1 Introduction

All models are an abstraction of reality that attempt to conceptualize key relationships of a system. Models can be both quantitative and conceptual in nature, but all models are integrators of multiple fields of knowledge. Consequently, models generally have several important and varied uses. Forest growth and yield models are no different. Foresters often have a general sense of a stand's developmental trajectory and what can be done to alter it. However, it generally takes years of experience to achieve this level of expertise and, even then, quantifying the predictions can be difficult. Forest growth models attempt to bridge this gap by providing model users the ability to predict the future condition of the forest. Ultimately, growth models are the quantitative generalizations on the knowledge of forest stand development and their response to silvicultural treatments.

Forest growth and yield models have a long, and rapidly expanding, history of development (Figure 1.1, 1.2). Their development and use has particularly increased in the last two decades, due in part to the greater availability of personal computers to perform both data analysis and complex simulations (Figure 1.2). This has resulted in a wide array of modeling approaches, each with their own advantages and disadvantages. In particular, models differ in the type of data used and the method of construction. This book attempts to provide an overview of the primary concepts involved in forest modeling, the various techniques used to represent the determinants of growth, and the techniques needed to both develop and use a growth model properly.

Although the concepts of forest growth and yield have long been a part of forestry, they have been defined and named in various ways, particularly in the US (Bruce, 1981). In this book, *increment* is defined as the difference between tree or stand dimensions from one time period to the next, while *growth* is the final dimension from one time period to the next. In other words, increment is determined by either solving a growth equation or by observing growth at two points of time (Bruce, 1981).

Forest Growth and Yield Modeling, First Edition. Aaron R. Weiskittel, David W. Hann, John A. Kershaw, Jr. and Jerome K. Vanclay.

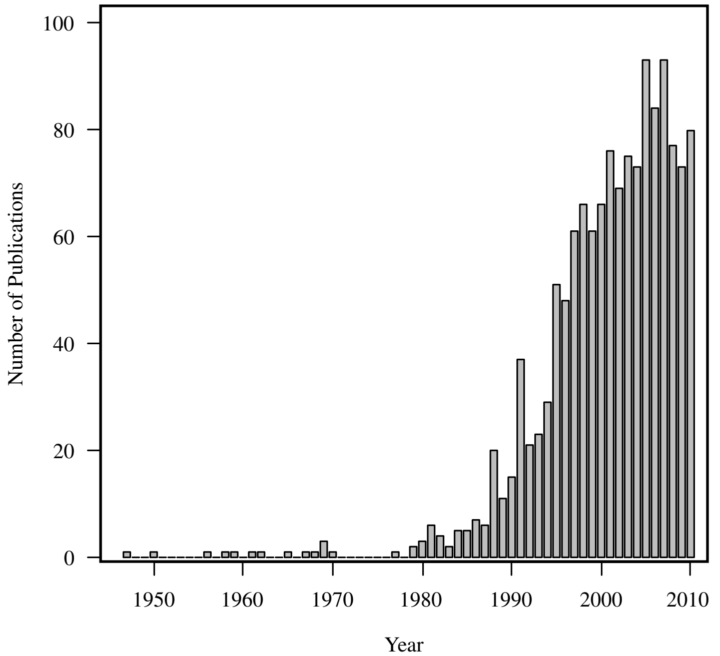

Figure 1.1 Number of publications on growth and yield, by publication year, based on a keyword search of the CAB Direct database (www.cabdirect.org, accessed December 21, 2010).

This book is focused on models that predict the development of a single forest stand (Figure 1.3). Although a distinction between empirical and mechanistic models is often made (e.g. Taylor *et al*., 2009), this is not a useful metric of differentiation, as all models are on a spectrum of empiricism. Instead, this book groups forest stand development models into four broad categories: (1) statistical models; (2) process; (3) hybrid; and (4) gap (Table 1.1; Figure 1.4).

