

Review and comparison of tree- and stand-based forest growth models for potential integration into EnSym

Patrick J. Baker¹ & Andrew Robinson²

June 8, 2010

¹School of Biological Sciences, Monash University, Victoria 3800, Australia.
`patrick.baker@sci.monash.edu.au`

²ACERA and Department of Mathematics and Statistics, University of Melbourne, Victoria 3010, Australia. `A.Robinson@ms.unimelb.edu.au`

Contents

Table of Contents	2
List of Tables	3
List of Figures	4
1 Executive Summary	5
2 Scope of the report	7
3 EnSym and the Ecotender Process	8
4 Framework for Model Review	10
4.1 Introduction	10
4.2 Filter 1: Model classes	11
4.3 Filter 2: Model attributes	17
4.4 Filter 3: EnSym-specific requirements	20
5 Review and comparison of available growth models	22
5.1 Key empirical forest growth models	22
5.1.1 FVS	22
5.2 Key process-based forest growth models	25
5.2.1 ET-Pan	25
5.2.2 3PG+	27
5.2.3 ALMANAC _{BF}	28
5.3 Key gap models	32
5.3.1 JABOWA and offspring	32
5.4 Key hybrid forest growth models	33
5.4.1 SORTIE	33
5.4.2 FVS-BGC	36
5.4.3 Statistical model melding	39
5.5 Key issues in adopting a forest growth model into EnSym	40

5.5.1	Representation of forest growth and critical ecosystem processes . .	40
5.5.2	Data availability	42
6	Recommendations for forest growth modelling in EnSym	43
A	A comparison of 3PG+ and ALMANAC_{BF}	52

List of Tables

4.1	Selected examples of forest growth models.	12
4.2	Key characteristics of forest growth model classes.	18
5.1	FVS: parameter definitions and example coefficient values for white pine in Northern Idaho variant (Wykoff <i>et al.</i> 1982)	24
5.2	ALMANAC _{BF} : parameters required for model runs	31
5.3	SORTIE: parameters required for model runs	34
5.4	SORTIE: parameter definitions and example coefficient values for eastern white pine	36
5.5	Qualitative assessment of the capacity of different forest vegetation models to represent carbon and water variability. Rating scheme is +, +/-, -, or unknown	41
6.1	Summary table of costs and benefits associated with report recommendations.	45

List of Figures

4.1	Gap model representation of vegetation	15
5.1	ET–Pan: key submodels in the PERFECT cropping system model	26
5.2	SORTIE: key processes and components of the model.	35
5.3	FVS–BGC: relationship of STAND–BGC to FVS	38
A.1	ALMANAC: model outputs vs. observed data.	56

Chapter 1

Executive Summary

- EnSym and the EcoTender project construct simulations of potential future catchment conditions under a range of management scenarios. These simulations are used to assess and rank tendered land management projects for financial support by the DSE. A key component of the EnSym modelling framework is BioSym, EnSym’s biophysical modelling engine and predicts future conditions for hydrology, nutrient loading, and crop growth. Because reforestation is one of the driving land management priorities of DSE, understanding the impacts of establishing new forests on the biophysical components of the catchment is critically important. However, the current vegetation models that are used in BioSym (ET–Pan and 3PG+) have their shortcomings. The purpose of this review is to assess the potential for other forest growth models to be integrated into BioSym and the EnSym modelling framework.
- A wide range of forest growth models have been developed to characterise how forest structure and composition change over time. These models fall into four general model classes: empirical, process-based, gap, and hybrid models. Empirical models use inventory data and statistical modelling to develop quantitative relationships between two or more tree or stand attributes (*e.g.*, dbh and tree volume, stand basal area and growth). Process-based models attempt to predict the growth or condition of trees or stands by representing the underlying processes that generate them (*e.g.*, photosynthesis, respiration) and how these processes are modified by a range of external variables (*e.g.*, climate, soil). Gap models characterise the establishment, growth, and mortality of individual trees in small forest patches as a function of biotic (*e.g.*, competition) and abiotic (*e.g.*, climate, soil) factors. In a sense, they represent processes that occur at the forest stand level, as opposed to process-based models, which focus on processes occurring at the individual tree level. Hybrid models combine elements of empirical and process-based models.
- We used three “filters” to search through the large number of forest growth models to identify several candidate models for incorporation into BioSym. The first

filter was model class. We wanted to ensure that the full range of model classes was represented in our evaluation. The second filter was generic model attributes. These include model portability, extendability, source code availability, and documented fit. The third filter was EnSym-specific requirements. These were based on discussions with the DSE's EnSym modelling group and focused on two major themes: characterisation of carbon allocation and the distribution of water within a catchment.

- The filtering approach left a small subset of candidate models for more detailed evaluation. The empirical model was FVS. The process-based models were ET-Pan, 3PG+ and ALMANAC_{BF}. The hybrid models included SORTIE, FVS-BGC, and a description of a statistical approach to melding results from different forest dynamics models. Gap models were discussed only briefly as they were considered inappropriate for EnSym's modelling needs.
- Based on our evaluations of the candidate models we identify six potential courses of action for modelling tree and stand growth in BioSym. These include maintaining the *status quo* (*i.e.*, using or combining ET-Pan or 3-PG+), exploring the possibility of developing a Victorian variant of ALMANAC_{BF}, using a statistical melding approach, developing a new hybrid model, and conducting an inter-model comparison for several candidate models. We provide brief discussions of the relative merits of each of these approaches.

Chapter 2

Scope of the report

The aim of this report is to examine the range of forest growth models that might be used to represent long-term changes in terrestrial vegetation and the associated impacts on catchment hydrology as part of DSE’s EnSym catchment modelling framework.

We provide a broad overview of the major classes of forest growth models, their strengths and weaknesses, and their potential applicability to EnSym. We then provide detailed descriptions of representative models in each of the main model classes. These descriptions include a brief history of the model’s development, the purposes for which it was designed and, where different, the purposes to which it has been applied, the key drivers of the models, including descriptions of model parameters, and key outputs of the models. From these detailed reviews we compare the selected models on the basis of a range of criteria provided by DSE. These criteria were designed to highlight the potential for integration into and utility for EnSym and the current EcoTender process.

We allow for the possibility that EnSym and the selected forest modelling approach will be used for purposes not currently considered in the EcoTender process. However, these speculative uses are accorded less weight in our evaluations because of the uncertainty associated with them.

We conclude by synthesising our results and making several recommendations about how different modelling approaches from within EnSym might most effectively capture changing forest conditions and the potential impacts on stand- and catchment-scale processes.

Chapter 3

EnSym and the Ecotender Process

EnSym is a decision-support toolbox that is also a framework for a number of component models. EnSym encloses BioSym, which provides the needed biophysical modeling function. BioSym comprises model components that fall into eight broad classes: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, agricultural management, and pesticides¹. This report focuses on the tree growth and dynamics model of BioSym, which is in the crop growth class. It may be necessary to use the tree model to represent the growth and change of other vegetation types.

EnSym constructs simulations of future landscape conditions using BioSym. The conditions are described using a number of state variables, and are computed using dynamic inputs. The simulations are performed on scenarios that are organized into ten non-overlapping catchments that cover the state. The catchments are divided into polygons, which are defined by overlays of land use, slope, aspect, and soil type, of which there are approximately 30. Simulations are organized by catchment. A simulation tracks the state variables on each polygon within the catchment. The simulation uses 50 contiguous years (1957–2007) of daily climate data from the climate station that is closest to the polygon. The climate data are scaled to the polygon using statistics (*e.g.*, mean annual temperature) that are estimated from a smooth surface that is fitted to the climate stations data.

The Ensym framework is used to analyse and compare EcoTenders, which are proposals that specify a land-management strategy for a property that is located on a polygon, for which DSE will compensate the land owner. EcoTenders are submitted by land managers and assessed for ecological impact by DSE. Projected runoff, erosion, and recharge under the proposed land use are compared with similar projections under 1750's land use (essentially forest). Proximity to 1750's values is considered valuable. The major question that is trying to be answered is: if one revegetates, what are the impacts on local- and

¹Ha, J. "A programmer's guide to BioSym — the Biophysical Modelling Toolbox of EnSym", Unpublished Draft

catchment-scale hydrology, especially runoff?

The challenge represented by the detailed simulation of a range of ecological responses to a range of management scenarios across an entire state is staggering. The state is divided into 20 bioregions, and vegetation is classified into approximately 700 Ecological Vegetation Classes (EVCs²), leading to about 7000 unique combinations of bioregion and EVC. Simplifications are essential. For example, rather than supporting 7000 different sets of parameters for the vegetation model, the combinations are categorized into about ten distinct classes.

The concern that spurred the present review is the observation of excess groundwater recharge with certain scenarios using the 3-PG+ forest growth and dynamics model for simulating vegetation. These anomalous observations did not occur when the forest growth was simulated using ET-Pan. The vegetation model is only asked to provide estimates of daily moisture uptake and interception, for the purposes of comparing EcoTenders. The vegetation model is considered a key component in estimating water-uptake, infiltration, interception/throughfall, etc. However, carbon is also important to know, not as part of the scoring process, but carbon credits are budgeted. Also, biodiversity credits are important in the EcoTender process, and these may be influenced by vegetation structure.

²http://www.dpi.vic.gov.au/dpi/vro/vrosite.nsf/pages/veg_evc

Chapter 4

Framework for Model Review

4.1 Introduction

Forest growth models are quantitative descriptions of various aspects of forest growth and development. Since the development of empirical yield tables for French and German forests in the late 1700s, forest scientists have attempted to capture the key patterns and processes of forest growth in quantitative models (Pretzsch 2009). The earliest forest growth models were essentially sets of simultaneous equations that were used to estimate the volume of wood in a forest stand of a given age. Over the past 250 years major advances in mathematics, statistics, computer science, tree physiology and forest ecology have led to substantial increases in the complexity of forest growth models, with some contemporary models having highly complex nested structures that support > 100 free parameters.

Although greater model complexity is now readily achievable given computational advances, the complexity of any given model is determined primarily by the question(s) that the model is being used to address. The focus of this review is the potential for integrating forest growth models into a broader catchment modelling framework, which is used to assess the potential consequences of specific, coordinated management decisions on catchment-scale hydrological, biogeochemical, and ecological processes. This focus presents an interesting challenge because the historical focus of nearly all forest modelling has been on the accurate prediction of standing timber volume or woody biomass. As such, many of the models that are used to represent forest growth may not be well-suited to incorporation into EnSym if they cannot accommodate the simulation of important higher-order processes, such as groundwater flow, nutrient transport, or erosion.

A large number of candidate models was identified for this project. Indeed, we found > 100 models in a single day of searching. These models vary in a number of ways, which we discuss below. However, much of the inter-model variability is driven by variability in the forest-, species-, and output-specific objectives. The fundamental differences among

the models can be grouped into a much smaller number of classes. Given the large number of potential candidate models, it was necessary to develop a structured approach to model evaluation (Stage 2003). We identified three levels of assessment, which we refer to as “filters”, to allow us to reduce the number of potential models to a few candidate models, but without reducing the range of potential modelling approaches. The three filters are as follows.

- **Model classes** There are many types of forest growth models, reflecting different modelling philosophies, simplifying assumptions, data requirements, and model outputs. We felt that it was important to consider as broad a range of model types or classes as possible to ensure that these different approaches were represented. Examples of model classes include: empirical models, gap models, process-based models, and hybrid models. We present a brief overview of each of these and some of their general strengths and weaknesses.
- **Model attributes** Decision-support systems that address applied questions commonly use existing models as components of the modelling framework. Individual models will have certain attributes that make them more or less readily integrated into a broader modelling framework. These attributes include: license and terms of use, data requirements, availability of source code, ease of adaptation of the model to new sites/species, and model complexity. We developed a set of generic criteria for model evaluation that we felt were important when considering the potential for adapting a new forest growth model to the EnSym framework.
- **EnSym-specific requirements** EnSym is used to evaluate scenario-based land management options in Victoria. This application requires EnSym to provide specific biophysical outputs that are relevant to the management questions being asked. Some of these outputs are more important than others (*e.g.*, water, carbon sequestration). Based on discussions with the EnSym modelling group we identified and ranked specific forest growth model features necessary for inclusion in EnSym. These features focused primarily on the capabilities of the model to represent the major biophysical attributes of the modelled ecosystems (*e.g.*, groundwater flow, evapotranspiration).

