are similar in size, composition, and location. Stands are generally 1 to 50 ha in size and are the basic spatial unit at which most management decisions are made. Based on their spatial resolution, three primary classes of empirical models exist: (i) whole stand; (ii) size class; and (iii) individual tree.

23.2.1.1 Whole stand

Whole-stand models describe the stand in terms of a few values like total volume, basal area, or the number of individuals per unit of area and predict the change in these attributes over time. Whole-stand models are the simplest type of empirical model and have the longest history of development. One of the earliest examples of a whole-stand model in North America is the yield tables of Meyer (1929), which described growth in terms of stand age and site index. These yield tables were generalized into compatible growth yield equations that predicted changes in stand volume as a function of initial stand conditions and age (Buckman, 1962; Clutter, 1963; Moser, 1972). Some widely used whole-stand growth models are DFSIM (Curtis *et al.*, 1981), TADAM (García, 2005a), and GNY (MacPhee and McGrath, 2006). Whole-stand models are most appropriate for evenly aged stands of a single species. Although techniques have been developed to represent management activities with whole-stand models (Bailey and Ware, 1983; Pienaar *et al.*, 1985), they are not the most efficient approach, particularly when multiple thinnings are intended to be represented. However, whole-stand models continue to be developed using modern statistical techniques (Barrio-Anta *et al.*, 2006; Castedo-Dorado *et al.*, 2007) as they are easy to use, relatively robust, and can be more accurate in long-term predictions (Cao, 2006).

23.2.1.2 Size class

A forest is generally made up of trees of varying sizes, so a size-class model divides each stand into multiple groups of similar-sized individuals, which are projected through time. Some of the most common size-class models are stand-table projections (e.g. Trincado *et al.*, 2003), matrix-based (e.g. Picard *et al.*, 2002), and diameter-distribution models (e.g. Qin *et al.*, 2007). Stand-table projections and matrix-based approaches are similar in that the frequencies of trees in each cohort are projected through time by estimating the probability of moving from one group to another. A diameter-distribution approach uses statistical probability distributions to describe the frequency of trees in different size classes and their changes through time. The Weibull probability distribution has been commonly used because it is flexible, relatively easy to integrate, and the parameters can be determined in multiple ways (Cao, 2004). Some examples of size-class models are FIBER (Solomon *et al.*, 1995) and CAFOGROM (Alder, 1995), which are both developed for mixed-species forests. However, most size-class models are again best suited for even-aged, single-species and unmanaged stands.

23.2.1.3 Individual tree

An individual-tree growth-and-yield model depicts the changes in each tree located in a particular forest. These models provide the highest resolution of predictions, but require the most data for both development and application. Since the individual tree is the focal point, these models are effective for representing even-aged, single-species stands as well as stands that are mixed-species (Porté and Bartelink, 2002) and multi-cohort (Peng, 2000). These models are also effective for representing the effects of management, particularly of complex thinning regimes. They have multiple components including diameter growth, height growth and mortality equations (see below).

One key distinction of empirical individual-tree models is whether they are distance dependent or distance independent. Distance-dependent models require the location of each tree included in the simulation to be known, whereas distance-independent models assume the trees are randomly distributed in the forest. Using tree location, distance-dependent models estimate competition indices such as size-distance (Opie, 1968), area potentially available (Nance *et al.*, 1988), and exposed crown surface area (Hatch *et al.*, 1975). Distance-independent models represent competition using variables such as basal area in larger trees (Wykoff, 1990), crown closure in higher trees (Hann *et al.*, 2003), and relative tree diameter (Glover and Hool, 1979). Most comparisons between the effectiveness of distance-dependent and distance-independent measures of competition for predicting growth have found distance-independent to be just as effective (Biging and Dobbertin, 1995; Wimberly and Bare, 1996; Corral Rivas *et al.*, 2005). This result suggests that knowledge of tree location is not worth the effort or expense of collecting that information, but emerging remote-sensing technologies may make it much easier to acquire this spatial information in the future.

Some key examples of distance-dependent, individual-tree models are SILVA (Pretzsch *et al.*, 2002) and TASS (Mitchell, 1975), while FVS (Crookston and Dixon, 2005) and PROGNAUS (Monserud *et al.*, 1997) are some widely used distance-independent, individual-tree models. Individual-tree models have been widely modified to account for the effects of forest management activities like fertilization and thinning (Hann *et al.*, 2003). Since the individual tree is the focus, the implementation of complex thinning regimes is relatively straightforward (Söderbergh and Ledermann, 2003).