Statistical models rely on the collection and analysis of data that will characterize the targeted population in a manner that allows statistical variability to be estimated for parameters. The primary intent of statistical models is for prediction of forest stand development and yield over time. Process models represent key physiological processes (e.g. light interception, photosynthesis), often for understanding and exploring system behavior, which are then combined to characterize both tree and stand development. Hybrid models merge features of statistical and process models and are used both for understanding and for prediction. Gap models are designed to explore long-term ecological processes, generally for understanding interactions that control forest species succession. Models that integrate the development of multiple forest stands, such as landscape models, exist (e.g. Mladenoff, 2004), but will not be covered in this book.

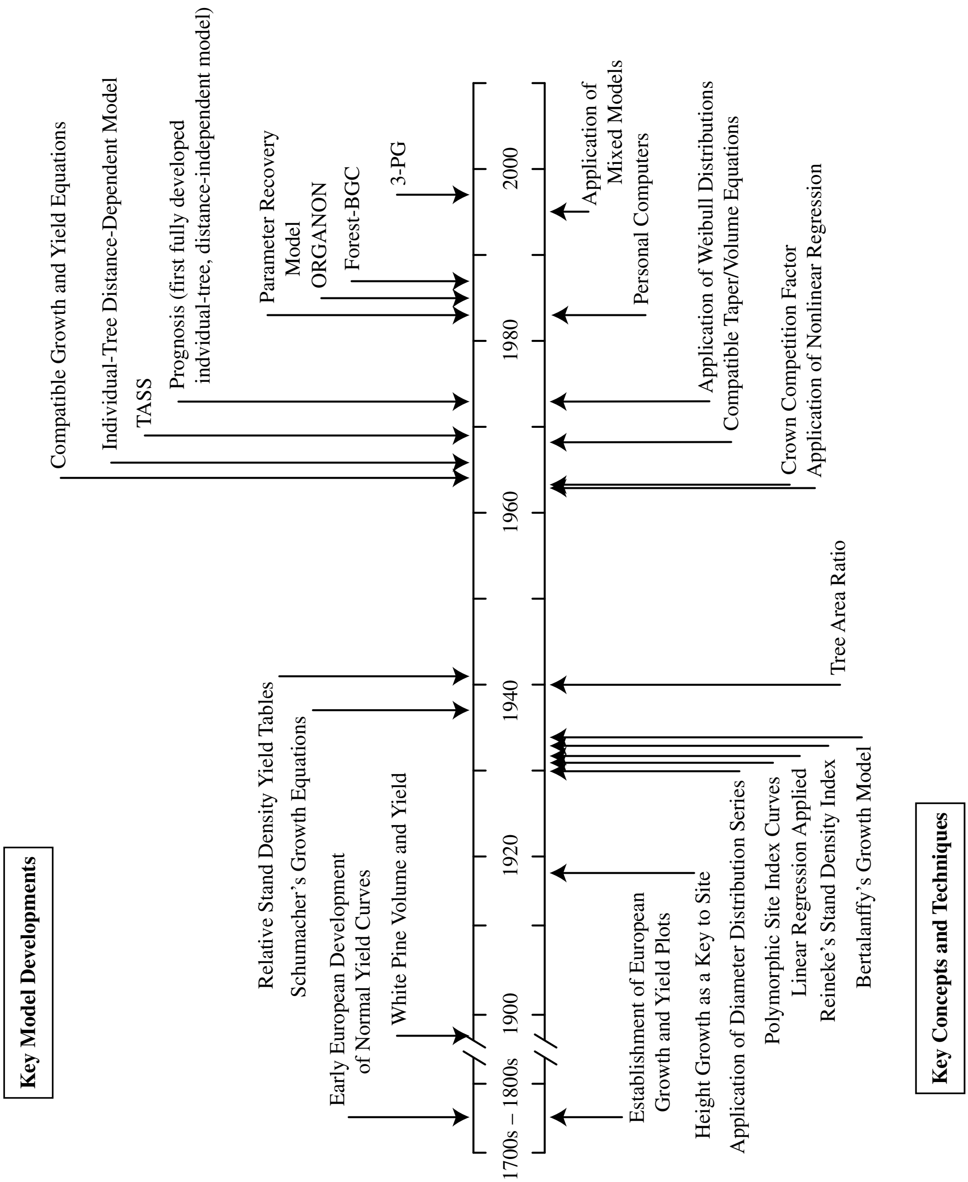

Figure 1.2 Key milestones in model development and associated concepts and techniques.