In the following sections, we provide an overview of each of these filters in the context of identifying a short-list of candidate models for detailed evaluation for use with EnSym.

4.2 Filter 1: Model classes

Over the past 40 years a wide variety of computer-based models that represent changes in forest structure and composition over time have been developed for various regions of the

world. While the number of models and their variants is very large, most models can be readily classified into a much smaller number of general model classes (Monserud 2003, Landsberg 2003, Taylor *et al.* 2009). Here we provide an overview of the main classes of forest models, their relative strengths and weaknesses, and their potential applicability to EnSym. Table 4.1 provides a few examples of models in each of the major model classes.

Table 4.1: Selected examples of forest growth models.

Model Name	Model Class	Relevant citations
CROBAS	Empirical	Mäkelä (1997)
FVS	Empirical	Stage (1973), Teck <i>et al.</i> (1997)
JABOWA	Gap model	Botkin <i>et al.</i> (1972)
FORET	Gap model	Shugart and West (1977)
SORTIE	Gap model	Pacala <i>et al.</i> (1996)
3-PG (and derivatives)	Process-based	Landsberg and Waring (1997)
ALMANAC _{BF}	Process-based	MacDonald <i>et al.</i> (2008)
CABALA	Process-based	Battaglia <i>et al.</i> (2004)
CABLE	Process-based	Kowalczyk <i>et al.</i> (2006)
PERFECT/ETPan	Process-based	Thomas <i>et al.</i> (1995)
Forest-BGC	Process-based	Running and Coughlan (1988)
ForestETP-3D	Process-based	unpublished
Maestro/a	Process-based	Wang and Jarvis (1990), Medlyn (2004)
PnET	Process-based	Aber and Federer (1992)
Forest5	Hybrid	Robinson and Ek (2003)
TRIPLEX	Hybrid	Peng <i>et al.</i> (2002)
FVS-BGC	Hybrid	Milner <i>et al.</i> (2003)
Macaque	Other	Lane <i>et al.</i> (2009)

Empirical models

The primary objective of empirical models is predictive. Empirical models use inventory data and statistical modelling to develop quantitative relationships between two or more metrics, *e.g.*, dbh and tree volume, stand basal area and growth (Monserud 2003). The earliest forest growth models — yield tables — were simple empirical models that estimated the standing volume of wood for a given age and site quality.

In general, empirical models avoid any representation of ecological or physiological processes. As a consequence, these models are typically simpler, more efficient, and provide better estimates, including estimates of uncertainty, than other classes of forest growth models. However, they have substantial data requirements. Empirical forest growth models are driven by parameters, which may be site- and species- specific, and which must be estimated. The parameter estimation requires time-series data, whether as repeat inven-

tories, chronosequences, or historical data (*e.g.*, dendrochronological reconstructions and repeated aerial photography), to estimate parameters.

Empirical models are typically aspatial; that is, they do not track the locations of individual trees. However, empirical models can be incorporated into spatially explicit modelling at higher spatial scales (*e.g.*, catchments and landscapes).

Empirical models have several shortcomings that are relevant to adoption by EnSym. First, there is little long-term data available for the landscapes of southeastern Australia with which to parameterise the models. In particular, areas that were long ago de-forested and are being considered through the EcoTender program for reforestation have little to no forest inventory data available. Another issue of potential concern is that because empirical models are parameterised from existing data, they assume that future growing conditions will be the same as those in the past. Consequently, such models may misrepresent future growth if climate conditions that affect tree growth change sufficiently.

Process-based models

Process-based, or mechanistic, models attempt to predict the growth or state of features of trees and stands by representing the processes that generate them, and how those processes are modified by a range of external variables (*e.g.*, climate and soils, Landsberg 2003). In this way, process models differ substantially from empirical models, which are based on a statistical description of the dynamics of specific dimensions of the trees and stands.

Process-based models are typically complex, highly parameterised models that represent photosynthesis, transpiration, water uptake, and nutrient utilisation at the scale of individual leaves or tree crowns on hourly or daily timesteps. The primary challenge of process-based models is to determine which features are essential to track in order to be able to identify and characterise the growth of the target trees and stands. In brief, the problem is how to satisfactorily formulate the following general relationship that describes the balance of carbon (Landsberg 2003):

$$P_n = \alpha(\theta, N, T)\phi_{abs} - R \quad (4.1)$$

where P_n is net primary production, α is a function that describes photosynthetic conversion efficiency, θ , N , and T describe water relations, nutrition, and temperature, respectively, ϕ_{abs} represents absorbed photosynthetically active radiation, and R accounts for carbohydrate losses due to respiration. The term $\alpha(\theta, N, T)\phi_{abs}$ represents gross primary production (GPP). Once the respiration losses are subtracted, the net carbon gain (*i.e.*, P_n) must then be allocated to different components of the plant specifically, the stem, branches, roots, and foliage. This approach—estimation and allocation of net carbon assimilation—is often referred to as the *carbon balance* approach.

Models are simplifications of reality. However, some models are more complex than others. Given that process-based models cannot possibly describe all the necessary physiological processes of a plant, they must make some simplifying assumptions. Process-based models vary widely in the degree to which the underlying processes are reduced. At one extreme are highly parameterised models such as CABALA, which requires >100 parameters to describe tree and stand growth. At the other extreme are models such as ALMANAC, which uses about 20 parameters, to represent tree growth. Most process-based models are intermediate in their complexity, requiring 40–70 parameters. This requirement presents two major challenges to the application of process-based models.

1. The model must be supplied with parameter estimates. Although some of these parameter values may be known from prior research, others can only be given intervals of likely variation, and yet others cannot be determined on the basis of current knowledge (Mäkelä *et al.* 2000). All process-based models share this fundamental problem: uncertainty around the parameter estimates is rarely known or described.
2. The large number of parameters makes understanding the influence of individual parameters and parameter interactions exceedingly difficult. One of the commonly stated strengths of process-based models is their potential for estimating growth in geographic regions for which forest inventory data on growth and yield is lacking. In reality, however, the large parameter sets often require model tuning and modification to match observed patterns of tree and stand growth (Duursma *et al.* 2007). Few process-based models have been developed and independently verified without recourse to pre-verification modification. As Taylor *et al.* (2009) note, “the strength of pure mechanistic models lies in their explanatory and descriptive ability as a research tool. They are not suited, nor necessarily intended, to be predictors of forest succession, particularly at the temporal and spatial scales required for strategic planning.”

Gap models

Forest gap models were developed and used by forest ecologists to model the development or “succession” of forest communities over time. The first gap model, JABOWA, was developed in the late 1960s (Botkin *et al.* 1972) and has been the progenitor of nearly all of the many gap models that were subsequently developed¹. Gap models were designed to evaluate the changes in biomass, structure, and composition of a small patch of forest that forms when a large tree dies and forms a gap in the canopy. These models achieve this by modelling the establishment, growth, and mortality of individual trees as a function of biotic (*e.g.*, competition) and abiotic factors (*e.g.*, soil, climate). With the creation of

¹Monserud (2003) identifies more than 50 extant gap models as of 2004

a canopy gap, there is a release of suppressed trees and a pulse of seedling establishment, which lead to the subsequent development patterns within the stand.

Gap models use a number of simplifying assumptions to accommodate the fundamental complexity of forest dynamics (Bugmann 2001). Here we describe the underlying assumptions of JABOWA to illustrate these, noting that most subsequent gap models make all or some of the same assumptions.

1. The forest stand is made up of many small patches of land, each of which can differ in age and developmental stage. Patch sizes are typically 100–1000 m².
2. Patches are homogeneous horizontally. The locations of individual trees within the patch are not considered.
3. The leaves of each tree are arranged in an indefinitely thin layer at the top of the stem (Figure 4.1). This assumption allowed the modellers to avoid the issue of within-crown shading, but introduces a large bias into the model.
4. Each patch operates independently. There are no interactions among patches.

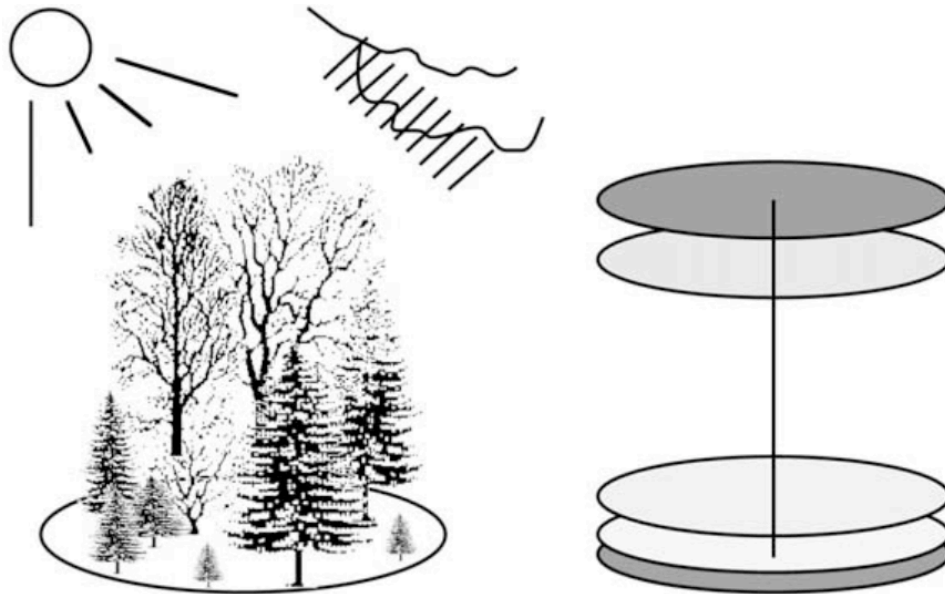


Figure 4.1: The basic idea underlying gap models (Bugmann 2001). (Left panel) The spatial scale of a given patch and the dynamics within it. (Right panel) The simplified representation of vertical canopy structure used in JABOWA and many of its descendents, which led to the cutting “green slime on sticks” characterization.

Gap models have several shortcomings that have limited their application to problems of management (Bugmann 2001). First, gap models do not address uncertainty,

although some variants (*e.g.*, ZELIG) simulate multiple gap replicates. Second, validation of gap models is difficult and rarely done. Gap model predictions are usually made over 100–1000+ years, that is, a time frame that exceeds most historical records. Third, gap models follow the fate of every individual tree, which is computationally intensive. For more complex gap models, such as SORTIE, which track the spatial location of individual trees and determine light availability as a function of neighbors, this focus on the individual introduces a major computational burden. Finally, most gap models do not allow individual patches to interact. Each patch was treated as an independent unit, free from the effects of other patches. ZELIG introduced the ability to allow patches to interact in 1- or 2-dimensional fashion (Urban 1990). Several other gap models now allow for spatial interactions among patches, but with the attendant computational burden.

Gap models are relatively well-suited to estimating above-ground biomass as they track DBH (diameter at breast height, 1.4 m) for all individuals in a patch. Various formulations of allometric models are then used to allocate the biomass among different tree parts. In most gap models, it is assumed that stem biomass makes up the majority of an individual's biomass. Allometric equations are used to estimate height, stem biomass, and leaf biomass from DBH; however, most other biomass compartments (*e.g.*, fine and coarse roots, branches, twigs) are ignored (Bugmann 2001).

Gap models do account for soil–water relationships, but most use a relatively simple Thornthwaite–Mather-type scheme (Bugmann 2001). Some gap models use more sophisticated approaches, *e.g.*, Penman–Monteith, but few explicitly deal with the fate of water in each patch. In most cases, forest gap models use a single-layer, or “bucket”, approach in which the average conditions of the soil profile are described.

Hybrid models

Hybrid models contain elements of both empirical and process-based models. In reality, no models are purely empirical or process-based (Korzukhin *et al.* 1996) — all empirical models have process-based elements and all process-based models have empirical elements (Mäkelä *et al.* 2000). For example, some parameters in process-based models cannot be easily estimated from theory. In order to be used, many process-based models are “tuned”, that is, a range of parameter estimates are applied and the one that is most consistent with the expected model performance is retained. However, empirical tools exist — and are used in hybrid models — to estimate the unknown parameters and their associated uncertainties, and to evaluate the model outputs. Likewise, the choice and inclusion of certain parameters in good empirical models is driven by knowledge of the underlying process rather than statistical tests. For example, quadratic terms in elevation were included in the diameter growth model of Prognosis (Wykoff *et al.* 1982) regardless of their statistical significance, because the model creators reasoned that using only a linear

term would result in behaviour that was biologically unrealistic.

