12.1 Introduction

The ability to project stand growth processes is an important aspect of managing multiaged stands. Some level of predictability is necessary for all management decisions because it reduces uncertainty and assists with risk management. For commodity production, investment decisions may be based on potential production values. For objectives related to non-commodity values, predictability provides short- and long-term forecasting of stand structural features, wildlife habitat, resistance to disturbances, or aesthetics. Regardless of the objective, tools are required to project commodity production and changes in stand structure. The ability to predict changes in stand structure also helps measure performance and provides repeatability in management treatments.

This chapter provides an overview of growth projection tools and their potential uses for projecting multiaged and other complex stand structures. The chapter begins with a discussion of assessing site quality in complex stands where traditional tools designed for even-aged stand are not suited. Growth projection tools are presented from the most simple to the most complex. These tools vary in their potential utility for complex stands and also in their data requirements. There have also been many efforts to develop optimal stocking regimes to achieve volume production or economic objectives. Optimization methods rely on growth projection tools which in turn rely on estimates of site quality.

12.2 Site Quality Assessment

Forest site quality is important because it determines how rapidly stand development and other changes in stand structure will occur. It is also important for assessing the suitability of species to a site and the capability of the site to support certain levels of density or stocking. Projecting changes in structure and suitability of different types of resource management on forest lands is an important aspect of forest planning and has a long history in forestry dating back several centuries. Reviews of forest site productivity assessments and classifications have been provided by Carmean 1975, Bailey et al. 1978, Daniel et al. 1979, Hägglund 1981, Barnes et al. 1982, Vanclay 1992, 1994, Skovsgaard and Vanclay 2008, 2013, Weiskittel et al. 2011, Bontemps and Bouriaud 2014, and many others.

There are many ways to evaluate site productivity. Foresters traditionally expressed the potential productivity as volume per unit area of total volume or merchantable volume units. This was generally referred to as direct productivity because it measured the variable (wood volume) that was the ultimate objective of management (Jones 1969, Daniel et al. 1979, Vanclay 1992, Skovsgaard and Vanclay 2008). Volume yields or site productivity were recognized as being dependent upon site quality and other factors. Direct measurement of site productivity is difficult so alternative methods of site productivity assessment are more common. These include
phytocentric and geocentric methods (Skovsgaard and Vanclay 2008). Phytocentric methods include site index and analysis of vegetation. Site index is based on the recognition that the height growth of dominant trees in even-aged stands is independent of tree density and is therefore representative of the quality of the site. Vegetation methods are based on the recognition that certain plants are found on, and indicative of, certain environments (Spilsbury and Smith 1947, Cajander 1949). Geocentric methods use soil characteristics, topography, climate, and other variables to estimate site quality (Coile and Schumacher 1953, Hills 1953, Krajina 1965, Steinbrenner 1979).

**Site index** is the average height of dominant or codominant trees at a specified index age such as 50 or 100 years (Helms 1998). It is the most common method of site quality estimation. Early forest scientists recognized the relationship between dominant height growth and site productivity and developed volume yield tables for even-aged stands that used site index as a variable. Site index requires dominant trees that were free of competition, or free-to-grow, through their entire development. This situation is not common in a multiaged stand and non-existent in stands managed with traditional multiaged systems where trees generally develop through several periods of suppression (Figure 12.1). However, for methods that rely on openings such as group selection, or methods that use relatively low stockings, suitable free-to-grow trees may be found. Otherwise, conventional site index does not work in multiaged stands.

Vegetation approaches or soil-site relationships may be used in multiaged stands. The presence of existing plants was long ago recognized as indicative of certain site characteristics. However, vegetation is also influenced by management, other human activities, and natural factors such as disturbances. Indicators therefore have to be reliable in cases with widely different land use histories. Early uses in forestry included the work of Salisbury and Smith (1947) in the Pacific Northwest that used the abundance of only a few plants rather than their frequency. Other vegetation approaches included Cajander’s (1926, 1949) work in Finland and Daubenmire’s work in the western USA (Daubenmire 1952, 1976, Daubenmire and Daubenmire 1868). Cajander used understory plants, and Daubenmire used both understory and overstory plants, as indicator species to predict a climax community. These are often termed habitat types or plant associations. These approaches have been criticized for their reliance on concepts related to succession and climax vegetation (Cook 1996, O’Hara et al. 1996, Kusbach et al. 2012) but are still in common use.