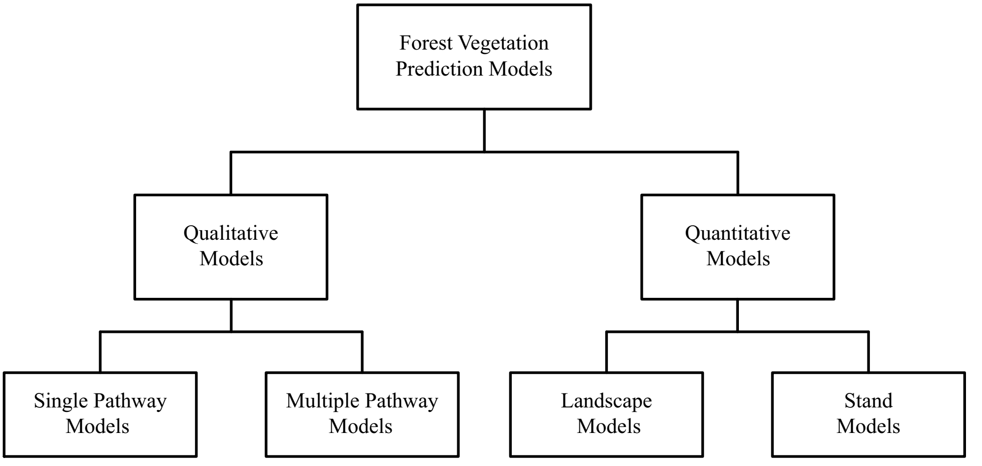

Figure 1.3 Types of forest vegetation prediction models. Adapted from Taylor *et al.* (2009).

Within any given model category, models differ in their resolution (both spatial and temporally), spatial dependence, and degree of determinism. Spatial resolution refers to the basic unit for predictions, with the simplest being a whole-stand approach (Chapter 4), and the individual-tree approach is the most detailed (Chapter 5). A size-class model is a compromise between the whole-stand and individual-tree approaches (Chapter 4). Some process models even have a spatial resolution of an individual leaf within a tree crown. In addition, a significant amount of effort has been made in combining predictions from models with different spatial resolutions (Chapter 10).

Temporal resolution is the basic time step for model predictions. Several process models have daily or even hourly time steps, while statistical models generally have 1- to 10-year temporal resolutions. Models also vary in their use of spatial information. Distance-dependent or spatially explicit models require spatial location information; often individual-tree x–y coordinates are needed. Distance-independent or spatially implicit models do not require this information.

Finally, models differ in their use of deterministic approaches, which means that a particular function will always return the same output return value for any given set of input values. In contrast, stochastic approaches incorporate some purely random element and will give different return values in successive runs with any given set of input values. Stochasticity can be an important element of forest modeling, as some relevant factors like natural disturbances that ultimately govern the growth and yield of a particular stand can be random or unpredictable. However, a model with too many stochastic elements can make interpretation a challenge.

Stochasticity is one approach for addressing the variability that is inherent in all aspects of modeling. Even models in fundamental sciences like physics and chemistry have purely random elements. However, biological systems are even more variable and models need to

Table 1.1 Categories of quantitative single stand forest development models and their definition, use, advantages, and disadvantages.