Mäkelä *et al.* (2000) suggest that empirical and process-based models can be improved by incorporating the strongest features of each type into the other type. Several different approaches have been used to achieve this mix of empirical and process-based modelling. Radtke and Robinson (2006) provide a summary of the most common hybrid approaches. These include:

1. using a weighted mean of the predictions as a prediction
2. embedding an established empirical model in an established process-based model or *vice versa*
3. creating a new model and allowing both statistical and process criteria to dictate model structure and parameter values
4. constraining process-based model predictions using empirical yield tables
5. using statistical tools such as Bayesian melding to combine observed data and model information

Hybrid models have received considerable attention in the past few years due to the growing recognition of the importance of both empirical and process-based approaches. Indeed, an architect of one of the most widely used process-based models has argued that hybrid models are where real advances in model forest growth and dynamics will be made (Landsberg 2003, the model is 3-PG).

Summary

The differences between these different approaches may be less important than their similarities. Indeed, Robinson and Ek (2000) argue that the important modeling choices refer to the scale of representation and the scale of application, where the scales are: temporal, spatiophysical, and mechanistic. We provide a summary of examples of these model classes in Table 4.1, and of the relevant points concerning model classes in Table 4.2.

4.3 Filter 2: Model attributes

Hundreds of substantially different forest growth models have been developed over the past 20–30 years. The diversity of models derives from several sources: underlying assumptions about forest growth, different modelling philosophies and objectives, constraints on available data at the time of model development, and required outputs. All of these factors impose constraints on what an individual model can or cannot do.

Assessing different models is not straightforward, and in many cases may yield equivocal results (Robinson and Monserud 2003). When a model is being considered as one

Table 4.2: Key characteristics of forest growth model classes.

Class	Temporal Scale		Spatial Scale	Opportunities	Issues
Empirical	Annual, Decadal		Stand, Forest, Landscape	High-quality predictions of future states	Cannot predict climate change. Need local data.
Process-based	Hourly, Monthly	Daily,	Tree, Stand	Lower data requirements than empirical models. Better suited to assessing non-tree processes (<i>e.g.</i> , runoff, nutrient transport)	Most cannot handle multiple species, complex forest structures, and management operations. Most require extensive tuning with local data.
Gap	Decadal, Centennial	Centennial	Tree-fall gap (100–1000 m ² m)		Long time-scale. Focus on stand-level processes (<i>e.g.</i> , recruitment, growth, mortality, not tree-level processes (<i>e.g.</i> , photosynthesis, transpiration))
Hybrid	Daily to Centennial		Tree, Stand, Landscape	Wide range of approaches	Requires expertise and parameterised empirical models

component of a broader modelling framework, a range of attributes will directly influence the potential for successful integration. Some of the attributes are quite generic. For example, the computer language that the program is written in may be more or less easily integrated into the larger project. In the extreme, the model components might be binary units that can be chosen and combined to represent the target processes. Other attributes are more purpose-driven. For example, in using a forest growth model such as DFSIM, which was developed for Douglas-fir (*Pseudotsuga menziesii* in the northwestern USA, the model may be readily ported to EnSym because of the computer language it was written in or the way in which it was coded, but the exclusive focus on a single species from one region may make it unsuitable for modelling eucalypt-dominated forests in southeastern Australia. Similarly, TASS/TIPSY, the individual tree simulator developed by the British Columbia Forest Research Branch, requires highly detailed measurements of shoot growth of large numbers of trees for parameterisation. Such data are not available for Australian tree species and, in the case of the eucalypts, the species may be so distinctly different in branching architecture and growth patterns that the model is completely inappropriate.

Given the diversity of forest growth models and specific purposes of the EnSym modelling framework, we have adopted a modified version of the criteria established for model adaptability described by Robinson and Monserud (2003) as a filter allowing us to winnow the number of models.

1. **Portability** — A portable model is one that can be changed to accommodate a new situation, be it a different location or different set of tree species. Portability depends on the ease with which new model parameters can be estimated from available data and the ability of the model to alter its predictions based on the new data. Where models can be calibrated for new conditions using local data on growth dynamics (*e.g.*, tree or stand growth data) or static site-based variables (*e.g.*, soils, site index, mean annual precipitation and temperature), they are inherently more portable.
2. **Extendability** — An extendable model is one to which new modules can be readily added. For this either the source code must be available (see next bullet point) or the model must be coded in some protocol that permits post-compilation connection of modules. Extendability of the module may depend on programming style (*e.g.*, object-oriented programming).
3. **Source code availability** — The primary goal of this review is to identify forest growth models that have the potential to be integrated into the EnSym modelling framework. While it is possible to incorporate models without modifying the source code, the executable code represents the fundamental workings of the program. Model documentation might provide qualitative and/or quantitative descriptions of the model, but the source code represents exactly what happens. Access to the

source code can therefore provide clarity about the model, and access to it may allow for gains in computing efficiencies when it is being integrated.

4. **Documented fit** — A well-documented model includes key information about the major components, meaning the submodels and their component parameters, in the model. At a minimum, a well-documented model will include information on equation form, parameter estimates, measures of uncertainty associated with parameter estimates, sample size, and goodness of fit statistics. The documentation will include information about the sample design or designs from which the fitting data came. This information allows the user to identify the driving variables and determine how they are used, and is of particular value when refitting the model for a new set of conditions. The model documentation should also describe the range of conditions for which the model has been parameterised, including geographic range, site quality, tree sizes, and species. Publication of model details or overview in peer-reviewed journals is a common source of model and fit documentation and provides some assurances that the model is sufficiently well-documented and of reasonable quality.

4.4 Filter 3: EnSym-specific requirements

EnSym is used to prioritise the allocation of funding among competing bids for land management in the DSE's EcoTender program. While it is anticipated that EnSym will be applied to a wider range of land management questions in the future, the primary application of EnSym currently is for the EcoTender program. As a consequence, the required outputs from a forest simulator to be used in EnSym are relatively specific. In the most general sense, EnSym needs to know how vegetation influences the distribution and movement of water around the landscape, how carbon is allocated within the landscape, and how the natural development of the vegetation will modify these patterns over time. A prioritised list from the EnSym modelling group included the following requirements and their relative rankings:

- **High priority**
 - Tree/forest growth processes
 - Allocation of growth to leaf, root, stem, litter
 - Dry matter production
 - Carbon storage
 - Root depth
 - Consumption of surface/soil water by trees/forest
 - Effect on tree/forest growth of limited water availability

- **Low to medium priority**

Plantation parameters

- **Low priority**

Nutrient demand and consumption

Effects of limited nutrient availability

- **Very low priority**

Habitat

Use of groundwater by trees/forest

Two obvious themes emerge from this list. The first is the need to know the allocation of carbon within trees and stands over time. The second is the need to know the distribution of water within the catchment.

Chapter 5

Review and comparison of available growth models

In this chapter we review and describe a sample of the available forest growth models, organised by model class. In each case we note the core literature, describe some of the function, and provide details, where possible, about the diameter growth projection strategy of the model. A detailed description of each model is beyond the scope of this report, however, an examination of the differences and similarities between how the models handle diameter growth is illuminating. Also, diameter growth is one of the few functions that the models have in common.

5.1 Key empirical forest growth models

5.1.1 FVS

The obvious empirical model candidate for integration into Ensym is the Forest Vegetation Simulator (FVS, Teck *et al.* 1997). FVS is an individual-tree, non-spatial forest growth model built around a set of empirically derived equations of diameter growth, height growth, crown ratio, regeneration and mortality. In a comparison of empirical forest growth models, Robinson and Monserud (2003) concluded that FVS was the most adaptable model evaluated due to its portability, extendability, source code availability, and documented fit.

The core model of the western US variants of FVS was originally known as Prognosis (Stage 1973), and covered northern Idaho and western Montana. The geographic reach of FVS and its variants has been greatly extended over the past 30 years. There are now 20 variants across the US National Forests, two in British Columbia, Canada, and one in Austria, making it one of the most widely used empirical forest growth models in the world.

FVS is now capable of simulating a wide range of different forest processes other than simple volume growth. In the past two decades a large number of add-on packages have been developed. These extensions are able to simulate fuel loads and fire risk, biogeochemical cycling, insect outbreaks, habitat suitability, and forest planning options (Crookston and Dixon 2005). A key factor behind the adoption of FVS as a forest growth modelling platform is that the source code is openly available and in the public domain (Crookston and Dixon 2005). In addition, the original northern Idaho variant of FVS has undergone extensive critical testing and is well documented. Although other regional variants have been less well scrutinised, given the wide adoption of FVS for forest growth modelling, its predictions have likely received closer inspection across a wider range of growing conditions and species than any other growth model.

To provide some context, we present the diameter growth model of Prognosis, the parent model of FVS, along with some example parameter values. The full model is documented in Wykoff *et al.* (1982). FVS projects diameter growth by projecting the ten-year change in the square of inside-bark diameter:

$$DG = \sqrt{dib^2 + dds} - dib \quad (5.1)$$

The ten-year change in the square of inside-bark diameter is predicted using the following equation, which has been split into portions to provide insight to the equation structure.

$$\begin{aligned} \ln(dds) = & HAB + LOC \\ & + b_1 \cdot \cos(ASP) \cdot SL + b_2 \cdot \sin(ASP) \cdot SL + b_3 \cdot SL + b_4 \cdot SL^2 \\ & + b_5 \cdot EL + b_6 \cdot EL^2 \\ & + b_7 \cdot (CCF/100) + b_{11} \cdot (BAL/100) \\ & + b_8 \cdot \ln(DBH) + b_{12} \cdot DBH^2 + b_9 \cdot CR + b_{10} \cdot CR^2 \end{aligned} \quad (5.2)$$

where the parameters are defined and coefficients provided for western white pine (*Pinus monticola*), as an example, in Table 5.1. The first row provides geographical and biophysical-specific intercepts. The second and third rows control the topographical effects on simulated growth; the two slope and aspect interaction terms provide a seamless approach to projecting the effect upon growth of aspect, which is a circular variable (Stage 1976). The fourth row presents the portion of the model that represents competition of the local vegetation. The final row provides the effects of the current dimensions of the tree itself upon its growth. The other dimensions of the trees are all predicted as functions of the tree diameter.

For the purposes of use within the EnSym model framework, FVS has three major shortcomings:

Table 5.1: FVS: parameter definitions and example coefficient values for white pine in Northern Idaho variant (Wykoff *et al.* 1982). Where the parameter is a class-specific intercept we provide the number of classes and the range of values. Location refers to the nearest National Forest. See text for an explanation of the handling of slope and aspect.

Label	Coef	Value	Interpretation
<i>HAB</i>			3 Habitat-specific intercepts; range 0.21955–0.52413
<i>LOC</i>			2 Location-specific intercepts; 0.15050, 0.25383
<i>ASP</i>			Stand aspect (deg). -0.02384 (c) and -0.04285 (s).
<i>SL</i>	b_3	-0.30352	Stand slope ratio (percent/100).
<i>SL</i> ²	b_4	0.0	Stand slope ratio (percent/100), squared.
<i>EL</i>	b_5	0.04126	Stand elevation (hundreds of feet).
<i>EL</i> ²	b_6	-0.000578	Stand elevation (hundreds of feet), squared.
<i>CCF</i> /100	b_7	-0.10407	Stand crown competition factor
$\ln(DBH)$	b_8	0.84748	Natural log of tree diameter at 1.4m
<i>CR</i>	b_9	1.13594	Ratio of crown length to total tree height.
<i>CR</i> ²	b_{10}	0.0	Ratio of crown length to total tree height, squared.
<i>BAL</i> /100	b_{11}	-0.37061	Total basal area of trees larger than the subject tree.
<i>DBH</i> ²	b_{12}		2 Location-specific slopes; -0.000224 , -0.000618

1. FVS does not model surficial hydrology. While there has been an attempt to develop a hydrology extension for FVS, this attempt is still ongoing and is not yet available for evaluation. However, in principle, given estimates of tree-level growth within a stand, it should be possible to develop empirical relationships between the leaf biomass and water uptake of a given stand, as well as rooting depth profiles for individual trees of a given size and species.
2. The adaptability of FVS is dependent on sufficient available forest growth and dynamics data for re-parameterisation of the growth and mortality sub-routines. In North America and Europe, where FVS has been extensively adopted, large-scale, long-term forest inventory programs have been ongoing for decades. The rich database of species-specific growth and mortality across a wide range of site conditions allows for robust parameterisations of FVS. In Victoria, where long-term forest inventory is scarce, it would be difficult to obtain sufficient data for individual EVCs (or even bioregions) to be able to parameterise FVS. In some cases — for example, the economically important species, Mountain Ash (*Eucalyptus regnans*) and Alpine Ash (*Eucalyptus delegatensis*) — there may be opportunities for parameterising FVS or using species analogues from North America for testing FVS as a potential tool. However, these forests are probably of less interest to the EcoTender program than the extensively modified agricultural landscapes of northern and western Victoria. One possibility would be to investigate data resources available at

NSW Forestry, which maintains an extensive state-wide network of forest inventory plots. In some cases, these data may provide coverage of forest communities and EVCs that co-occur or have similar analogues in Victoria.