Geocentric or environmental approaches included Coile and Schumacher’s (1953) work relating soil properties to site index in loblolly and shortleaf pine in the southeastern USA. They found factors such as the depth of the A horizon and water holding capacity of the B horizon were highly correlated with site index. Steinbrenner (1979) developed a similar system for the Douglas-fir region of the Pacific Northwest that included a range of soil and physiographic variables. Other soil or physiographic systems include those developed by Hills (1953), Hodgkins (1956), Della-Bianca and Olson (1961), and Carmean (1979).

Some systems have attempted to link different types of variables to evaluate site quality. For example, Steinbrenner’s (1979) system used both soil descriptions and physiographic
variables. In British Columbia, Canada, Krajina (1965, 1969, Klinka et al. 1989) developed a biogeoclimatic system that integrates vegetation, soils, physiography, and climate into a site classification system. The classification of the vegetation community, or *biogeocoenoses*, is defined much like a Daubenmire (1952, 1976) habitat type in that both are based on climax vegetation but the zonation of soil types limited Krajina’s Biogeoclimatic Ecosystem Classification to a single soil series. Ecosystem process models also have the capability to estimate potential or actual forest production at small or large scales. Examples include Forest-BGC (Running and Coughlan 1988), 3-PG (Landsberg and Waring 1997), or CABALA (Battaglia et al. 2004). Milner et al. (1996) used Forest-BGC to quantify potential site productivity as the culmination of mean annual increment on forest sites in the northern Rocky Mountains of North America.

Whereas vegetation and soil/environment site quality assessment approaches are better suited to multiaged stands than site index, these approaches are only developed for a subset of potential forest types where multiaged management may be practiced. However, even where these systems are developed there may not be a direct link to timber production potential. If productivity estimates are desired, then some systems may have these linkages. For example, Steinbrenner’s (1979) system was related to site index, and the habitat type system of Pfister et al. (1977) was related to site classes or groupings of site indices. Rayner’s (1992) analysis of different site assessment approaches for karri in southwest Australia found that the vegetation, soils, physiographic, and climatic approaches were not as effective as site index for estimating productivity. Hence, there may be tradeoffs associated with predicting volume productivity using methods other than site index. The reliance on site index for predicting volume productivity in these other site quality approaches demonstrates the value of the site index method (Skovsgard and Vanclay 2008).

Estimating site index in mixed-species stands may also be difficult. Whereas the intent is to estimate the productive potential of the site, it is well-established that species provide different site index estimates on the same site (Doolittle 1958, Olson and Della Bianca 1959, Carmean 1979, Shoulders and Tiarks 1980). The estimate with one species might indicate a higher or lower productivity than a different species on the same site. These variations may be indicative of differences in potential productivity if the two species were grown in separate monocultures, or that inter-specific interactions affected growth, or may simply provide variable estimates of inherent productivity. In both cases, these differences demonstrate that mixed species stands add another complication to the basic concept of site quality estimation.

There is a long-term recognition of the need for an alternative “site index” for complex stands. In irregular red spruce stands in eastern North America, McLintock and Bickford (1957) used a height over diameter relationship as a measure of site quality instead of height over age as a site index. Comparing observed height-diameter relationships for dominant trees to standard curves, like conventional site index, provided an index of productivity. In Australia, Vanclay and Henry (1988) used a similar approach in cypress pine (Figure 12.2), and in sub-tropical eucalypts
(Vanclay 1992). The key in these approaches is using an intermediate diameter within the normal growth range (Figure 12.2) much like the index age used in height-based site index.

In tropical forests in Australia, Vanclay (1992) developed a “growth index” based on diameter increment adjusted for tree size and competition. The method used basal area to represent competition and did not use age or tree height. In temperate forests, coast redwood has a highly irregular height growth pattern, even among dominant trees in even-aged stands. As a measure of productivity, Berrill and O’Hara (2014) found that basal area increment was a better predictor of site productivity than site index in redwood stands of a range of stand structures. Forms of ecological site classifications (Bailey et al. 1978, Barnes et al. 1982) combine different approaches into a more integrated site evaluation that relies on multiple factors. These approaches provide evaluations for forestland suitability for different uses as well as basic productivity and these approaches are applicable to complex stands. An alternative approach for multiaged stands is to estimate site index in a nearby and similar even-aged stand and then assume differences are minimal.