Type of model	Definition	Important uses	Advantages	Disadvantages	Key references
Statistical	Utilize empirical data and statistical techniques like regression to derive quantitative relationships	Update forest inventories; compare forest silvicultural treatments; estimate sustainable harvests	Robust; long history of development; rely on data generally available; output geared for operational decisions; can represent a wide range of conditions and sampling schemes	Require high quality empirical data; can extrapolate poorly; generally insensitive to climate	Taylor *et al.* (2009)
Process	Represent key plant physiological processes like photosynthesis, which are then scaled to the stand-level to estimate growth	Understand the underlying mechanisms influencing growth; test hypotheses about plant behavior; predict potential forest productivity	Can theoretically extrapolate to novel situations; sensitive to climate; mechanistic	Dependent on several difficult-to-measure parameters; input data not widely available; high computational demand; output often unusable for operational decisions	Mäkelä *et al.* (2000a); Landsberg (2003)
Hybrid	Combine statistical and process approaches in attempt to take advantage of the strengths of both approaches	Predict growth using climatic factors; prediction of novel forest silvicultural treatments	Robust; sensitive to climate; minimize the number of required parameters; can use traditional forest inventory data	Accuracy improvements can be minimal when compared to a purely statistical approach; climate and soils input data not widely available	Monserud (2003)
Gap	Rely heavily on ecological theory and interpretation of species dynamics relative to both competition and environmental conditions	Predict long-term forest succession; test ecological theories	Incorporate a variety of natural disturbance agents; long time scales	Prediction accuracy is often low compared to statistical models; difficult to initialize with forest inventory data; several subjective parameters	Bugmann (2001); Shugart (2002)