3. FVS is designed to use a 10-year time step.

It is worth noting that FVS has also been combined with the process-based model, STAND-BGC, to create the hybrid model FVS-BGC. We discuss FVS-BGC in greater detail in Section 5.4.2.

5.2 Key process-based forest growth models

We briefly describe two process-based forest growth models, 3PG+ and ALMANAC_{BF}, and one process-based crop model, ET-Pan. We include ET-Pan and 3PG+ because they are currently used in EnSym; however, we only offer a limited discussion of each because they are both described in detail elsewhere (*e.g.*, Feikema *et al.* 2010, for 3PG+). We focus most of our attention on the new process-based model ALMANAC_{BF}, which addresses many of the shortcomings recognised in 3PG+ with respect to applications within the EnSym modelling framework (*e.g.*, no mixed species, poor coupling to surficial hydrology).

5.2.1 ET-Pan

ET-Pan is based on the PERFECT (Productivity, Erosion and Runoff, Functions to Evaluate Conservation Techniques) cropping system model, which combines a dynamic crop growth model, a water balance model, and an erosion model to assess potential production and erosion risks (Littleboy *et al.* 1992). The PERFECT model was designed specifically for agricultural crops such as wheat, sorghum, and sunflower growing in Queensland. The model uses a dynamic crop growth model, a simple crop water-use model, empirical relationships describing hydrology and erosion in catchments, validated components of existing models (*e.g.*, EPIC, CREAMS), and land-use operations.

Inputs include daily climate data (*i.e.*, daily rainfall, pan evaporation, temperature and solar radiation), soil parameters, cropping sequence details (*e.g.*, crop type, length of fallow), crop growth parameters, and fallow management options (Figure 5.1). PERFECT provides the scope for detailed descriptions of the soil profile, with up to 10 layers varying in thickness. The model includes a detailed evaluation of soil water balance and the role of infiltration, evapo-transpiration, drainage and runoff on available water. Crop growth can be simulated as static (*i.e.*, effectively as an unchanging leaf area index) or dynamic (*i.e.*, with daily dry matter accumulation estimated as a function of transpiration and transpiration efficiency).

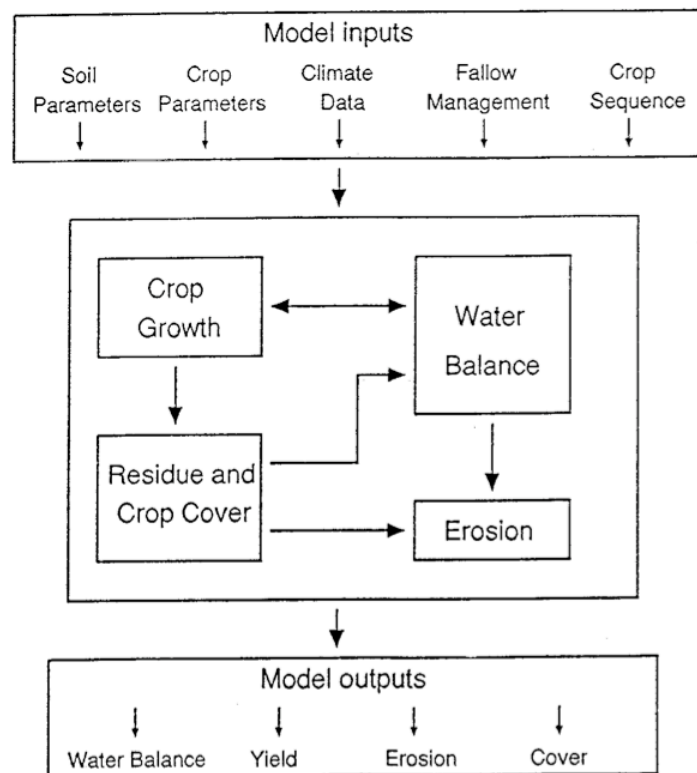


Figure 5.1: Schematic diagram of PERFECT model on which ET-Pan is based. From Littleboy *et al.* (1992)

One advantage of ET-Pan/PERFECT is that the underlying submodels (*e.g.*, water balance, erosion, crop growth) have been tested independently and shown good agreement with observed data. In particular, the water balance submodel was extensively tested as part of other models (*e.g.*, CREAMS, EPIC, CERES). In addition to evaluations of the algorithms driving the submodels, PERFECT has been tested as an integrated cropping systems model across a wide range of environmental and management conditions. Overall model performance when compared to independent data on soil water balance, runoff, erosion, and crop production was excellent, with consistently strong 1:1 relationships between estimated and observed datasets.

The primary concern with using ET-Pan in EnSym for forest growth modelling is that it does not simulate trees. It may be possible to modify the crop growth submodel to accommodate perennial growth of trees, but this might require significant effort. In addition, it is not clear if ET-Pan can effectively model mixed-species crops—another desirable forest growth model feature when considering incorporation into EnSym and the aims of the EcoTender process.

5.2.2 3PG+

3PG is a process-based model that was designed to provide tools for forest managers working in plantations or with relatively homogeneous, even-aged forests (Landsberg 2003). Landsberg and Waring (1997) designed 3PG to bridge the gap between strict empirical growth and yield models and process-based carbon balance models, that is, a hybrid model; however, the early developers and users refer to it as a process-based model¹. 3PG has two basic modules: biomass production and carbon allocation. It runs on a daily time-step and requires values for total photosynthetically active radiation, mean vapour pressure deficit, total rainfall, soil water storage capacity, and fertility. The model produces estimates of DBH, stand volume and biomass, and projected leaf area.

3PG+ is one of the incumbent vegetation dynamics models in BioSym. 3PG+ does not differ greatly from 3PG (Miehle *et al.* 2009). 3PG and 3PG+ both use the carbon-balance approach (Equation 4.1; Feikema *et al.* (2010)); the net increase in stand-level carbon is modelled as the difference between gross primary production (GPP) and respiration. GPP is projected as a function of the amount of photosynthetically active radiation that is absorbed, and how efficiently that radiation is used. The efficiency of the radiation use is a function of temperature, stand age, moisture availability, and nutrient availability, the latter two of which have their own detailed sub-models. Respiration is assumed to be a constant fraction of GPP, so net primary production (NPP) is also.

The stand-level NPP is then allocated amongst different components of the stand: stems, roots, branches, and crown. The stand-level stem biomass is divided equally among the trees (w_i) and then diameter (d_i) is calculated using an allometric function of the form

$$d_i = \beta_1 \cdot w_i^{\beta_2} \quad (5.3)$$

where β_1 and β_2 are species-specific allometric coefficients.

For the purposes of use within the EnSym model framework, 3PG+ has several advantages:

1. It simulates the processes of core interest in the EcoTender process; namely, the distribution of water and carbon within a catchment.
2. It is already used in BioSym, so the costs of implementation are low.
3. It is supported by a research group at the University of Melbourne, who are actively developing 3PG+ for Victorian forests.

However, 3PG+ also has several notable shortcomings:

1. It appears to generate anomalous projections of runoff when tree densities are low.
- Because the catchment-scale predictions of runoff feed into other submodels within

¹*e.g.*, http://www.fsl.orst.edu/~waring/3-PG_Workshops/WorkshopContents.htm (26/04/2010)

EnSym that predict erosion, nutrient loading, and other hydrological variables that are taken into account in the EcoTender process, this is a concern.

2. It does not model mixed-species stands. However, recent work by Nightingale *et al.* (2008) in tropical rainforests in Queensland suggests that species-specific parameterisation might not be necessary to provide a reasonable representation of forest processes.
3. Despite model simplification being a stated motivation for the original 3PG project, the model and its variants retain large numbers of parameters. Feikema *et al.* (2010) list 77 parameters that are used in 3PG+. CABALA requires >100 parameters (Battaglia *et al.* 2004). Determining appropriate values for all of these parameters and, where appropriate, species-specific differences among them, is a major challenge to implementation of such models.
4. It is not clear how easy it is to parameterise 3PG+ for new species. EnSym currently has about a dozen parameter sets for 3PG+ that were developed primarily for various plantation eucalypt species. These differ only slightly. Extending 3PG+ to new forest types or EVCs will require the development of new parameter sets for 3PG+. This will require calibration and validation datasets, which are not readily available for most forest types or EVCs.

5.2.3 ALMANAC_{BF}

ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) is a field-scale model that describes the competitive dynamics of agricultural plants grown in monocultures or polycultures (Kiniry *et al.* 1992). To do this, ALMANAC uses simple algorithms that partition available light among competing individuals and species. Importantly, ALMANAC uses the same soil and weather input data as the Soil and Water Assessment Tool (SWAT), and simulates plant growth in the same manner as SWAT's plant growth model. However, ALMANAC was developed for agricultural crops, not forests. Recently, MacDonald *et al.* (2008) adapted ALMANAC to simulate tree growth as a stand develops after a disturbance in boreal forests of western Canada. Although the original ALMANAC model simulated tree growth, the primary goal was to assess the impact of tree cover on understorey growth, not to describe changes in the forest. This limited the application of ALMANAC in forested catchments. ALMANAC_{BF} directly addressed this shortcoming by adding:

1. a general description of the trees in a forest stand (*i.e.*, number of trees, mean DBH, foliar biomass),
2. a mechanism to account for differences in productivity among sites, and

3. an algorithm that simulates stand development (“succession”) by shifting the competitive advantage among species over time.

MacDonald *et al.* (2008) developed $ALMANAC_{BF}$ to address questions relating to the impact of forest harvesting on the hydrology of boreal forest catchments. They were particularly interested in the impact of the revegetation process on catchment-scale hydrology as recently harvested stands are colonised and dominated by annuals, perennials, and, eventually trees. These are questions and modelling issues that are directly relevant to EnSym and the EcoTender process.

$ALMANAC_{BF}$ simulates light interception and species-specific radiation use efficiency to calculate daily potential biomass accumulation. Increases in seasonal LAI and height growth are a sigmoid function of growth degree days. When available water in the rooting zone is insufficient to meet potential evapotranspiration, leaf area and biomass growth are reduced. Currently, $ALMANAC_{BF}$ ignores nutrient limitations due to the complexity of representing nutrient feedback mechanisms in forests (MacDonald *et al.* 2008). $ALMANAC_{BF}$ is driven by a combination of environmental variables (*e.g.*, soil hydraulic conductance, soil water-holding capacity, daily precipitation, minimum and maximum daily temperature, relative humidity) and a relatively small set of parameters to characterise vegetation growth dynamics (Table 5.2).

A key innovation of $ALMANAC_{BF}$ is the ability to model multi-species competition. It does this by partitioning photosynthetically active radiation (PAR) among competing species, where the fraction of PAR intercepted by all species is estimated from Beer’s Law after summing the products of the extinction coefficient (k) and LAI for each species:

$$Fraction(PAR) = 1 - \exp\left(\sum_{i=1}^n k_i \times LAI_i\right) \quad (5.4)$$

For each species the amount of PAR that is intercepted is a function of that species’ light extinction coefficient, fraction of total stand leaf area, and current height. Species-specific shading is simulated by estimating the amount of PAR that each species intercepts, which depends on its height relative to the height of the main canopy (Kiniry *et al.* 1992). Stand development in $ALMANAC_{BF}$ is described by changes in relative species dominance over time since disturbance. These changes are mainly driven by shading in the understorey, where the amount of light available to grow diminishes as the height and leaf area of the upper canopy increases. The model accomplishes this by using species-specific factors that limit the annual potential LAI available to drive growth:

$$LAILIM_m = \left[\frac{(HT_m \times LAIP_m)}{\sum_{i=1}^n (HT_i \times LAIP_i)} \right]^{LTSNS_m} \quad (5.5)$$

where $LAILIM_m$ is the maximum potential leaf area of species m under the forest canopy, $LTSNS_m$ defines how a species responds to shading, HT_i and HT_m are the heights of species i and m , and $LAIP_i$ and $LAIP_m$ are the maximum leaf areas achieved in the preceding year.