Most site quality research has focused on volume productivity in even-aged stands. Nevertheless, the management of complex stands can benefit from this information. This includes information on productivity, information on species suitability, and insights into establishing suitable stocking levels. It could be argued that many complex stands will not be managed to maximize volume production so site productivity information is not necessary. However, the site productivity information can guide species selections, stocking levels, and help guide treatment intervals. It also is a key variable in most stand growth projection systems. Traditional site index is the most developed procedure for assessing site productivity, but much of the development of site index has been focused on even-aged stands for timber production. Alternative methods that focus on assessing vegetation or environmental variables may provide the best insights into the potential of complex stands to meet management objectives. But at present, these applications are not well developed.

Site quality assessment is an important part of multiple benefit forestry including the management of complex stand structures. Approaches are needed to quantify stand growth and potential productivity for use in growth projection models and provide meaningful comparisons between different sites. Approaches are also needed to provide more qualitative assessments of site potential for other resource uses. Site index is an effective site quality assessment approach for even-aged stand production but there are other methods that provide alternative information. This is also true for complex structures: methods are needed that can quantify potential timber production and assess site potential for alternative uses.

12.3 Growth Projection

The objective of multiaged stand growth prediction is to project future development of the stand and the changes in stand structure. Projections of wood volume production allow the land manager to project future revenue and make decisions on stocking levels and the length of cutting cycles. In other cases, projections may provide information on future stand structures and
corresponding information about wildlife habitat, disturbance risks, and the stand component
information of large-scale or landscape vegetation patterns. The concepts related to growth
prediction of multiaged stands vary depending on the stand structure, or specifically the
horizontal and vertical heterogeneity of the stand. Complex forest stands can be viewed as
existing on a gradient of spatial patterns ranging from relatively uniform to very heterogeneous.
The structural feature that distinguishes homogeneous from heterogeneous multiaged stands is
largely the size and arrangement of openings. Growth prediction concepts vary depending on the
size of the openings. Using the terms small and large openings to be consistent with the
terminology of Chapter 6, concepts related to small openings created through systems such as
single tree selection are presented separately from concepts related to large openings from
systems such as group selection.

Multiaged stands managed with the single tree selection system to form regular or
uniform stand structures are generally assumed to have negative exponential or reverse-J
diameter distributions (Figure 7.12). Other diameter distributions are possible, as are
distributions of other tree dimensions. The distributions change over time but are often assumed
to fluctuate from an initial structure to a pre-harvest structure and then back again. These
structures are assumed to have a relatively uniform spatial distribution. Over time, these stands
may be managed to a specific target diameter distribution such as a negative exponential
distribution (Chapter 7). The use of a consistent diameter distribution provides the opportunity to
project the changes in this diameter distribution over time. This type of consistency in stand
structure over time provides the opportunity to easily project changes.

As opening size increases, stand heterogeneity also increases. This is often an objective
of multiaged systems, but makes projections of stand development more difficult. A stand with a
fully regulated group selection system will essentially have the stand segmented into groups of
equal area. If groups are large, traditional even-aged projection tools can be used to project the
development of individual groups and then summed for stand growth. For example, even-aged
stand yield tables can be used by yield table ages correspond to age classes in the multiaged
stand. Calama et al. (2008) used this approach adapting even-aged models to multiaged stands of
stone pine in Spain. When groups are small or variable in size, achieving equal area per age class
becomes more difficult and there may be significant edge effects. However, even-aged stand
projection approaches can be used for these stands, but there must be a greater acceptance of the
potential error involved. Alternatively, average stand data for heterogeneous stands can be
projected as though it were a more homogeneous stand structure.