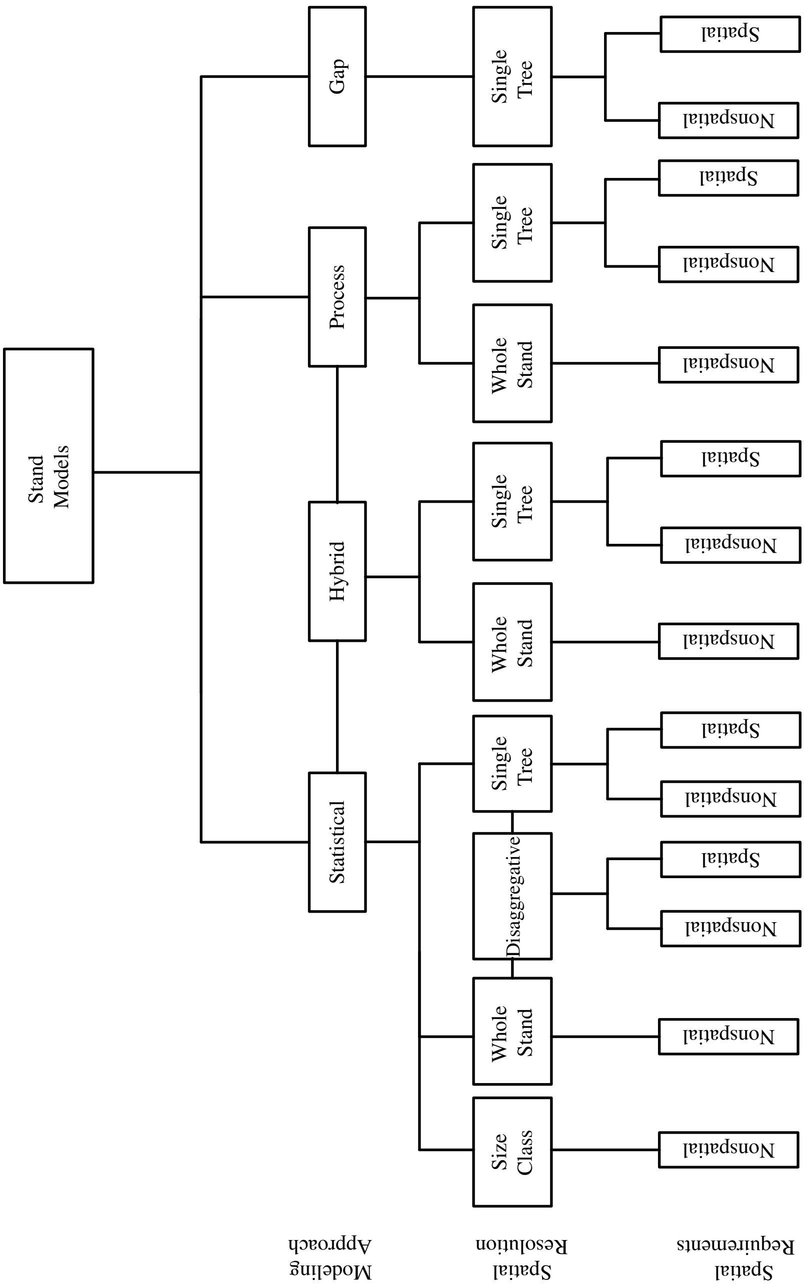

Figure 1.4 Types of forest vegetation prediction models that are focused on the stand-level.

recognize the important sources. Therefore, the models examined in this book have a framework that is based upon our current biological knowledge and are parameterized with the knowledge that the parameters are uncertain.

Forest growth models have several components. At minimum, forest stand development models must represent growth (Chapter 6) and mortality (Chapter 8). Models must also have components that relate the traditional tree measurements of diameter and height to other attributes like total volume or biomass with the use of static equations (Chapter 7). Comprehensive growth models include components to predict regeneration and ingrowth (Chapter 9) and representation of silvicultural treatments (Chapter 11). In addition, understanding the key biological determinants of growth and yield, namely competition (Chapter 2) and site potential productivity (Chapter 3), is important.

1.1 Model development and validation

As with most fields, forest modeling is both an art and a science. Ideally, the development of any model involves a comprehensive understanding of the system and an approach for detecting the crucial relationships. This often means that modelers must be multidisciplinary. In addition, model development is often an iterative and collaborative effort between modelers, fundamental scientists, and model users. The process of modeling is an assessment of current understanding of forests, information needed for management, and crucial knowledge gaps.

Consequently, research questions can often be generated by assessment of model strengths and weaknesses. This also illustrates an important modeling distinction, namely the use of models for prediction versus understanding, which will be further discussed below. Although there are important general modeling philosophies like Occam's principle of parsimony, which suggests that models should be as simple as possible, but as complex as necessary (Kimmins *et al*., 2008), achieving this is often easier said than done.

Regardless of modeling approach, empirical data of one type or another will be required for either model construction (Chapter 14) or model evaluation (Chapter 15). Data can often vary greatly in its quality and overall usefulness for modeling. Among others, data quality is influenced by how well the data represents the population of interest, the variables collected, and the degree of measurement error, which is often an overlooked yet important determinant of predictability (e.g. Hasenauer and Monserud, 1997). The statistical tools used to construct models are continually changing and evolving. Chapter 14 provides a brief overview of the key statistical techniques in order to give a better context to statistical forest growth and yield models.

To be useful for a given purpose, a model must be representative of reality to some degree. Consequently, a variety of methods have been used to verify model predictions (Chapter 15). This has ranged from simple statistical tests to complex stochastic simulations. Each has their own merits, but, in general, models must be verified using multiple approaches to ensure full reliability. If model predictions are found to be inadequate, a larger question quickly becomes how to fix or re-calibrate the model. This can often be a complicated undertaking, but emerging approaches may simplify the process.