23.2.2 Mechanistic Models

Empirical models generally cannot be extrapolated to new situations that were not covered in the data used to develop them. Empirical models also commonly rely on site index, which is the dominant height at a specified reference age, to represent the potential productivity of a site. However, site index has several known problems (Skovsgaard and Vanclay, 2008). Finally, most empirical models view climate as static. In contrast, mechanistic models represent tree processes physiologically to avoid these limitations. Although mechanistic models have a long history of development, they have been used primarily for research rather than forest-management purposes (Mäkelä *et al.*, 2000), because they often require extensive parameterization, rely on information not commonly available in forest inventories, and the output is often expressed in terms of little interest to forest managers, such as gross or net primary production (NPP). Regardless, several mechanistic models such as CABALA (Battaglia *et al.*, 2004), BIOME-BGC (Petritsch *et al.*, 2007) and CenW (Kirshbaum, 2000) have been developed to understand better the effects of forest management.

Most mechanistic models represent physiological processes at the whole-stand level because it simplifies the calculations and there is a better understanding at this scale (Landsberg, 2003b). Thus, differences between mechanistic models are in their temporal resolution, level of detail in physiological processes, and the representation of belowground processes. A monthly temporal resolution is commonly used because this type of climate information is widely available from websites like PRISM (2011) and some physiological processes scale better at this resolution. The limitation is that daily variation is not represented despite the fact that it can drive many physiological relationships.

Previous reviews have explored differences in various approaches in representing physiological processes such as light interception (Wang, 2003), photosynthesis (Medlyn *et al.*, 2003), respiration (Gifford, 2003), and carbon allocation (Lacointe, 2000). The representation of these processes has varied from highly simplistic to very complex. A general standard in most process-based models used for forest management is to use the Beer–Lambert law to estimate light interception, the Farquhar *et al.* (1980) equation for photosynthesis, and assume functional balance and allometric relations for carbon allocation (Le Roux *et al.*, 2001) (see also Chapter 12). For below-ground processes, some models treat the soil as a single layer and ignore most nutrient cycles (e.g. Running and Gower, 1991), while others rely on very detailed models of soil processes (e.g. Kirschbaum and Paul, 2002). Regardless of their temporal resolution or level of detail, most mechanistic models are highly sensitive to leaf-area index (LAI) because it drives the within- and below-canopy microclimate, determines and controls canopy water interception, radiation extinction, transpiration, and carbon gas exchange (Bréda, 2003).

Even today, basic physiological parameters are unavailable for several tree species, which can make using a mechanistic model challenging. An interesting alternative to parameterizing each individual equation used in a process-based model from the literature or with new data is the use of a Bayesian optimization technique. This technique has been demonstrated several times and often with promising results (Van Oijen *et al.*, 2005; Svensson *et al.*, 2008; Deckmyn *et al.*, 2009). In this approach, Markov chain Monte-Carlo simulation is used to vary the model parameters and calibrate model predictions to observed data. The further application of this technique and increased availability of climate data should help increase the use of mechanistic models for representing forest management, particularly under climate change (Schwalm and Ek, 2001). When properly parameterized, mechanistic models can be just as effective or even better than empirical models in short-term simulations (Miehle *et al.*, 2009). However, mechanistic models can struggle with long-term projections because of the difficulty in representing mortality accurately (Hawkes, 2000).

23.2.3 Hybrid Models

Hybrid models combine features of both empirical and mechanistic approaches. This approach relies on the robustness of empirical models, while increasing their ability to extrapolate and avoid limitations with site index. Hybrid models have been suggested as the most effective means for representing the effects of forest management because they provide output of interest to forest managers and avoid the heavy data requirements of most mechanistic models (Landsberg, 2003a). Several hybrid models have been developed for single-species, even-aged stands like CroBAS (Mäkelä, 1997), DF.HGS (Weiskittel *et al.*, 2010), and SECRETS (Sampson *et al.*, 2006). One widely used hybrid model is 3-PG (Landsberg and Waring, 1997), which has been parameterized for a variety of forest types (Landsberg *et al.*, 2003).