**12.4 Growth Projection Tools**

There are a variety of systems or tools designed for projecting stand development and
many can be applied in complex stand structures (e.g., Hann and Bare 1979, Vanclay 1995, Peng
2000). They vary in their complexity and their imbedded assumptions, but are typically divided
into empirical and mechanistic models (Figure 12.3). Many of these tools were designed to
model both simple even-aged stands and more complex multiaged stands. Most of these models
require a site quality assessment, usually in the form of a site index. Hence difficulties with site quality estimation may limit the tools that are available and affect the accuracy of predictions. Growth prediction tools are presented here from simplest to most complex and from stand-level to individual tree models per previous classifications (Munro 1974, Burkhart and Brooks 1990). This order of presentation also generally applies to the chronology of development of these tools as new computing technologies are greatly expanding the capabilities of growth projection. More detailed overviews of growth projection tools can be found in Avery and Burkhart (1994), Vanclay (1994, 1995), Husch et al. (2003), Peng (2000), Pretzsch (2009), and Weiskittel et al. (2011).

Traditional **yield tables** date back several centuries in Europe and much earlier in China (Vanclay 1994). Yield tables are often organized by age and site index for an individual species. The yield estimates are best in uniform stands. Hence fully-stocked, or normal stands, are one type of yield table for even-aged stands. The earliest European yield tables were based on rotation-length data, but tables in North America and elsewhere were based on less complete information and fitted to guide curves (Peng 2000). Another development was the variable-density yield table which presented separate yield tables for a range of stand density. For mixed-species stands or multiaged stands these problems are more complicated. Neither the age or site index of even-aged stands will usually be applicable to complex stands. Duerr and Gevorkiantz (1938) suggested finding even-aged groups of trees in multiaged stands and using them to develop yield functions for the entire stand. Others have suggested using the dominant species and then prorating the stand yield estimates by the percentage of the dominant species (MacKinney et al. 1937). Although the yield table approach has served forestry well for decades and even centuries, it has limitations for complex stands. These limitations are chiefly the difficulties in expressing stand age and site quality in multiaged stands, and the varying contributions to productivity from different species in mixed-species stands.

Stand growth and yield equations are another way to project volume growth in complex stands. These equations project average stand conditions from some initial stand age. They are derived from existing stand inventory data with repeat measurements. The simplest (stand-level) equations do not consider individual trees, and mortality during the estimation period can be modeled separately or is implicitly part of the estimated stand volume growth. A typical form might include an initial volume, a measure of stocking, and a time interval. Equations might be developed for different groups of sites or site may be included as a separate variable in prediction equations (Vanclay 1994). This procedure is crude because it does not generally consider species composition or any tree-level variation related to stand structure. Growth and yield equations are also not particular adept at characterizing management treatments such as thinning. However, the basic concept can be applied to even- or multiaged stands if the only objective is the change in volume or basal area with time. For example, Moser and Hall (1969) and Moser (1972) developed volume growth equations for multiaged hardwood stands in eastern North America.

**Whole stand distribution models** project a stand structure – as represented by a size-class distribution – forward over time. Most commonly, diameter size class distributions are
used. These models have been effective at projecting changes in uniform, even-aged stands, particularly plantations where unimodal, normal distributions are common. The size class distribution is characterized by a mathematical function such as a Weibull or beta function. Existing plot data are used to project changes in the distribution over time based on site quality. For even-aged stands, temporary plots that obtain a stand age can be used to develop these models. Diameter-height relationships, stem taper relationships, and volume equations can be applied to individual size classes to estimate volumes, which are then summed for stand volume. Silvicultural treatments such as thinning can be effectively modeled using changes in the post-treatment size-class distribution.

Whole stand models can also be used in multiaged stands where a negative exponential size-class distribution (e.g., Figure 12.4) can be represented with a mathematical function such as an alternate form of a Weibull function. Unlike the even-aged stand where the stand moves forward, the multiaged size-class distribution is moved forward with growth, and moved back with treatment (Figure 12.4). This may be a simpler modeling problem. Whole stand modeling can therefore be relatively simple providing that the diameter size class distribution is also simple. Interval data provided by permanent plots or repeated measurements is needed to project changes because a stand age is not applicable in multiaged stands.

Negative exponential diameter distributions are well-suited to whole stand modeling approaches, and this may be an impetus to manage for a negative exponential distribution: maintaining a uniform and preset size-class distribution improves predictability. Other size-class distributions would be more difficult, particularly if they varied between cutting cycles. Example applications of whole stand approaches to multiaged stands include Ek (1974) and Adams and Ek (1974) who used non-linear functions to develop stand-table projection models in northern hardwoods in North America. Hyink and Moser (1983) demonstrated how parameters that describe diameter size-class distributions can be predicted in multiaged hardwoods in eastern North America.