1.2 Important uses

Models are tools designed to be used in a variety of ways (Chapter 16). The key uses of any well-developed model are prediction and education in its broadest sense (Figure 1.5). In forestry, some key prediction roles of growth models are (1) update forest inventories; (2) assess alternative forest silvicultural systems; (3) determine the influence of disturbance agents like insects or disease; (4) estimate sustainable yield of forest products; and (5) generalize regional trends. Growth and yield information is required to make all major forest management decisions. Some of the basic decisions that require accurate growth and yield information include: (1) even-aged stand-level decisions; (2) uneven-aged stand-level decisions; (3) forest- or ownership-level decisions; and (4) regional and national decisions. The type of information needed from a forest growth and yield model

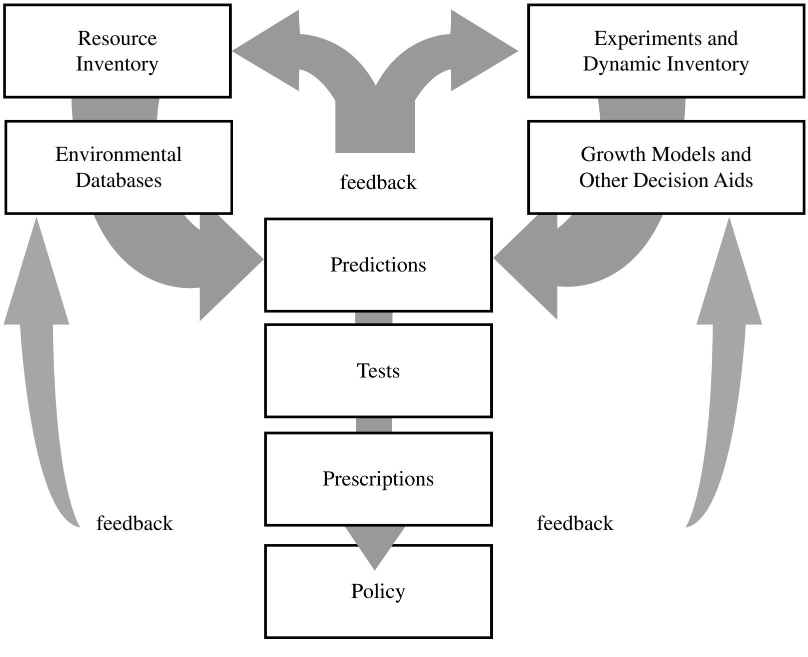

Figure 1.5 The role of growth models in decision making, forest management, and the formation of forest policy. Adapted from Nix and Gillison (1985).

Table 1.2 Uses of growth and yield models to aid in key forest management decisions.

Type of decision	Important factors to consider	Reference
Even-aged stand-level	Planting density; thinning strategy; fertilization strategy; species or species mix; rotation length	Hann and Brodie (1980)
Uneven-aged stand-level	Sustainable diameter distribution; cutting cycle length; species mix; fertilization strategy; conversion strategy	Hann and Bare (1979)
Forest or ownership level	Schedule of stand treatments; allowable harvest; wildlife habitat; aesthetics	Bettinger *et al.* (2009)
Regional or national level	Carbon sequestration potential; allowable harvest; wildlife habitat	Bettinger *et al.* (2005)

to make these different decisions depends on the spatial and temporal level at which information is needed (Table 1.2).

For example, a silviculturist would primarily use a growth and yield model to project the development of the stand under alternative treatment strategies such thinning or fertilization regimes. A forest planner would likely use a growth and yield model to stratify individual stands in a forest into homogeneous units, project the development of each stratum, and use a harvest scheduler to determine the optimal silvicultural system and allowable harvest. A policy-maker would generally use a growth and yield model to depict regional or national trends like carbon sequestration potential or sustainable harvest levels to set effective policies. In fact, growth models were used in the United States, by the Chicago Climate Exchange and the California Climate Action Registry, to set standards for carbon credit trading and greenhouse gas registries at regional and national scales.

Additional uses of models are the visualization of management alternatives and the assessment of forest stand dynamics on wildlife habitat and streamside conditions for fish habitat. Consequently, the implications of basing decisions on a growth and yield model at any level are often quite significant, which both model developers and users need to be aware of.