MacDonald *et al.* (2008) parameterised $ALMANAC_{BF}$ with data from temporary and permanent sample plots and available climate and soils data. Several parameters were iteratively adjusted (“refined”) until the model output provided the best fit to the observed sample plot data. Other parameters were taken from the literature (*e.g.*, coefficients for allometric equations). The model outputs were then compared to a withheld set of data to assess its predictive capacity. In general, the $ALMANAC_{BF}$ simulations provided good estimates of most tree and stand parameters (*e.g.*, stem density, canopy height, and mean DBH), although tended to overestimate foliar biomass. In addition, changes in species composition and relative dominance were well-represented by the stand development component of $ALMANAC_{BF}$ ’s algorithms for changing species dominance as a function of height, potential LAI, and shade-bearing capacity. Importantly, from the perspective of EnSym, the $ALMANAC_{BF}$ model was also used to predict evapotranspiration across a range of site quality, species mixtures, and times since disturbance. Although the authors did not have data for assessing the model output, the consensus was that the predictions were qualitatively correct (MacDonald *et al.* 2008).

For the purposes of EnSym, the $ALMANAC_{BF}$ approach has several appealing features:

1. It uses a relatively simple approach to partition available PAR among species, thus enabling modelling of mixed-species stands. The mixed-species model builds on the functionality of SWAT for mixed cropping systems. The $ALMANAC_{BF}$ /SWAT approach allows for mixed cropping systems that included trees. This would be highly relevant to reforestation of existing agricultural lands in many Victorian landscapes, particularly where low-density tree plantings are being considered to maintain some grazing.
2. It is relatively simple and uses many of the same inputs and functions as SWAT, which is already embedded in EnSym. SWAT was developed specifically to model hydrological processes, so $ALMANAC_{BF}$ provides a functional tree/stand growth model to work in conjunction with a good hydrology model.
3. It uses “ecosite” classifications as part of its assessment of site productivity. For Victoria, where >600 expected vegetation classes (EVCs) occur, this approach may allow for constructive use of the EVCs within the modelling framework.

Table 5.2: Adjustable coefficients in the crop parameters input file used in the growth equations in ALMANAC_{BF}. Modified from MacDonald *et al.* (2008)

Name	Units	Range used	Explanation
Annual growth coefficients			
Biomass-energy ratio	$Kg\ ha^{-1}\ per\ MJ\ m^{-2}$	15–20	Potential biomass production rate per unit PAR
Extinction coefficient	$MJ\ m^{-2}\ per\ m^2\ m^{-2}\ LAI$	0.5–0.55	Radiation interception capacity
Optimal and min. growth temperatures	$^{\circ}C$	15, 4	Define heat units (HU) and temperature stress
Max. vapour pressure deficit relationship	kPa	1.0	Water use and water stress calculations
Slope of biomass-energy ration:VPD relationship	$Kg\ ha^{-1}\ per\ MJ\ m^{-2}\ per\ kPa$	-6.5	Water use and stress calculations
Max. stomatal conductance	$m\ s^{-1}$	0.005–0.01	Water use and stress calculations
Leaf area decline fraction	$\%HU$	0.99	Leaf area development with HU accumulation
Leaf area decline rate	$m^2\ m^{-2}\ (\%HU)^{-1}$	0.2–1.0	Leaf area development with HU accumulation
Leaf area development curve	$m^2\ m^{-2}\ (\%HU)^{-1}$	Fixed	Leaf area development with HU accumulation
Plant population coefficients	$m^2\ m^{-2}\ (\%cover)^{-1}$	Fixed	Leaf area development with HU accumulation
Leaf area	$m^2\ m^{-2}$	3.0–4.5	Maxima for sigmoid curve calculations
Height	m	15–30	Maxima for sigmoid curve calculations
Root depth	m	0.5	Maxima for sigmoid curve calculations
Long-term growth coefficients			
Height curve	$myear^{-1}$	%max at fixed year	Defines potential height at a given year
Leaf area development curve	$m^2\ m^{-2}\ year^{-1}$	% max at fixed year	Defines potential leaf area at a given year
Leaf area limitation factor	unitless	0.25–0.99	Defines a species' tolerance to shading
Optimum stem number coefficients [max, min]	$stems\ ha^{-1}$	8,000–500,000; 340–7,000	Calculates optimum stem number over time
Stem number coefficient	$year$; unitless	10–20; 13.54	Species-specific coefficients describing timing and steepness of decline in stem number
Allometric equation coefficients	$Mg\ ha^{-1}$	From literature	Empirical coefficients used in equations relating DBH to foliar and total biomass (4 parameters/species)
Shade tolerance coefficients	unitless	0.85–1.00; 0.25–0.30	Defines how species react to shade

5.3 Key gap models

The focus of gap models is primarily on long-term dynamics of forests and the attendant changes in forest structure and composition. Most gap models focus on changes that occur at the scale of centuries to millennia and address questions related to climate change, long-term land management practices, and species extinctions and introductions. In addition, few gap models have addressed questions of hydrology or nutrient dynamics—most have focused on light availability. As such, we feel that gap models are not an appropriate class of model for inclusion in EnSym. However, we provide a very brief description of a few of the main gap models available.

5.3.1 JABOWA and offspring

The JABOWA family presents a succession of gap models. JABOWA is an aspatial, mechanistic, gap-style forest succession model (Botkin *et al.* 1972). Commonly cited as the original gap model (see *e.g.*, Shugart 1984), JABOWA has spawned a large following of adaptations (see Botkin 1993, Appendix 6, and below). It was constructed from a small collection of simple yet powerful assumptions about how forests grow and how the environment affects this growth. The primary use of JABOWA has been for long-term speculation about ecosystem dynamics, as opposed to short-term silvicultural decision support. This context and usage leads to different modelling requirements than for the models above. The strength of JABOWA has been its clear design and open architecture, which has led to considerable flexibility in development.

Two of JABOWA's descendents, FORET and LINKAGES, are representative of the subsequent development of JABOWA-type models. FORET was the first extension of JABOWA (Shugart and West 1977). Unlike its predecessor, it explicitly included sprouting as a distinct regeneration mechanism, as that process is common to species in the Appalachians for which the model was parameterized. Tree growth was modeled as a function of climate, area of leaves above the tree, tree crowding, and tree size. The FORET model was originally used to determine the impact of chestnut blight on forests in eastern Tennessee. LINKAGES is a descendent of JABOWA, extended to explicitly address soil processes and long-term forest productivity (Pastor and Post 1985, Post and Pastor 1996). The model derives from FORET but also incorporates moisture and nutrient dynamics, among the latter, focusing on nitrogen.

The JABOWA heritage of models terminates, at this time, in SORTIE (Pacala *et al.* 1996), which we describe in detail below in the next section on hybrid models.

5.4 Key hybrid forest growth models

Hybrid models are among the most diverse forest growth models because many different approaches to linking empirical and process-based have been employed. We describe three approaches here that span the range of hybrid models. The first hybrid model we discuss is SORTIE, a highly parameterised gap model that is driven by stand-level processes such as recruitment, mortality, and growth (*cf.* tree-level processes such as photosynthesis and respiration in process-based models such as 3PG+). The second hybrid model is FVS-BGC, an implementation of the process-based model, STAND-BGC, as an extension of the empirical forest growth model FVS. The third hybrid model—statistical model melding—is more of an approach than a model. Statistical model melding involves either statistically aggregating predictions from two models or using an empirical model to constrain the predictions of a process-based model.

5.4.1 SORTIE

SORTIE was originally written and parameterised for the deciduous-dominated mixed-species forests of the northeastern USA. The SORTIE modelling approach, development, field methods, and testing have been thoroughly described (Pacala *et al.* 1996). Over the past decade the model has been extensively modified for the conifer-dominated temperate mixed-species forests of northwestern British Columbia (SORTIE-BC, Coates *et al.* 2003).

SORTIE is an individual-tree vector spatial model that owes much to the gap model tradition of JABOWA (Botkin *et al.* 1972). SORTIE simulates four processes: competition for light, tree growth as a function of light availability and tree history, mortality, and seedling recruitment as a function of parent abundance and seedbed substrate. These modules were designed and published along with the appropriate maximum likelihood estimators that can be readily estimated from field data (Pacala *et al.* 1996). Although the model was originally designed to cover the range of growth processes (light, moisture, nutrients, and temperature), the geographic homogeneity of the available data confined the original model to simulating responses to only light. Model predictions include:

1. spatial distribution, diameter and height of all individuals in a simulated stand
2. DBH and height distributions by species
3. changes in basal area and density, by species, over time, and
4. tables of basal area and densities of adults, saplings, and seedlings.

Although SORTIE has its intellectual origins in the gap model, we use it here as an example of a hybrid model because it attempts to represent critical processes within a forest, such as light transmission, photosynthesis, and radiation-use efficiency, but using

Table 5.3: Required parameters for simulations with SORTIE. Species-specific parameters for growth, mortality, and dispersal are all derived from empirical observations and maximum likelihood estimation. From http://www.sortie--nd.org/software.sample_par_file.html/.

Name	Range used
Allometry parameters	
New seedling diameter at 10 cm	0.2
Adult & sapling height–diameter function	Species-specific
Adult & sapling crown radius–diameter function	Species-specific
Adult & sapling crown height–height function	Species-specific
Seedling height–diameter function	Species-specific
Maximum tree height (m)	23.2–38.4
Slope of asymptotic crown radius	0.087–0.116
Slope of asymptotic crown height	0.319–0.664
Slope, intercept of DBH to diameter at 10cm relationship	0.75, 0
Slope of asymptotic height	0.024–0.063
Slope of height–diameter at 10cm relationship	0.03
Tree population parameters	
Minimum adult DBH (cm)	10
Maximum seedling height (m)	1.35
Initial density (stems/ha) 0-1cm DBH	25
Light parameters	
Beam fraction of global radiation	0.5
Clear sky transmission coefficient	0.65
First, last day of growing season	120, 270
Number of azimuth sky divisions for quadrat & GLI light calculations	18
Number of altitude sky divisions for quadrat & GLI light calculations	12
Minimum solar angle for quadrat & GLI light (radians)	0.779
Height at which GLI is calculated for quadrats (m)	0.675
Growth parameters	
Adult constant area growth ($cm^2 yr^{-1}$)	0.3
Asymptotic diameter growth	0.125–0.266
Slope of growth response	0.033–0.159
Relative Michaelis–Menten growth–diameter exponent	1
Mortality parameters	
DBH of maximum senescence mortality rate (cm)	100
Mortality at zero growth	0.014–0.99
Light-dependent mortality	0.2–9.38
Senescence mortality α , β	-20, 0.135
DBH at onset of senescence	100
Adult & juvenile background mortality rate	0.01
Dispersal parameters	
Minimum DBH for reproduction (cm)	10
Canopy function used	Weibull
Weibull canopy annual STR	0.036–0.09
Weibull canopy β , θ	2, 3
Weibull canopy dispersal	0.00000001–0.000687