Three primary classes of hybrid model frameworks currently exist, namely: (i) empirical growth equations with a physiologically derived covariate; (ii) empirical equations with a physiologically derived external modifier; and (iii) allometric models. The degree of hybridization within each of these classes varies greatly, so an exact classification of a hybrid model is difficult. For example, Milner *et al.* (2003) linked the Forest Vegetation Simulator (FVS) and STAND-BGC such that both models ran simultaneously in parallel and a user selected the degree of coupling. An example of an empirical growth equation with a physiologically derived covariate is given in Baldwin *et al.* (2001), who related site index to NPP from a process-based model and allowed it to vary during a simulation. Henning and Burk (2004) provide an example of an empirical equation with a physiologically derived external modifier and found it improved projections. Allometric hybrid models rely on simplified representations of physiological processes and empirical equations that relate tree size to biomass. CroBAS and 3-PG are two examples of allometric hybrid models. Both models use the concept of light-use efficiency to relate light interception to gross primary production (GPP), which avoids the complications of a detailed canopy-photosynthesis equation. In addition, 3-PG avoids estimating respiration by assuming NPP is one-half of GPP, which has been supported by some empirical studies (Waring *et al.*, 1998). Allometric equations are used to convert typical forest inventory data into biomass and to estimate carbon allocation. However, using a mean tree approach like 3-PG to accomplish this can result in a significant bias as the diameter distribution becomes more varied (Duursma and Robinson, 2003).

Relative to purely empirical models, the degree of improvement achieved with a hybrid model has varied. At the stand level, hybrid models have been quite effective at improving predictions (Battaliga *et al.*, 1999; Snowdon, 2001; Dzierzon and Mason, 2006), whereas less modest gains have been achieved at the individual tree level (Henning and Burk, 2004; Weiskittel *et al.*, 2010). The range of the reported improvements can vary widely at both the stand and tree levels because of the breadth of conditions covered by evaluation data, the length of the simulations, and differences in the adequacy of the empirical model. Interestingly, Henning and Burk (2004) found climate-dependent growth indices almost as effective as the process-based ones, while Snowdon *et al.* (1998) found just the opposite. Regardless, the use of hybrid models will likely continue to increase in the future as the understanding of physiological processes improves and the complexity of questions facing forest managers broaden.

23.2.4 Knowledge-based Models

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 (see also Chapter 18). All these characteristics make knowledge-based models extremely useful in forest management. One example of a knowledge-based system that has been developed is the NorthEast Decision model (NED) (Twery *et al.*, 2005). This is a series of interconnected models including several growth-and-yield models that allow users to easily address a variety of management objectives and compare a range of alternatives.

23.3 Components of empirical models

Empirical models are widely used by forest managers. In particular, individual-tree-based empirical models are becoming the new standard as they are flexible and the most effective approach for representing a range of stand structures, especially uneven-aged (Peng, 2000) and mixed-species stands (Porté and Bartelink, 2002). Consequently, it is important for forest managers to understand the components of empirical models and the limitations associated with each one.

23.3.1 Allometric equations

Allometric equations are a key component of several hybrid models but in empirical models they are often used to fill in missing values, predict hard-to-measure attributes like volume and, in some cases, estimate growth. Allometric equations can take many forms depending on their intended use. In empirical models, the primary allometric equations are for total tree height, height to crown base, crown width, stem form, and biomass.

The use of allometric equations to predict total tree height is quite common and they have taken multiple forms (see Huang *et al.*, 1992). Although total tree height is strongly correlated with tree diameter at breast height (DBH), this relationship varies by species and stand conditions so additional covariates are commonly included. Tree DBH accounts for the majority of the variation in tree height, even across a large range of stand conditions. Hanus *et al.* (1999) found DBH to explain between 36% and 83% of the original variation for several conifer and hardwood species in south-western Oregon. In general, hardwood heights tend to be harder to predict because of the lack of a true leader and the difficulty of measuring it accurately. Constructing a well-behaved tree-height allometric equation requires selecting an appropriate model form and an extensive dataset that covers a range of stand conditions. Some researchers have found that including national and state champion trees in their dataset significantly improves the equation's predictive power.