Whole stand models have the capability to project both stand structure and volume yields in multiaged stands. The transformation from even-aged to multiaged stands with these models is relatively simple. However, consistent size-class distributions are necessary and these models become less successful with more complicated stand structures. Their greatest utility in projecting complex stands will be for relatively simple structures where the primary attribute of the modeling effort is projections of volume growth. However, designing stand structures should be driven by meeting management objectives, not modeling efficiency.

Another form of projection system that is applicable to complex stands uses size classes as the basic unit for projection rather than stands or individual trees. These size class models project the growth of individual size classes and aggregate to the stand level. Stand table projection is a form of a size class model where diameter size classes are advanced through the diameter distribution at a certain rate as a function of tree size, stocking, site quality, and mortality rates. A future stand table could then be developed from a previous table given growth, mortality, and harvest factors. For a hypothetical 5 cm diameter class, a certain percentage of
trees might advance one class, two or more classes, or not advance at all. Forms of movement ratios or growth-index ratios – developed from inventory records – are used to make these calculations. The stand table projection method has been used in a variety of forest types and management regimes. For example, Korsgaard (1989) developed a simulation system based on stand table projection for mixed forests in Malaysia. **Matrix models** are another form of size class models (Buongiorno and Michie 1980). These models project changes in structure but allow greater efficiency in summarization of transition functions. They have been developed for a number of different forest types including temperate (Hao et al. 2005), boreal (Kolström, 1998), and tropical forests (Mendoza and Setyarso 1986). These models are commonly used in multiaged forests and although they typically use diameter classes as the state variable, age classes, species, or canopy strata can also be used.

A widely-used group of stand projection tools are **individual-tree models**. These models project the growth of individual trees which are aggregated to the stand-level. These models are often categorized as either models that do not require spatial locations of trees (distance-independent) and those that do (distance-dependent; Munro 1974, Peng 2000). Although these models are generally designed to guide management, some are more applicable to research (Mohren and Burkhart 1994, Battaglia and Sands 1998, Peng 2000, Groot et al. 2004). In either case, they are important for the analysis and assessment of complex forest structures.

There are a number of classifications of individual-tree growth projection models. There are the distance-dependent/independent classes, the empirical/mechanistic classes, and individual-tree models that focus on stands and others that are focused on gaps. Many of these models were developed to either provide greater predictive potential in complex stands or to gain a better understanding of stand-level processes. Many of these developments can be viewed as moving from describing forest dynamics to explaining forest dynamics (Bossel 1991).

**Distance-independent individual-tree models** simulate the growth of the individual tree and sum individual tree results to produce stand-level results. Spatial locations of individual trees are not a requirement of these models. Projections are based on individual trees or by size classes. Stand-level variables that are often required include site index, stand age, and measures of density. Competition is often described with indices that describe density and crown competition (Biging and Dobbertin 1995) based on average stand characteristics. These models generally run on typical stand inventory data. Many of these models are well-suited to projecting development of complex stand structures when issues over quantifying site quality and stand age are resolved. Examples include PROGNOSIS/FVS (Stage 1973, Wycoff et al. 1982, Teck et al. 1996), PROGNAUS (Monserud and Sterba 1996), and many others.

**Distance-dependent individual-tree models** require data on spatial locations of individual trees. These models project individual trees forward, and tree growth is summed to produce stand-level results. Information on tree bole sizes, crown sizes, and spatial patterns among trees can be used to describe competition (Biging and Dobbertin 1992). Mechanistic or process models nearly always fall into this category. These models may attempt to describe photosynthesis, respiration, and nutrient cycling to describe how stands grow and also how these
processes interact to affect other processes. Examples include the FOREST model (Ek and Monserud 1974, SORTIE model (Coates et al. 2003), SILVA (Pretzsch et al. 2002), and many others.