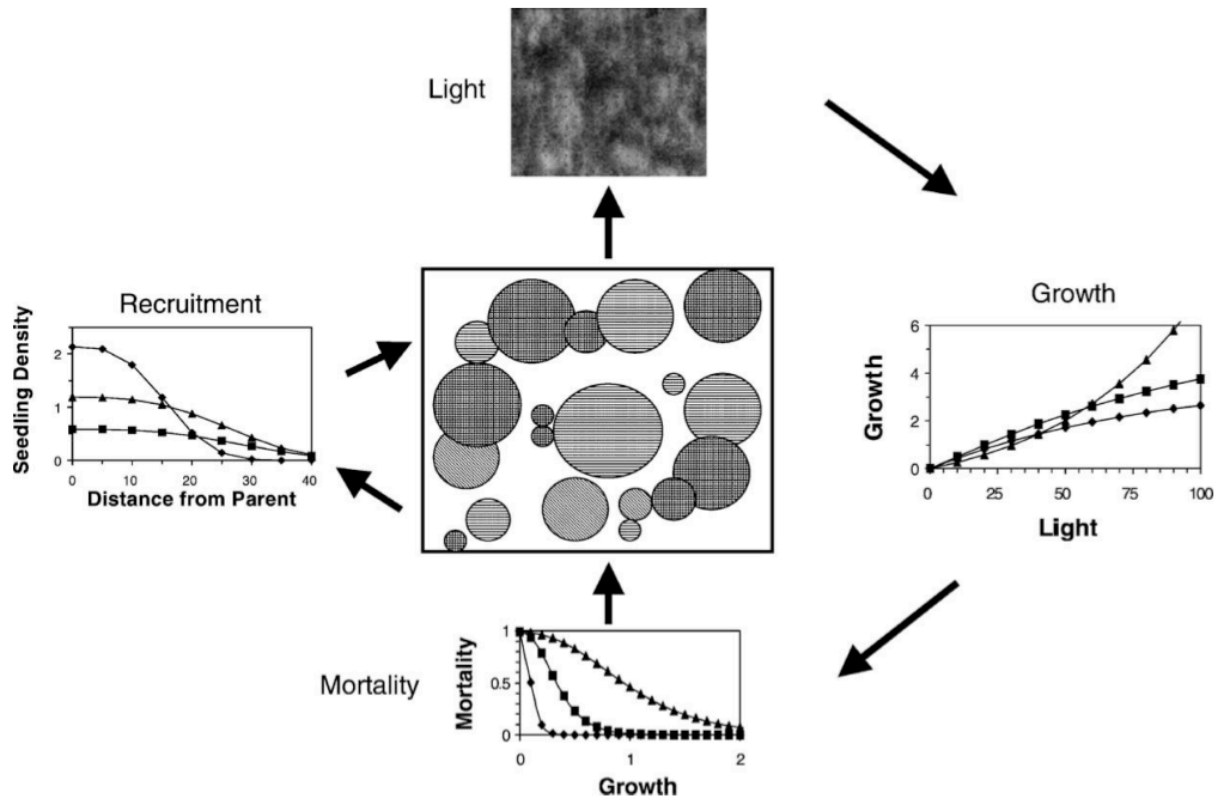


Figure 5.2: Schematic diagram of the SORTIE model describing the main modules driving simulated forest dynamics. From Coates *et al.* (2003)

parameters that are derived from extensive empirical observations and statistical fitting (Table 5.3, Pacala *et al.* 1993, 1996, Ribbens *et al.* 1994, Kobe *et al.* 1995).

The SORTIE approach to projecting tree growth is as follows (see Pacala *et al.* 1994, for further details). Tree radial growth is predicted as the product of the current radius, r , and a Michaelis–Menton function of the available light:

$$w = \frac{r \cdot A \cdot L}{\frac{A}{S} + L}, \quad (5.6)$$

where the parameters are defined and coefficients provided for eastern white pine (*Pinus strobus* L.), as an example, in Table 5.4.

The available light, L , is a general light index (GLI) that is computed for each subject tree (Canham 1988). The GLI “...integrates the seasonal and diurnal movements of the sun, the mix of diffuse and beam radiation, and the spatial distribution of canopy openness in units of percent of full sun” (Pacala *et al.* 1994). SORTIE includes the identities and locations of competing trees in its consideration of competition for light resources. Tree height is then predicted as a function of tree radius.

Table 5.4: SORTIE: parameter definitions and example coefficient values for eastern white pine (Pacala *et al.* 1994). State variables do not have parameter values.

Label	Value	Interpretation
r		Current tree radius (cm).
L		Available light level at tree (see text).
A	0.230	Asymptotic relative growth rate at high light.
S	0.019	Slope of MM curve at zero light.

For the purposes of EnSym, the SORTIE approach has several significant shortcomings:

1. It is dependent on rigorously estimated parameter sets obtained from large empirical datasets. The requirements for parameterising SORTIE are sufficiently burdensome that the original version from the northeastern US has only been reparameterised for a handful of other forest types to date (*e.g.*, mixed conifer–hardwood forests in British Columbia).
2. SORTIE is a spatially explicit model of forest dynamics. Thus, it requires x, y coordinates for each individual tree in a stand. Spatial data of this sort is not collected in standard forest inventories and is not readily available for most forests.
3. It does not directly model any hydrological processes. However, as with FVS, the estimates of tree size (DBH, tree height, crown depth) could potentially be used to estimate total leaf area, which could be fed into a model that uses leaf area to calculate water flux within a site.
4. Like most gap models it was designed to explore changes in forest structure and composition over centuries. Consequently, it may not have sufficiently fine temporal resolution for some of the biophysical modelling requirements of the EnSym project.

5.4.2 FVS–BGC

FVS–BGC is a hybrid model that uses the process-based model, STAND–BGC (Milner and Coble 1995), operating at daily and monthly time steps, as an extension of the empirical model, FVS, which operates on 10-year time steps. STAND–BGC is an “individual–entity”, distance-independent model derived from the stand-level process-based model FOREST–BGC (Running and Coughlan 1988). Milner and Coble (1995) use the term “entity” because STAND–BGC can grow grasses, shrubs, and trees; however, grasses and shrubs are treated on a per unit area basis, while trees have unique dimensions. STAND–BGC is a carbon and water balance model that is driven by climate. Stomatal conductance, net canopy photosynthesis, transpiration, and maintenance respiration

are calculated on a daily time step, while growth respiration and carbon allocation are calculated on a yearly time step. STAND-BGC is particularly sensitive to changes in soil water potential, which has a strong influence on stomatal conductance and therefore net canopy photosynthesis. It uses a multiple canopy framework to accommodate light attenuation in stratified stands, allowing for entities to compete for light. Soil water is partitioned into surface and subsurface layers (*i.e.*, a two-bucket model) and accessed by species depending on their life form (*e.g.*, small trees, grasses, and shrubs can only access the surface layer). Each entity transpires stratum by stratum, with a new water potential recalculated for the entity after each stratum's transpiration. At night, the soil layers equilibrate to an overall site water balance. At the end of each year the net carbon gain for each entity is allocated among plant parts, consistent with allometric ratios.

STAND-BGC requires approximately 35 parameters to describe physiological processes. Twenty-two of these are common to all plants; the rest are life-form specific. The model runs are initialised with data on species, height, DBH, live crown ratio, and trees per hectare (for tree entities) or percent cover (for grasses and shrubs). When STAND-BGC is run within FVS, it uses the FVS output to initialise its runs. The two models can then run in parallel over a 10-year time step. Both models can output the results of their simulations. STAND-BGC can then be initialised for the next time step with the FVS model output or with its own model output. One advantage of using the FVS initialisations is that process-based models do not typically represent management operations (*e.g.*, thinning) or insect and disease effects well. FVS and its various extensions do.

While originally developed for conifer forests in the Interior West of the US (Milner and Coble 1995), FVS-BGC has recently been adapted to deciduous forests of the eastern US (Wang *et al.* 2008). Comparisons between FVS-BGC model simulations and forest inventory data in both regions demonstrated that the model provides good estimates of tree height, DBH, and carbon sequestration under a range of environmental (*e.g.*, water stress) and management (*e.g.*, thinning) conditions.

For the purposes of EnSym, the FVS-BGC approach has several attractive features:

1. It is capable of representing physiological processes occurring in complex, mixed-species stands.
2. FOREST-BGC, from which the process-based component of FVS-BGC derives, was developed with particular attention to the role of soil water stress on plant growth. As such it should perform well in representing water flux as a forest stand changes in structure over time.
3. Species-specific physiological parameters can be derived from standard field-based measurements of gas exchange, leaf area, and dry weights (Wang *et al.* 2008). This would allow for rapid expansion of the forest types that could be used in FVS-BGC.

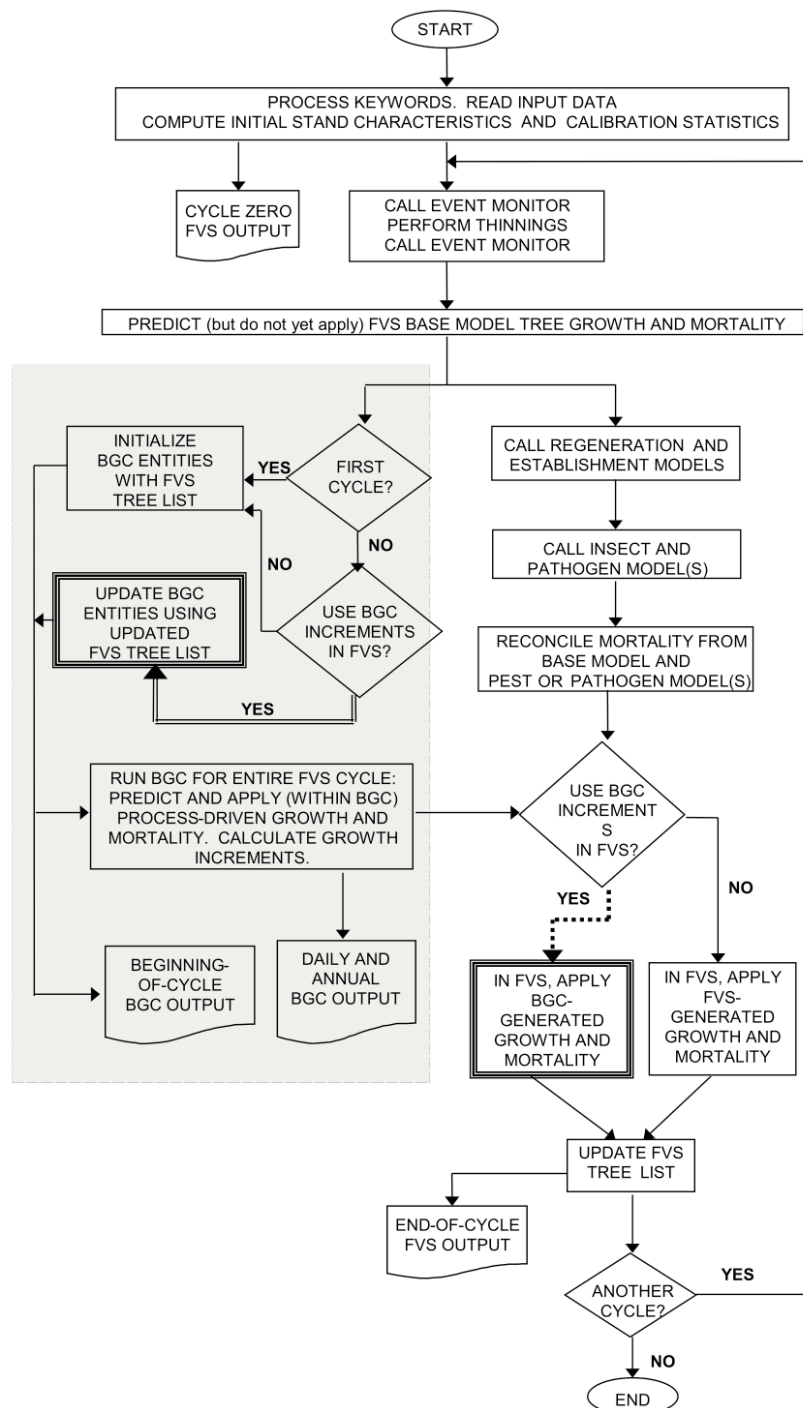


Figure 5.3: Flowchart showing how STAND-BGC operates as an extension of the empirical growth model, FVS. STAND-BGC cycles are daily and monthly, while FVS operates on a 10-year time step. Growth increments can be produced by either FVS or STAND-BGC, with the latter producing annual growth increments within each 10-year FVS time step. From Milner *et al.* (2003)

4. Some early work on BIOME-BGC, a generalised version of FOREST-BGC, was conducted in Murray-Darling Basin (Hatton *et al.* 1993, Pierce *et al.* 1993) and may be available to facilitate the development of STAND-BGC-type model for Victorian forests, particularly in the arid north and west of the State.

However, FVS-BGC also has some shortcomings:

1. FVS is not available for Victorian forests. All of the issues with FVS detailed in Section 5.1.1 apply to FVS-BGC.
2. FVS-BGC only applies to trees >1.37 tall (*i.e.*, $\text{DBH} > 0$), so early stand development patterns are not represented.

5.4.3 Statistical model melding

Statistical model melding is a family of hybrid modeling techniques rather than a hybrid model. Here we briefly describe some of the themes that these techniques follow.