Tree growth is strongly linked to crown size, which is often expressed as crown ratio (CR) or the ratio of crown length to total tree height. Consequently, crown variables are commonly included in several equations used in growth-and-yield models. However, crown measurements are significantly less common than observations of total tree height. Although CR has been more commonly modelled (Belcher *et al.*, 1982; Wykoff *et al.*, 1982; Hynynen, 1995; Hasenauer and Monserud, 1996; Soares and Tomé, 2001), Hann and Hanus (2004) found that height-to-crown-base (HCB) equations produced more precise predictions of crown recession when compared to CR equations. A properly formulated CR model should be constrained to give predictions between 0 and 1, while an HCB equation should give predictions that do not exceed the total tree height. Consequently, the most common model form used to model CR and/or HCB has been the logistic form because it can be constrained to asymptote at 1 or total tree height (Ritchie and Hann, 1987; Hasenauer and Monserud, 1996; Hanus *et al.*, 2000; Temesgen *et al.*, 2005; Ducey, 2009). Unlike allometric height equations where tree-size variables predominate, tree size and measures of competition are of equal importance in CR/HCB equations (Hasenauer and Monserud, 1996; Temesgen *et al.*, 2005). Crown ratio and HCB are generally much harder to predict than total tree height, particularly for hardwood species (Hasenauer and Monserud, 1996). Consequently, significant biases in predicting CR or HCB can be incurred, which can have important implications for long-term growth projections (Leites *et al.*, 2009).

Several key variables used in growth-and-yield models rely on estimates of crown width. For example, the crown-competition factor of Krajicek *et al.* (1961) requires an estimate of maximum crown width (MCW) for all trees in a stand. Like defining the live crown base of an individual tree, multiple definitions of crown width exist. Maximum crown width generally refers to the width reached by an open-grown tree, while largest crown width (LCW) is the width of a stand-grown tree. Crown profile is the change in crown width within an individual tree. Maximum (Ek, 1974; Paine and Hann, 1982; Hasenauer, 1997) and largest (Moeur, 1981; Hann, 1997; Bechtold, 2003) crown-width equations exist for several species. Generally, DBH is effective at capturing most of the variation in both MCW (Paine and Hann, 1982) and LCW (Gill *et al.*, 2000). Two primary approaches have been used to model crown profile: (i) direct and (ii) indirect characterization. Direct characterization uses deterministic or stochastic models to predict crown width (radius or area) from tree attributes, whereas indirect characterization predicts the attributes of individual branches and computes crown width based on trigonometric relationships. The direct characterization has been the predominant form of predicting crown profile (Nepal *et al.*, 1996; Baldwin and Peterson, 1997; Biging and Gill, 1997; Hann, 1999; Marshall *et al.*, 2003), but the indirect approach has also been used for several species (Cluzeau *et al.*, 1994; Deleuze *et al.*, 1996; Roeh and Maguire, 1997).

Stem form and volume are the two most important tree attributes for determining value and the primary interest of most growth-model users. A variety of approaches for determining both attributes exist, even for a single geographic region (e.g. Hann, 1994). The current trend has been to move away from stem-volume equations and rely more on stem-taper equations, which predict changes in stem diameter from tree tip to base. Taper equations have become preferred because they depict stem form, provide predictions of total volume, and can be used to determine merchantable volume to any height or diameter specification. Limitations of taper equations are that they are often overly complex, which may limit their ability to extrapolate beyond the dataset from which they were developed, and they are not optimized to give volume predictions. Similar to volume equations, most stem-taper equations are a function of only DBH and total tree height, and a variety of model forms exist. Taper equations are of three primary types, namely: (i) single (Thomas and Parresol, 1991); (ii) segmented (Max and Burkhart, 1976); and (iii) variable-form (Kozak, 1988). Goodwin (2009) gives a list of criteria for an ideal taper equation, but most of the widely used forms do not meet all the criteria, which is important to recognize.

Like stem volume, thousands of biomass equations have been developed around the world. For example, Jenkins *et al.* (2004) reported 2640 biomass equations from 177 studies in North America. Other extensive reviews have been done for Europe (Zianis *et al.*, 2005), North America (Ter-Mikaelian and Korzukhin, 1997), and Australia (Eamus *et al.*, 2000; Keith *et al.*, 2000), which highlight the vast amount of work that has been done on this topic. However, most biomass equations are simplistic with parameters determined from relatively small sample sizes. Zianis *et al.* (2005) found that more than two-thirds of the equations they examined were a function of just DBH and more than 75% of the studies that reported a sample size had less than 50 trees. As a result of using simple model forms fitted to small data sets, the application of the resulting equations to other populations can produce large predictions errors (e.g. Wang *et al.*, 2002). In addition, the development of universal (Pilli *et al.*, 2006) and generalized (Muukkonen, 2007) allometric equations ignores significant species variability and complex relationships, particularly when the goal is to estimate regional and national biomass (Zianis and Mancuccini, 2004). Efforts to localize allometric biomass equations without requiring destructive sampling by accounting for the relationship between tree height and DBH as well as wood density (Ketterings *et al.*, 2001) or the DBH distribution (Zianis, 2008) have been proposed. The most widely used biomass equations in North America are reported in Jenkins *et al.* (2003).