Mechanistic or process models are capable of simulating scenarios outside the range of empirical data. This is useful for projecting stands of unusual structures or management strategies, or for simulations in changing environments and climate. Distance-dependent individual-tree models are appropriate for projecting changes in complex forest structures, assuming they provide a realistic representation of tree growth across a range of growing conditions (e.g., at/near gap edges, in deep shade, etc.). The primary obstacles to operational use of mechanistic models is the need for stem mapped inventory data and the common view that these models are best for research purposes. Battaglia and Sands (1998) noted the potential of these models for guiding management decisions in lieu of empirical models. However, the required spatial data may be too expensive for management applications (Vanclay 1995). Distance-dependent individual-tree models have the potential to project complex stand structures and are most capable of all the different stand projection tools at including the intricacies of complex structures.

**Gap replacement models** are another form of individual-tree, mechanistic models that simulate the development of small patches within stands or larger units of forest (see Chapter 5.4). The individual tree is usually the simulation unit in these models. Individual trees are aggregated to represent the development of the gap (Shugart 1984, Peng 2000, Bugmann 2001, Schliemann and Bockheim 2011). A single-tree tree fall is the usual gap-initiating event. Gap replacement models are generally distance-independent and most are adaptations of the JABOWA or FORET models (Botkin et al. 1972, Shugart and West 1977). Gaps are individual patches that do not interact, but may be aggregated to represent a stand. Hence any stand-level simulations from gap replacement models are projections of independent patches that model the within-gap processes of growth, regeneration, competition, and mortality; however, these models generally assume no interactions from adjacent patches, including edge effects, on these processes.

Gaps are important structural elements that affect the dynamics of complex forests. Gap replacement models are useful for simulating gap effects and improving our understanding of gap dynamics. These models can simulate a variety of processes such as species changes, habitat development for wildlife, energy exchanges, and others. They have great utility for stand- and ecosystem-level analyses. However, gap replacement models are rarely used for management applications because of the limitations of working at the gap-scale and the data requirements for model implementation.

**12.5 Optimization Tools**

Determining the optimal stand structure has been a common objective in multiaged management and the subject of considerable research. **Optimization tools**, such as **linear programming**, are advanced tools within the field of **operations research**. The primary
Objective function of these optimization models has usually been maximization of a sustainable level of volume production. This is because of the easily quantifiable value of wood volume, and also because maximizing wood volume and value have traditionally been primary drivers in designing multiaged stand structures. Because of the emphasis on volume production, these optimization tools rely on growth projection tools to estimate wood volumes for different scenarios. The scenarios are stocking regimes that present different options for how growing space can be allocated to stand components.

Examples of optimization model applications using stand growth projection models include Adams and Ek (1974) with a whole stand model, Buongiorno and Michie (1980) with a matrix model, and Hasse and Ek (1981) with a distance-dependent model. Many other examples exist (Box 12.1), mostly with northern hardwood forests or ponderosa pine forests in North America (Hall and Bruna 1983, Haight et al., 1985, Haight 1987, Bare and Opalach 1988, Gove and Fairweather 1992, Anderson and Bare 1994, and others). These optimization models include many assumptions, much like studies of relative productivity (Chapter 13). If the objective is to create or maintain a predetermined stand structure then there have to be assumptions about species composition, cutting cycle length, and the initial condition or starting point for the analysis.

12.6 Synthesis

Quantification of growth processes for complex stands is essential for their management and for understanding stand- and ecosystem-level processes. Projecting change in multiaged stands has been hindered by limitations in tools to assess site quality which determines the rate of change in stand structure and volume production. Forest site productivity estimation has largely been based on dominant height growth, a concept with limited application in multiaged stands. Additional research in this area is needed.

Historically, growth projections relied on empirical approaches using large amounts of data to develop reasonably accurate estimates of stand growth and production. However, they are limited by available data and are not robust when accommodating unusual management strategies or changing environmental conditions. These empirical approaches also perform best in even-aged, single-species stands, and are less effective in more complex stands. Although these tools have the capability to project stands of a variety of stand structures, many assume the negative exponential diameter distribution as a standard. Many of these stand-level projection tools were developed in northern hardwood stands in North America where plentiful regeneration results in negative exponential diameter distributions.