Weighted Mean

The simplest approach to creating a model that is a hybrid of two other models is to statistically aggregate the predictions from each model (Robinson and Ek 2000). In order for the aggregation to be useful, it is necessary that the output of the models, usually the state variables, be commensurate, and that they have a formulation that honestly represents the uncertainty of their predictions. For example, imagine that we have two independent models that predict diameter growth as a function of current diameter; $f_1(d_t)$ and $f_2(d_t)$. Furthermore, let the variance of the prediction of f_1 be σ_1^2 and of f_2 be σ_2^2 . Then the hybrid prediction would be the weighted average:

$$f_{12}(d_t) = \frac{f_1(d_t) \cdot \sigma_2^2 + f_2(d_t) \cdot \sigma_1^2}{\sigma_1^2 + \sigma_2^2} \quad (5.7)$$

This approach, called compound estimation, treats the predictions as independent estimates of future values of the random variable. The advantage is that the variance of $f_{12}(d_t)$ is less than the variances of $f_1(d_t)$ and $f_2(d_t)$.

Bayesian melding

Other approaches to hybrid modeling involve model construction. Since we do not advocate the construction of a new model for EnSym, we will touch upon only one, Bayesian Melding, and then only briefly.

Bayesian melding is a statistical technique that supports the efficient estimation of parameters of complex models, subject to constraints that may be in the form of observed

data (Poole and Raftery 2000). The original application was called Bayesian synthesis, and was used to estimate uncertainty in a deterministic population dynamics model for bowhead whales (Raftery *et al.* 1995). A more recent forestry application was the estimation of parameters for the process-based forest growth and dynamics model, PnET-II (Radtke *et al.* 2002).

A detailed review of Bayesian melding is beyond the scope of this report. Briefly, the outcome of Bayesian melding is joint posterior probability density distributions for state variables and parameter estimates of the model. Bayesian melding uses Bayes' Theorem to combine information that may come from three distinct sources, as follows. *Direct* information refers to observations on the population of interest, typically stand or tree measures. *Indirect* information covers prior expectations that are expressed as prior probability density distributions. Finally, *model* information refers to the constraints that are placed on the relationships between the direct and indirect information by the deterministic model structure.

More recently, Radtke and Robinson (2006) used a variant of Bayesian melding to construct a hybrid model that combined a process-based model, PnET-II, with an empirical model, G-HAT. The variant involved generating sample data from G-HAT and using those data as the direct information, above.

5.5 Key issues in adopting a forest growth model into EnSym

5.5.1 Representation of forest growth and critical ecosystem processes

As forests and fields change, so too do many of the processes associated with them, such as water uptake and carbon storage. A major focus of EnSym is on the dynamic nature of different types of vegetation within a catchment. Most hydrological or biophysical models represent vegetation, but typically in a simple and static way. For example, Macaque uses fixed empirical relationships to describe the time-course of LAI at a site as a function of vegetation type and age (Lane *et al.* 2009). Some hydrological models that have vegetation subroutines can accommodate different types of land-use (*e.g.*, PnET-II3SL/SWAT, Kirby and Durrans 2007) within the same catchment. However, these representations of the vegetation are typically static — a site is classified as agricultural or forested and the appropriate parameter sets or subroutines are applied when the part of the catchment under that cover/management type is evaluated. Soil-Plant-Atmosphere models such as ET-Pan or CABLE (Kowalczyk *et al.* 2006) are similar in that they represent the vegetation as a fixed leaf area index. None of these models reproduce

the development of a forest from its earliest stages through to maturity. In contrast, most forest growth models, whether empirical, process-based, or hybrid, are designed specifically to account for these changes, particularly in terms of tree or stand biomass. Different models and model classes employ different approaches to achieving this goal, but all are able to model forest growth. Where they are limited, however, is in their representation of the role of water in the system. Most empirical models account for water limitations through a site index variable that integrates soil water availability, soil fertility, and other limits to growth. They do not explicitly take into account the uptake of water from within the soil profile. Empirical models are relatively good predictors of individual tree size and stand density, which together can be used to estimate stand leaf area. Given data on temperature, soil water holding capacity, precipitation, and vapour pressure deficit, it may be possible to use estimates of stand leaf area derived from forest growth models as input into static models such as ET-Pan, CABLE or SWAT that can then estimate the stand-level hydrological dynamics. Process-based models, in principle, should provide better representations of stand-level hydrology because they directly address water availability, water uptake, and water loss by the trees. However, the primary focus of most process-based models is on biomass, not water, and the dynamics of belowground processes, such as water uptake within the soil profile, is poorly known at best. Consequently, the water modelling components of most process-based models are among the most poorly understood and least well-parameterised submodels within a given process-based model.

Table 5.5: Qualitative assessment of the capacity of different forest vegetation models to represent carbon and water variability. Rating scheme is +, +/-, -, or unknown

Model	Model Class	Water	Carbon
FVS	Empirical	Unknown	+
ET-Pan	Process	+	-
3PG+	Process	+	+
ALMANAC _{BF}	Process	+	+
JABOWA	Gap	-	-
SORTIE	Hybrid	-	+
FVS-BGC	Hybrid	+	+
Model melding	Hybrid	+/-	+/-

5.5.2 Data availability

The greatest impediment to bringing one or more new forest growth models into the EnSym modelling framework is the lack of available data for model parameterisation, calibration, and validation. Forest inventory data in Victoria are sparse. Few of the existing inventory plots have been measured repeatedly over prolonged periods. Derivative data on forest ecosystem processes at the tree-, stand-, and catchment-scale, such as carbon flux, sap flow, catchment runoff, are also uncommon. As a consequence, it may be impossible to develop or modify empirical models that are highly dependent on data for parameter estimation. It also limits the opportunities to evaluate how well forest growth models perform relative to real ecosystems and to other forest growth models. This is a major problem for forest growth modelling in Victoria in general, but also for the EnSym project, specifically. One opportunity that may exist for certain sites is to use the extensive inventory data from NSW Forests as a first approximation for model development while local data are being collected.

Chapter 6

Recommendations for forest growth modelling in EnSym

Based on our review of available forest growth models and given the filters with which we have assessed them, we present several potential options for the development of forest growth modelling capacity within EnSym.

1. Business as usual. Use ET-Pan or 3PG+ without any further modification or consider using ET-Pan for small trees and letting 3PG+ take over when the trees are larger. This approach would require (i) determining where to effect the change, and then (ii) hacking the BioSym code, but neither step should represent too substantial a problem.
2. Look into $ALMANAC_{BF}$. EnSym already uses or has the capacity to use SWAT. The modification of $ALMANAC$ allows for modelling of mixed species stands, is readily integrated into SWAT to provide hydrological modelling and can provide reasonable biomass estimates. This approach would require a modeller willing to talk to the research group behind $ALMANAC_{BF}$. Also, this approach would need data for calibration and verification.
3. Use a hybrid modelling approach. Statistical tools are now available to enable melding of good biomass models (3PG+ or NCAS model) and good water models (SWAT, PERFECT). This approach would require a statistician to explore potential approaches to melding data and models.
4. Develop new hybrid model. Duursma *et al.* (2007) used a simplified process model with parameter estimates derived from direct field observation or statistical inference to explore wood volume production in dry forests in Idaho, USA. While this approach is attractive in some respects, it would require significant intellectual input to develop the hydrological aspects of the growth model — which is likely non-trivial

(particularly given the paucity of available data). We raise this as a possibility, but given the modelling challenges and data requirements, we do not recommend this as a course to be pursued.

5. Conduct model comparisons with independent evaluation datasets. Our report provides a review of the major model classes, some examples of models within these classes, and a discussion of their potential strengths and weaknesses with respect to incorporation into EnSym. However, we are not in a position to provide a quantitative or qualitative assessment of the *performance* of any of these models. All of those models that are not already available in EnSym were developed in ecosystems that are significantly different from those found in the Victorian landscape and would need to be reparameterised for application in Victoria before they could be compared with any rigour. We believe that the best way to do this would be to conduct a modelling contest with as many potential models as possible and a high-quality dataset relevant to the EnSym project's management goals. Recent inter-model comparisons of CO₂ exchange and transpiration in boreal forests (Amthor *et al.* 2001), carbon and water fluxes in oak forests of the southeastern USA (Hanson *et al.* 2004), and potential climate change on tree growth Schwalm and Ek (2001) provide useful templates for such an approach. Depending on the number of models that can be “plugged in” to EnSym with minimum effort, we expect that this would take approximately one year of work by a programmer/modeller. However, the outcome would give the most rigorous test of the capabilities (and limitations) of the various forest dynamics models.

Table 6.1: Summary table of costs and benefits associated with report recommendations.

Recommendation	Cost	Benefit	Risk
1. Business as usual	None	Easy	Inadequate representation of key processes
2. ALMANAC _{BF}	Modeller for 1 yr	Model may be better suited to EnSym's needs	ALMANAC _{BF} doesn't work for Victorian forests
3. Use existing hybrid model	Statistician for 1 yr	Better integration of existing models that address specific elements of desired outcomes (<i>e.g.</i> , carbon and water)	Statistical analyses limited by available data and large uncertainties
4. Develop new hybrid model	Modeller for 3 yrs	Model development guided by EnSym's needs	Massive undertaking that may not succeed given limited empirical data
5. Conduct model competitions	Modeller for 1 yr	Best way to evaluate the strengths and weaknesses of available models	No models are adequate to meet EnSym's needs

Bibliography

- Aber J, Federer C, 1992. A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems. *Oecologia* 92(4): 463–474.
- Amthor J, Chen J, Clein J, Frolking S, Goulden M, Grant R, Kimball J, King A, McGuire A, Nikolov N, 2001. Boreal forest CO₂ exchange and evapotranspiration predicted by nine ecosystem process models: Intermodel comparisons and relationships to field measurements. *J Geophys Res* 106(33): 623–633.
- Battaglia M, Sands P, White D, Mummery D, 2004. CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. *Forest Ecology and Management* 193(1-2): 251–282.
- Botkin D, 1993. *Forest dynamics: An ecological model*. Oxford University Press.
- Botkin D, Janak J, Wallis J, 1972. Some ecological consequences of a computer model of forest growth. *Journal of Ecology* 60: 849–872.
- Bugmann H, 2001. A review of forest gap models. *Climatic Change* 51(3): 259–305.
- Canham CD, 1988. An index for understory light levels in and around canopy gaps. *Ecology* 69: 1634–1638.
- Coates KD, Canham CD, Beaudet M, Sachs DL, Messier C, 2003. Use of a spatially explicit individual-tree model (SORTIE/BC) to explore the implications of patchiness in structurally complex forests. *Forest Ecology and Management* 186(1-3): 297–310.
- Crookston N, Dixon G, 2005. The forest vegetation simulator: A review of its structure, content, and applications. *Computers and Electronics in Agriculture* 49(1): 60–80.
- Duursma R, Marshall J, Robinson AP, Pangle R, 2007. Description and test of a simple process-based model of forest growth for mixed-species stands. *Ecological Modelling* 203(3-4): 297–311.

- Feikema P, Morris J, Beverly C, Baker T, Lane P, 2010. Description of the 3PG+ forest growth model. Technical report, Department of Forest Ecosystem Science, University of Melbourne, Melbourne, VIC.
- Hanson P, Amthor J, Wullschlegel S, Wilson K, Grant R, Hartley A, Hui D, Hunt J, Johnson D, Kimball J, 2004. Oak forest carbon and water simulations: model inter-comparisons and evaluations against independent data. *Ecological Monographs* 74(3): 443–489.
- Harper J, 1977. *Population biology of plants*. Academic Press, London, UK.
- Hatton T, Pierce L, Walker J, 1993. Ecohydrological changes in the Murray–Darling Basin. II. Development and tests of a water balance model. *Journal of Applied Ecology* 30(2): 274–282.
- Kiniry JR, Williams JR, Gassman PW, Debaeke P, 1992. A general, process-oriented model for two competing plant species. *Transactions of the American Society for Agricultural Engineers* 35: 801–810.
- Kirby J, Durrans S, 2007. PnET-II3SL/SWAT: Modeling the combined effects of forests and agriculture on water availability. *Journal of Hydrologic Engineering* 12: 319.
- Kobe RK, Pacala SW, Silander JA, Canham CD, 1995. Juvenile tree survivorship as a component of shade tolerance. *Ecol Appl* 5(2): 517–532.
- Korzukhin M, Ter-Mikaelian M, Wagner R, 1996. Process versus empirical models: which approach for forest ecosystem management? *Canadian Journal of Forest Research* 26(5): 879–887.
- Kowalczyk E, Wang Y, Law R, Davies H, McGregor J, Abramowitz G, 2006. The CSIRO atmosphere biosphere land exchange (CABLE) model for use in climate models and as an offline model. *CSIRO Marine and Atmospheric Research* .
- Landsberg J, 2003. Physiology in forest models: history and the future. *FBMIS* 1: 49–63.
- Landsberg J, Waring RH, 1997. A generalised model of forest productivity using simplified concepts of radiation–use efficiency, carbon balance, and partitioning. *Forest Ecology and Management* 95: 209–228.
- Lane PNJ, Feikema PM, Sherwin CB, Peel MC, Freebairn AC, 2009. Modelling the long term water yield impact of wildfire and other forest disturbance in eucalypt forests. *Environmental Modelling and Software* 25(4): 467–478.