23.3.2 Increment equations

Growth is the increase in dimensions of each individual in a forest stand through time, while increment is the rate of the change in a specified period of time. Although growth occurs throughout a tree, foresters are primarily concerned with changes in both tree DBH and height because of their ease of measurement and strong correlation with total tree volume. Tree growth has multiple inter- and intra-annual stages that must be considered by tree-list models. For example, a cumulative growth curve of height over age shows three primary stages: (i) juvenile period where growth is rapid and often exponential; (ii) a long period of maturation where the trend is nearly linear; and (iii) old age where growth is nearly asymptomatic. A diameter growth curve would show much the same trend, except there is a tendency toward curvilinearity during the period of maturity. Various theoretical model forms have been used to predict growth in forestry (Zeide, 1993), but most of them can be generalized with a single equation form (García, 2005b). The most common model forms include the Gompertz (1825), Bertalanffy (1949), and Richards (1959) equations. Although these theoretical models offer some biological interpretability (e.g. Zeide, 2004), it has been shown that well formulated empirical equations can be just as accurate or even more accurate for a wide range of data (e.g. Martin and Ek, 1984).

The dependent variables for updating individual tree DBH have included diameter increment (Hann *et al.*, 2006; Weiskittel *et al.*, 2007), diameter-inside-bark-squared (Cole and Stage, 1972), relative-diameter increment (Yue *et al.*, 2008), and inside-bark-basal-area increment (Monserud and Sterba, 1996). The optimal dependent variable has been debated, as West (1980) found no difference between using diameter or basal area to predict short-term increment (1 to 6 years) in *Eucalyptus*. Two general conceptual approaches to model formulation have been used to predict diameter increment: (i) a maximum potential increment multiplied by a modifier and (ii) a unified equation that predicts realized increment directly. Although the differences between the two are mostly semantic as they both can give reasonable behaviour (Wykoff and Monserud, 1988), they do illustrate a key philosophical decision in modelling increment. The potential-times-modifier approach to modelling diameter increment has long been used in the past, but suffers from the inability to estimate parameters simultaneously and estimating a potential increment change can be challenging. Consequently, empirical model forms that predict realized diameter increment have become more common and differ primarily in the covariates considered. The majority of equations include two expressions of DBH to induce a peaking behaviour (BAL), a measure of two-sided competition and site index.

Modelling height increment is generally much more difficult than diameter increment because of higher within-stand variability, a more limited number of remeasurements, and a closer connection to environmental factors rather than stand-level ones. Like diameter increment, a variety of approaches have been used to model height increment and the most common are of two types: (i) potential times modifier and (ii) realized. One alternative to a height increment equation is to predict diameter increment and use a static allometric height to diameter equation to estimate the change in tree height. In contrast to diameter increment modelling, the potential-times-modifier approach is commonly used for predicting height increment (Hegyi, 1974; Arney, 1985; Burkhart *et al.*, 1987; Wensel *et al.*, 1987; Hann and Ritchie, 1988; Hann and Hanus, 2002; Hann *et al.*, 2003; Weiskittel *et al.*, 2007; Nunifu, 2009). One reason for this is that dominant height equations can be easily rearranged to give good estimates of potential height growth rather than having to fit a separate equation or select a subjective maximum as was the case for potential diameter growth. The prediction of height increment with a realized approach has paralleled the approaches used for estimating diameter increment directly. For example, Hasenauer and Monserud (1997) used a height-increment-model form similar to the diameter-increment equation of Monserud and Sterba (1996), except tree height-squared was used instead of DBH^2.