Developments in individual-tree models provide tools for both management and research. These models range from the empirically-based to models based on mechanistic processes in forest ecosystems. The capability of these models – particularly the distance-dependent models – to represent complex processes and interactions between stand elements, makes them well-suited for modeling complex stands. However, requirements for spatial data for distance-dependent models and the general model complexity of individual-tree models may limit their usage.
Empirical approaches are limited to the past conditions from which the data they are based were derived. This generally limits projections to previous experiences where data exists. Mechanistic models offer the potential to look beyond existing data to explore alternative stand structures or the effects of climate change (Kimmins 1990, Bossel 1991). Peng (2000) described the weaknesses of empirical models as strengths for mechanistic models, and vice versa. These criteria included applicability to management or research, the number of parameters, and other criteria. Hence hybrid approaches that combine process and empirical models (e.g., Kimmins 1990) may offer opportunities to link the strengths of both approaches into useful stand projection systems.

Optimization tools have been used to find optimal stocking regimes for volume or economic production in multiaged stands. Much of the impetus for greater use of complex stand structures is to meet resource demands that are not as easily quantified as wood volume or economic production. Instead, the same factors motivating the use of mechanistic modeling approaches for unique stand structures or to anticipate effects of climate change, are requiring increasingly complex tools. These tools have a role in assessing forest management options. However, on many of the forest lands where managing for complex stand structures will be a dominant objective, managers may be making on-the-ground decisions based on the presence or absence of structural features such as snags, multiple species, or unique spatial patterns. The desire to retain or create these features at the individual stand level will create unique management decisions at each stand that cannot be easily quantified, modeled, or optimized on an individual stand basis.
Figure 12.1. Schematic of height growth of dominant tree in an even-aged stand compared to a tree that becomes dominant in a multiaged stand. The tree in the multiaged stand endures periods of various degrees of suppression before it emerges into the upper canopy, making it unsuitable as a site index tree.
Figure 12.2. Height-diameter curves for multiaged cypress pine in Queensland, Australia. Much like conventional site index, these curves are fit to existing data and an index age (25 years in this example) is established. The height (h) and diameter (d) of individual trees would be plotted on the curve to evaluate site productivity or “site form” for a given density and age (from Vanclay and Henry 1988, Vanclay 1994).
Figure 12.3. Chart showing classification of growth projection tools for multiaged stands (from Peng 2000).
Figure 12.4. Changes in stand structure as represented by diameter distributions for an even-aged stand (above) and a multiaged stand (below). Both diagrams show a stand in an initial stand structure and then the same stand after a growth period. Either situation can be modeled with a whole-stand model.
Box 12.1 Optimizing Transformation

Operations research in forestry has attempted to identify optimal stand structures for multiaged stands. Because these studies focus on an optimal structure, they attempt to meet a relatively static condition. Another management objective is transformation of an even-aged to a multiaged stand (Chapter 11). Rojo and Orios (2005) developed a decision support system to maximize net present revenue among options for transforming even-aged maritime pine to a multiaged structures in northwestern Spain. The decision support system used a transition matrix growth model and nonlinear programming.

The transformation begins from an even-aged stand and moves toward a target multiaged structure previously identified by Orios et al. (2004). Thinnings are used to reduce density and regenerate new age classes although trees less than 15 cm diameter were not modeled (Figure 12.5). The decision support system solutions were sensitive to the interest rate used. Higher interest rates led to solutions with heavier cutting in early thinnings whereas with an interest rate of zero the thinnings were late in the transformation process. The analysis used a target structure represented by a basal area of 17 m²/ha. However, the system found that there were several different stand structures which yield similar benefits. The decision support system was capable of also varying the initial stand structure, the target stand structure, the thinning treatments, and the economic constraints to test alternative transformation systems.

Analyses to develop optimal stand structures or management regimes can include multiaged as well as traditional even-aged applications. As with other studies (Buongiorno 2001, Hanewinkel 2001, Knoke and Plusczyk 2001), Rojo and Orois (2005) found the transformation process to be economically viable. This is apparently due, in large part, to the earlier harvests associated with transformation regimes which are usually attempting to regenerate new age classes earlier than many even-aged stands would be generating income (Knoke and Plusczyk 2001). Although many non-commodity values are difficult to quantify, similar tools can assess the ability of a transformation regime to achieve objectives other than optimizing a stand structure or maximizing returns. A key component of all these analyses, regardless of the objective, is a stand projection tool.
Figure 12.5 Potential solutions from an initial condition of an even-aged stand to the target condition of a multiaged stand. Various thinnings of different intensity or intervals between thinnings were compared as alternate pathways to achieve the target stand structure (from Rojo and Orois 2005).