There are several complex issues facing the practice of forestry today, like assessing the effects of climate change, forest carbon neutrality, and long-term sustainability. Answering these open questions with empirical data is often difficult, requires long-term investment, or is impossible. Consequently, growth and yield models are widely used by scientists as research tools to test hypotheses and understand system behavior. For example, the ORGANON growth and yield model (Hann, 2011) has been widely used by scientists to answer several research questions on a broad array of topics ranging from forest management, planning, and economics, to conservation issues (Table 1.3).

Models are good research tools as they allow the construction of what-if scenarios and experimentation with different parameter settings. In addition, the development and

Table 1.3 Examples of the applied uses of the ORGANON growth and yield model.

Study	Purpose
Forest management	
Maguire *et al.* (1991)	Examine the influence of alternative management on wood quality
Welty *et al.* (2002)	Assess strategies for managing riparian zones
Wilson and Oliver (2000)	Strategies for density management to ensure stability
Sessions *et al.* (2004)	Manage the consequences of wildfire
Forest planning	
Johnson *et al.* (2007a)	Develop large-scale, long-term plans for usage of forested landscapes
Sessions *et al.* (2000)	Develop mature forest habitat
Shillinger *et al.* (2003)	Predict future timber supply
Johnson *et al.* (2007b)	Large-scale assessment of socioeconomic effects on forest structure and timber production
Economics	
Birch and Johnson (1992)	Determine the economic impact of green tree retention
Fight *et al.* (1993)	Conduct a financial analysis of pruning alternatives
Busby *et al.* (2007)	Evaluate the opportunity cost of forest certification
Latta and Montgomery (2004)	Create cost-effective older stand structures
Wildlife	
Hayes *et al.* (1997)	Evaluate response of wildlife to thinning
Calkin *et al.* (2002)	Managing for wildlife biodiversity
Lichtenstein and Montgomery (2003)	Assessing influence of timber management on wildlife biodiversity
Andrews *et al.* (2005)	Strategies for creating northern spotted owl nesting sites
Nalle *et al.* (2004)	Strategies for joint management of timber and wildlife

construction of any growth model often leads to new and interesting research questions. This is because model development largely requires making and testing key assumptions, assessing patterns, and providing full disclosure, which are all basic tenets of the scientific method. In other words, developing a model requires the processes or system being modeled to be conceptualized and understood.

Forest growth and yield models are useful tools for education, a role that ORGANON has often played (Marshall *et al.*, 1997). This is because models require hands-on interaction, synthesis of multiple concepts, and critical thinking skills to assess the

Table 1.4 Model name, type, resolution, distance dependence, stochasticity, region, primary species, and reference for example models considered in the text.

Model name	Model type	Resolution		Distance dependent	Stochastic	Region/country	Primary species[a]	Reference
		Spatial	Temporal					
3-PG	Hybrid	Whole stand	Monthly	No	No	Several	DF, LP, EG, EN, NS, RP, SP, SS, WL	Landsberg and Waring (1997)
BALANCE	Process	Individual tree	One year	Yes	No	Germany	EB, NS	Grote and Pretzsch (2002)
CABALA	Hybrid	Whole stand	Monthly	No	No	Australia	EG	Battaglia *et al.* (2004)
CenW	Process	Whole stand	Monthly	No	User's choice	Australia	ED, RP	Kirschbaum (1999)
DFSIM	Statistical	Whole stand	Five year	No	No	Pacific Northwest, United States	DF	Curtis *et al.* (1981)
FIBER	Statistical	Size class		No	No	Northeast, United States	AB, BF, RS, BS, WS, EH, NC, SM, RM, YB, PB, QA, RO, TA, WA, WP	Solomon *et al.* (1995)
Forest-BGC	Process	Whole stand	Daily	No	No	Several	—	Running and Coughlan (1988); Running and Gower (1991)

(continued)

Table 1.4 (*Continued*)