23.3.3 Mortality equations

Tree mortality is a rare yet important event in forest stand development and has significant implications for long-term growth-and-yield model projections (Gertner, 1989). Of all of the attributes predicted in growth models, mortality remains one of the most difficult due to its stochastic nature and infrequent occurrence. For modelling purposes, it is important to note the type of mortality, which is generally described as *regular* or *irregular*. Regular mortality can also be expressed as density-dependent and is caused by competition-induced suppression. Irregular or catastrophic mortality is independent of stand density and is due to external factors such as disease, fire, or wind. Previous reviews on modelling mortality have concluded that there is no best way to model it for all applications (Hawkes, 2000). Nearly all of the tree-level mortality equations use logistic regression to estimate the probability of a tree dying (Hamilton, 1986; Monserud and Sterba, 1999; Hann *et al.*, 2003). Thus, the primary differences between individual tree-mortality equations that have been developed are: (i) the type of data used; (ii) the statistical methods for estimating parameters; (iii) the length of the prediction period; (iv) usage of additional equations to constrain predictions; and (v) the tree and stand variables utilized for predictions. Like allometric and increment equations, DBH has been the primary variable in most individual tree-mortality equations. DBH growth has also been used as a covariate in mortality equations (Monserud, 1976; Buchman *et al.*, 1983; Hamilton, 1986; Yao *et al.*, 2001). Although data intensive and often explaining a limited amount of variation, empirical equations of mortality tend to perform better than theoretical (Bigler and Bugmann, 2004) and mechanistic approaches (Hawkes, 2000).

23.3.4 Ingrowth and regeneration

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 (Botkin, 1993). 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). Miina *et al.* (2006) provide an overview of the techniques used to empirically predict ingrowth and regeneration. One effective alternative to empirical equations is to use imputation techniques based on extensive regional databases (Ek *et al.*, 1997).

Developments using knowledge-based models to predict composition of understorey after a minor disturbance or a newly regenerated stand after a major disturbance show some promise. 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 *et al.* (1994) developed a spatially explicit, data-intensive regeneration model, 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. However, this program requires mapped data of adults and transect sampling of seedlings, so it is unlikely to be useful in management applications. A knowledge-based model of oak regeneration developed by Loftis and others (Rauscher *et al.* 1997) does show promise using expert knowledge of ecological characteristics of tree species in the Appalachian region to predict composition of a new cohort 10 years after a major disturbance (Boucugnani, 2005).

23.4 Implementation and use

Growth models are widely used for a variety of purposes. In using a growth model, important considerations need to be made to ensure proper behaviour. Some of the most important considerations are validation and calibration (see also Chapter 2), visualization, and integration with other software systems (see also Chapter 27). Each of these aspects is discussed further below.

23.4.1 Validation and calibration

To be useful, a model needs to depict regional trends accurately. If a model is inaccurate, inappropriate management recommendations may be made or resource availability under or overestimated. This importance of proper validation and calibration is well illustrated in Maine. For example, Randolph *et al.* (2002) suggested that commercial thinning be delayed 10 to 15 years after a spruce-fir stand reaches a dominant height of 15 m and there were relatively few benefits of precommercial thinning based on simulations made by the north-eastern variant of the FVS growth-and-yield model. However, Saunders *et al.* (2008) found that FVS vastly underpredicted the growth of thinned stands, while overpredicting the growth of unthinned stands. Consequently, Saunders *et al.* (2008) recommended that precommercial thinning is beneficial on most spruce-fir sites and commercial thinning is best applied when the dominant height reaches 12 m based on simulations made by a recalibrated version of FVERSUS.

Proper validation and calibration is often not done because it is time-consuming and requires users to have long-term data available. Validation is also difficult because selecting the proper statistical test is not straightforward and various results can be obtained when different tests are used (Yang *et al.*, 2004). One technique that has worked well for model validation is the equivalence test of Robinson and Froese (2004). Froese and Robinson (2007) demonstrated the use of this technique for validating an individual-tree, basal-area-increment model. The method requires the researcher to select indifference thresholds for both the intercept and slope of the equivalence test. Rather than use a particular statistical test to validate a model, Yang *et al.* (2004) suggest that statistical tests should be combined with other validation techniques, particularly how well a model fits new and independent data.

Commonly, after a validation exercise, model calibration is attempted to improve predictions. Calibration can range from relatively simple single-equation modifiers that adjust predictions to more closely match observations to entire recalibration of the full model. An effective methodology for entire recalibration of the full model uses a Bayesian optimization framework and has been well demonstrated for calibrating complex mechanistic models (Gertner *et al.*, 1999; Van Oijen *et al.*, 2005; Deckmyn *et al.*, 2009). The current wide use of mixed-effects models has made local calibration of equations relatively easy. The use of this technique has been demonstrated for calibrating total height (e.g. Temesgen *et al.*, 2008) and stem taper (Trincado and Burkhart, 2006) but can be extended to any equation when it is estimated with a mixed-effects approach. Regardless of how it is done, validation and calibration are important steps to ensuring model predictions are reliable.

23.4.2 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 that is available to provide 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, for example trees, shrubs, and down material (SVS, 2011). It is in wide use as a secondary tool, connected to growth models such as FVS (2011), Landscape Management System (LMS; McCarter *et al.*, 1999) and NED (Twery *et al.*, 2005). Besides SVS, several other stand-level visualization tools exist, such as TREEVIEW (Pretzsch *et al.*, 2008), Sylview (Scott, 2006), and the Visible Forest (2011; Hanus and Hann, 1997).

At the landscape level, there are several tools available for visualization. These tools are particularly useful for maintaining or protecting views, visualizing the landscape under alternative management regimes, and harvest scheduling. The Environmental Visualization tool (ENVISION, 2011) is a very powerful and realistic landscape-level visualization tool. ENVISION uses an algorithm that allows simulated scenes to be matched with real photographs taken from known locations. UTOOLS and UVIEW are geographic analysis and visualization software for watershed-level planning (Agar and McGaughey, 1997). The system uses a database to store spatial information and displays landscape conditions of a forested watershed in a flexible framework (UTOOLS, 2011). 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. The tool has been developed to be compatible with most modern PCs (SmartForest, 2011; Uusitalo and Kivinen, 2000). Two additional landscape visualization tools are L-VIS (Pretzsch *et al.*, 2008) and SILVISO (2011). Like ENVISION, these are very highly detailed visualization tools but are unique in that they are tightly coupled with a forest-simulation model (Pretzsch *et al.*, 2008).

Regardless of the scale, Pretzsch *et al.* (2008) identified four tenets that all visualization tools should embody, namely: (i) they should cover temporal and spatial scales that are suited to human perception capabilities; (ii) they should be data-driven; (iii) they should be as realistic as possible; and (iv) they should allow free choice of perspective. Most of the described visualization tools address these tenets, but in different ways. Future efforts are focused on providing more realistic real-time visualizations.

23.4.3 Integration with other software

23.4.3.1 Habitat models

Providing wildlife habitat has long been one of the objectives of forest management. Often the availability of habitat has been assumed if the forest is managed to maximize timber. Controversies such as those over spotted owl and salmon habitat in the Pacific Northwest have shown that sometimes forest-management 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 are typically 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 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) were some of the first to 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. Simons (2009) demonstrated a rather large-scale application of a growth model, habitat suitability model, and a GIS platform to understand the influence of forest management on American marten, Canada lynx, and snowshoe hares.

23.4.3.2 Harvest-scheduling models

Broad-scale analyses are necessary for policy decisions and for including ecosystem processes with an area greater than a stand. Spatially explicit techniques are important and valuable because 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. One of the most widely used harvest scheduling models is Remsoft's WOODSTOCK software system (www.remsoft.com/forestry Software.php). Gustafson (1999) presented a model, HARVEST (www.nrs.fs.fed.us/tools/harvest/), to enable analysis of such activities across a landscape. The model has now been combined with LANDIS (Mladenoff *et al.*, 1996) to integrate analyses of timber harvesting, forest succession, and landscape patterns (Gustafson *et al.*, 2000; Radeloff *et al.*, 2006). LANDIS has recently been updated to LANDIS-II (www.landis-ii.org/; Scheller *et al.*, 2007) and been widely used throughout North America and beyond (Mladenoff, 2004; Swanson, 2009). 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.

23.4.3.3 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. 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 (2011; Gimblett *et al.*, 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.

23.4.3.4 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: (i) while at least one EM-DSS fulfilled each criterion in the questionnaire used, no single system successfully addressed all important considerations; (ii) ecological and management interactions across multiple scales were not comprehensively addressed by any of the systems evaluated; (iii) the ability of the current generation EM-DSS to address social and economic issues lags far behind biophysical issues; (iv) the ability to simultaneously consider social, economic, and biophysical issues is entirely missing from current systems; (v) 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 methodology.