Model name	Model type	Resolution		Distance dependent	Stochastic	Region/country	Primary species[a]	Reference
		Spatial	Temporal					
JABOWA	Gap	Individual tree	One year	No	Yes	Northeast, United States	AE, AB, BC, BF, BP, BW, BT, BN, RS, BS, WS, EH, NC, SM, RM, YB, PB, QA, RO, TA, WA, WO, WP	Botkin *et al.* (1972a, b)
ORGANON	Statistical	Individual tree	Five year, One year	No	User's choice	Pacific Northwest, United States	PM, BM, BO, LO, GC, OO, DF, RA, TO, WL, GF, IC, PY, PP, PL, WH, WF	Hann (2011)
CROBAS	Hybrid	Size class	One year	No	No	Finland; Quebec	JP, SP, NS	Mäkelä (1997)
PROGNAUS	Statistical	Individual tree	Five year	No	User's choice	Austria	NS, WF, EL, TP, SP, EB	Monserud *et al.* (1997)
Scube	Statistical	Whole stand	One year	No	No	British Columbia, Canada	WS, ES	García (2011)
SILVA	Statistical	Individual tree	Five year	Yes	Yes	Germany	BP, NS, WF, EB, SP, SO	Pretzsch *et al.* (2002)
SORTIE	Gap	Individual tree	One year	Yes	Yes	Northeast, United States; Quebec and British Columbia, Canada	AB, EH, JP, LP, SM, RM, TA, WA, WP, WH, YB	Pacala *et al.* (1993; 1996); Coates *et al.* (2003)
TASS	Statistical	Individual tree	One year	Yes	Yes	Pacific Northwest, Canada	DF, WS	Mitchell (1969; 1975)

[a]See Appendix 1 for species codes.

appropriateness of output. In addition, combining model prediction with visualization tools (Chapter 16) allows visual demonstration of key concepts like stand structure and stratification, which can be difficult to achieve with just words or in the field.

1.3 Overview of the book

Forest growth modeling is an evolving and comprehensive field that can be difficult to describe fully. Previous books on forest growth modeling have either become outdated (e.g. Vanclay, 1994), focused primarily on one geographic region (e.g. Hasenauer, 2006), or are specific to a particular modeling approach (e.g. Landsberg and Sands, 2011). This book attempts to provide a comprehensive overview of forest models from multiple perspectives in order to be useful to model developers, scientists, students, and model users alike.

The book is divided into 17 individual chapters that give an overview of the key concepts determining growth and yield (Chapters 2, 3), the different types of modeling approaches (Chapters 4, 5, 12, 13), and the various dimensions of developing, validating, and using a growth model (Chapter 14, 15, 16). Example models are described in detail for each modeling approach to illustrate key differences and provide information on some of the more widely used models (Table 1.4).

In particular, the components of statistical, distance-independent, individual-tree models are discussed in detail (Chapters 6, 7). Attention is given to this type of modeling approach because it has been widely adopted and extensively used for operational management planning. For example, statistical, distance-independent, individual-tree models are currently available and used throughout the United States (Crookston and Dixon, 2005), western Canada (e.g. Temesgen and LeMay, 1999), central Canada (e.g. Bokalo *et al.*, in review), eastern Canada (e.g. Woods and Penner, 2007), central Europe (e.g. Monserud *et al.*, 1997), and northern Europe (e.g. Hynynen *et al.*, 2002). The approach has been preferred because it can be used in a wide range of stand structures, particularly in uneven-aged (Peng, 2000) and mixed species stands (Porté and Bartelink, 2002). Throughout the book, specific attention is given to the ORGANON growth and yield model of the United States Pacific Northwest (Hann, 2011), as it has a long history of continuous development, is applicable to a large number of conifer and hardwood species in a wide array of stand conditions, and has been rigorously tested.

It is our hope that the book can help promote a more comprehensive understanding of forest models, and guide future modeling efforts.