There are few full-service DSSs for ecosystem management (Table 23.1). 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. 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. The NED (http://nrs.fs.fed.us/tools/ned/; 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. Recently, NED was expanded to NED-2 (Twery *et al.*, 2005). In contrast, INFORMS (Williams *et al.*, 1995) is a data-driven system that begins with a list of actions and searches the 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

Table 23.1 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	EMDS	Group negotiations	AR/GIS
Assessments	LUCAS*		IBIS*
		Vegetation dynamics	FVS
	RELM		LANDIS
Forest-level	SPECTRUM		CRBSUM
planning	WOODSTOCK		SIMPPLLE
	ARCFOREST		
	SARA	Disturbance	FIREBGC
	TERRA VISION	simulations	GYPSES
	EZ-IMPACT*		UPEST
	DECISION PLUS*		
	DEFINITE*		UTOOLS/UVIEW
		Spatial visualization	SVS*
	NED		SMARTFOREST*
	INFORMS		
Management-unit	MAGIS		LOKI
level planning	KLEMS	Interoperable system	CORBA*
	TEAMS	architecture	
	LMS*		IMPLAN
		Economic impact	
		analysis	SNAP
		Activity scheduling	

*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 Hervijnen, 1992); SMARTFOREST (Orland, 1995); CORBA (Otte *et al.*, 1996); SVS (McGaughey, 1997); LMS (Oliver and McCarter, 1996); LUCAS (Berry *et al.*, 1996).

and as intermediaries to facilitate idea generation and negotiation of alternative solutions for management on US National Forests.

23.5 Example model

23.5.1 Forest-vegetation simulator (FVS)

The FVS grew out of the original PROGNAUS model of Stage (1973) and is now available throughout the entire US (FVS, 2011; Crookston and Dixon, 2005). Currently, there over 20 different FVS variants and each is calibrated to a specific geographic area of the US. The basic FVS model structure has been used to develop growth models in British Columbia (Temesgen and LeMay, 1999) and Austria (Monserud *et al.*, 1997). All FVS variants are empirical distance-independent, individual-tree growth-and-yield models, but differ in the equation forms used due to differences in regional data availability. The model uses a temporal step of 5 to 10 years and can be used for simulations that last for several hundred years. To predict growth accurately, the FVS uses separate equations for large (> 127 mm DBH) and small trees (< 127 mm DBH). The diameter growth of large trees is driven by current tree DBH, whereas growth of small trees is primarily a function of their current height. Mortality is sensitive to variant- and species-dependent estimates of maximum stand density index (SDI). The model can simulate the influence of a variety of forest management activities such as harvesting, site preparation, thinning, and fertilization. The model can handle planted regeneration, but some variants do predict the amount of natural regeneration (Robinson and Monserud, 2003). The model will self-calibrate if tree-height or growth-measurement data are available.

Several extensions to FVS exist (see Crookston and Dixon, 2005). The extensions can represent the influence various disturbance agents such as western spruce budworm and mountain pine beetle. One of the widest used extension is the Fire and Fuels Extension (Reinhardt and Crookston, 2003), which is used to estimate tree-level biomass and the influence of fire on growth and mortality. Recently, a climate-sensitive variant of FVS was developed to address the expected influence of climate change on tree growth and mortality (Moscow Forestry Sciences Laboratory, 2011; Crookston *et al.*, 2010). The FVS interface is a Microsoft Windows-based program that allows for batch runs and file-based inputs. The model has been linked with external programs like SVS and LMS, and continues to be developed as new variants for south-western Alaska and the Acadian Region are currently being constructed.

23.5.2 Tree GrOSS and BWinPro

Forest-growth modelling in Europe also continues to progress along parallel tracks. One well-used modelling framework is TreeGrOSS, an open-source software framework for developing forest-growth models (TreeGrOSS, 2011). One instance of the framework is the silvicultural decision support system *BWINPro* (Nagel and Schmidt, 2006). Additional models and uses are described in Hasenauer (2006).

23.6 Lessons and implications

23.6.1 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 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-orientated models are still very useful in the long term, as they help increase understanding of the system and direct further investigations. Hybrid models have attempted to bridge the gap between mechanistic and empirical models.

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.

23.6.2 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 landowner. Indeed, identification of the landowner's objectives is the first step taught to silviculturists in forestry schools (Smith *et al.*, 1997). 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 pressure implies that decision makers need to be cognizant of the social components and context of their actions. Forest-management models that intend to help landowners 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.

23.6.3 People need to understand tradeoffs

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 (Cortner and Moote, 1999; Parker *et al.*, 1999). Models of human behaviour, social organizations and institutional function 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, 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 effectively identify, collect, and relate the social context and components of forest-ecosystem management in order to enhance and guide management decisions (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 is a critically important endeavour.

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