- Littleboy M, Silburn D, Freebairn D, Woodruff D, Hammer G, Leslie J, 1992. Impact of soil erosion on production in cropping systems. I. Development and validation of a simulation model. *Australian Journal of Soils Research* 30: 757–774.
- MacDonald J, Kiniry J, Putz G, Prepas E, 2008. A multi-species, process based vegetation simulation module to simulate successional forest regrowth after forest disturbance in daily time step hydrological transport models. *Journal of Environmental Engineering and Science* 7(S1): 127–143.
- Mäkelä A, 1997. A carbon balance model of growth and self-pruning in trees based on structural relationships. *Forest Science* 43: 7–24.
- Mäkelä A, Landsberg J, Ek A, Burk T, Ter-Mikaelian M, Agren G, Oliver C, Puttonen P, 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. *Tree Physiol* 20(5-6): 289.
- Medlyn B, 2004. A MAESTRO retrospective. In Mencuccini M, Grace J, Moncrieff J, McNaughton KG (Editors), *Forests at the Land–Atmosphere Interface*, chapter 8, pages 105–121. CAB International.
- Miehle P, Battaglia M, Sands PJ, Forrester DI, Feikema PM, Livesley SJ, Morris JD, Arndt SK, 2009. A comparison of four process-based models and a statistical regression model to predict growth of *Eucalyptus globulus* plantations. *Ecological Modelling* 220: 734–746.
- Milner KS, Coble DW, 1995. A mechanistic approach to predicting the growth and yield of stands with complex structures. In O’Hara KS (Editor), *Uneven-aged management: Opportunities, constraints, and methodologies*, volume 56 of *MFCES Miscellaneous Publications*. University of Montana, Missoula, MT, USA.
- Milner KS, Coble DW, McMahan AJ, Smith EL, 2003. FVS-BGC: a hybrid of the physiological model STAND-BGC and the forest vegetation simulator. *Canadian Journal of Forest Research* 33(2): 466–479.
- Monserud R, 2003. Evaluating forest models in a sustainable forest management context. *Forest Biometry, Modelling and Information Sciences* 1: 35–47.
- Nightingale J, Hill M, Phinn SR, Davies ID, Held A, Erskine PD, 2008. Use of 3-PG and 3-PGS to simulate forest growth dynamics of australian tropical rainforests. parameterisation and calibration for old-growth, regenerating and plantation forests. *Forest Ecology and Management* 254(2): 107–121.

- Pacala SW, Canham CD, Saponara J, Silander JA, Kobe RK, Ribbens E, 1996. Forest models defined by field measurements: estimation, error analysis and dynamics. *Ecological Monographs* 66(1): 1–43.
- Pacala SW, Canham CD, Silander JA, 1993. Forest models defined by field measurements: I. the design of a northeastern forest simulator. *Canadian Journal of Forest Research* 23: 1980–1988.
- Pacala SW, Canham CD, Silander JA, Kobe RK, 1994. Sapling growth as a function of resources in a north temperate forest. *Canadian Journal of Forest Research* 24: 2172–2183.
- Pastor J, Post WM, 1985. Development of a linked forest productivity-soil process model. Technical Report Report ORNL/TM-9519, Oak Ridge National Laboratory, Oak Ridge, TN.
- Peng C, Liu J, Dang Q, Apps M, Jiang H, 2002. TRIPLEX: a generic hybrid model for predicting forest growth and carbon and nitrogen dynamics. *Ecological Modelling* 153(1-2): 109–130.
- Pierce L, Walker J, Dowling T, McVicar T, Hatton T, Running S, Coughlan J, 1993. Ecohydrological changes in the Murray–Darling Basin. III. A simulation of regional hydrological changes. *Journal of Applied Ecology* 30(2): 282–294.
- Poole D, Raftery AE, 2000. Inference for deterministic simulation models: the bayesian melding approach. *J Am Stat Assoc* 95: 1244–1255.
- Post WM, Pastor J, 1996. LINKAGES - an individual-based forest ecosystem model source. *Climatic Change* 34(2): 253–261.
- Pretzsch H, 2009. *Forest dynamics, growth and yield: From measurement to model*. Springer, New York, USA.
- Radtke P, Robinson AP, 2006. A Bayesian strategy for combining predictions from empirical and process-based models. *Ecological Modelling* 190(3-4): 287–298.
- Radtke PJ, Burk TE, Bolstad PV, 2002. Bayesian melding of a forest ecosystem model with correlated inputs. *Forest Science* 48: 701–711.
- Raftery AE, Givens GH, Zeh JE, 1995. Inference from a deterministic population dynamics model for bowhead whales. *J Am Stat Assoc* 90: 402–416.
- Ribbens E, Silander JA, Pacala SW, 1994. Recruitment in forests: calibrating models to predict patterns of tree seedling dispersal. *Ecology* 75: 1794–1804.

- Robinson AP, Ek A, 2000. The consequences of hierarchy for modeling in forest ecosystems. *Can J For Res* .
- Robinson AP, Ek A, 2003. Description and validation of a hybrid model of forest growth and stand dynamics for the Great Lakes region. *Ecological Modelling* 170(1): 73–104.
- Robinson AP, Monserud R, 2003. Criteria for comparing the adaptability of forest growth models. *Forest Ecology and Management* .
- Running S, Coughlan J, 1988. A general model of forest ecosystem processes for regional applications i. hydrologic balance, canopy gas exchange and primary production processes. *Ecological Modelling* 42(2): 125–154.
- Schwalm C, Ek A, 2001. Climate change and site: relevant mechanisms and modeling techniques. *Forest Ecology and Management* 150(3): 241–257.
- Shugart HH, 1984. *A theory of forest dynamics: The ecological implications of forest succession models*. Springer-Verlag, New York.
- Shugart HH, West DC, 1977. Development of an Appalachian deciduous forest model and its application to assessment of the impact of the chestnut blight. *Journal of Environmental Management* 5(161–179).
- Stage A, 1973. Prognosis model for stand development. Technical Report INT-137, USDA Forest Service, Intermountain Forest and Range Experimental Station, Ogden, Utah.
- Stage AR, 1976. Notes: An expression for the effect of aspect, slope, and habitat type on tree growth. *Forest Science* 22(4): 457–460.
- Stage AR, 2003. How forest models are connected to reality: evaluation criteria for their use in decision support. *Can J For Res* 33(3): 410–421.
- Taylor AR, Chen HY, VanDamme L, 2009. A review of forest succession models and their suitability for forest management planning. *Forest Science* 55(1): 23–36.
- Teck R, Moeur M, Adams J (Editors), 1997. *Proceedings of Forest Vegetation Simulator Conference*, volume INT-GTR-373. USDA Forest Service, Intermountain Research Station.
- Thomas E, Gardner E, Littleboy M, Shields P, 1995. The cropping systems model PERFECT as a quantitative tool in land evaluation: An example for wheat cropping in the Maranoa area or Queensland. *Australian Journal of Soil Research* 33(3): 535–554.

- Urban DL, 1990. *A versatile model to simulate forest pattern: A user's guide to Zelig 1.0*. University of Virginia, Department of Environmental Sciences, Charlottesville, Virginia.
- Wang Y, Bauerle W, Reynolds R, 2008. Predicting the growth of deciduous tree species in response to water stress: FVS-BGC model parameterization, application, and evaluation. *Ecological Modelling* 217(1-2): 139–147.
- Wang YP, Jarvis PG, 1990. Influence of crown structural properties on PAR absorption, photosynthesis, and transpiration in sitka spruce – a simulation study. *Tree Physiology* 7: 507–524.
- Wykoff WR, Crookston NL, Stage AR, 1982. User's guide to the stand prognosis model. General Technical Report INT-GTR-133, United States Department of Agriculture.

Appendix A

A comparison of 3PG+ and ALMANAC_{BF}

3PG+ has been used as the standard vegetation model in EnSym and its predecessors for several years. Due to perceived shortcomings of 3PG+ with respect to groundwater dynamics and erosion, it has recently been replaced with ET-Pan until the issue is resolved or another model is adopted. In our review, we identified the forest vegetation model ALMANAC_{BF} as a candidate model for EnSym because it 1) models mixed-species community dynamics, 2) uses the same inputs and functions as SWAT, which is already embedded in EnSym, and 3) can be parameterised for a wide range of vegetation types, which would be well-suited to the EVC framework used in Victoria. In this Appendix we provide a direct comparison of 3PG+ and ALMANAC_{BF} focusing on how ALMANAC_{BF} addresses specific deficiencies noted in 3PG+, how each model addresses the same processes (*e.g.*, diameter growth, mortality), and how uncertainties in the model and model parameters are accommodated.¹

Key differences between ALMANAC_{BF} and 3PG+

Two factors distinguish ALMANAC_{BF} from 3PG+. First, ALMANAC_{BF} can model mixed-species stand development, whereas 3PG+ cannot. In their publication describing ALMANAC_{BF}, MacDonald *et al.* (2008) use data from mixed-species boreal forest stands in central Canada to parameterise and test their model. Their analyses included conifers and deciduous trees, as well as changes in understorey vegetation. Second, ALMANAC_{BF} is a considerably simpler model. ALMANAC_{BF} uses 19 parameters, of which seven are species-specific. Most of the parameter values were taken from the published literature or existing growth and yield tables. Some parameters, such as maximum stand density, were

¹We make this comparison with the important caveat that it is based solely on the published literature available to us describing the two models. A more comprehensive evaluation of how each model handles specific processes would require access to the source codes and programming documentation.

fit from available forest inventory data. In contrast, 3PG+ requires >50 parameters for a single-species stand.² One of the key sources of model simplification is that ALMANAC_{BF} uses the ‘maximal tree method’ to fit many of its relationships. The ‘maximal tree method’ involves the imposition of a regular curve (*e.g.*, an exponential decay or a sigmoidal curve) that is anchored using maximal known or imaginable values. MacDonald *et al.* (2008) used available forest inventory data to provide these values. The advantage of this approach is that it makes it easy to find estimates for the parameters; the disadvantage is that it is not considered a particularly reliable approach. In contrast, 3PG+ relies on model components that attempt to represent what is known about forest stand processes. This leads to more complex functional forms of many processes, requiring more parameters to be fit. While this approach may be more satisfying scientifically, it is much more difficult to deploy operationally because of the large number of parameters required.

How ALMANAC_{BF} and 3PG+ model the same processes

ALMANAC_{BF} and 3PG+ are fundamentally different forest growth models; however, many of the underlying processes that drive them are the same or similar. This makes their respective representations of common processes an obvious point of comparison. To do this requires a comparison of equivalent model ‘states’. Because ALMANAC_{BF} can handle mixed-species stands and 3PG+ cannot, our comparison is made for a single-species stand, which both can represent. Here we focus on how each model represents growth and mortality. We provide more detail on the mechanics of the ALMANAC_{BF} model, as 3PG+ has recently been described in great detail by Feikema *et al.* (2010).

Biomass Growth

Both models use a similar approach to model radiation interception and conversion. First, Beer’s law is applied to characterise PAR interception. Second, a biomass conversion parameter is used to translate the amount of light intercepted into biomass. In ALMANAC_{BF} this is referred to as radiation use efficiency (RUE); in 3PG+ this is referred to as radiation conversion efficiency. In both models, the conversion of light into potential growth is modified by parameters that account for water, temperature, and nutrient limitation.³

The ALMANAC_{BF} publication was unclear about how biomass accumulates. It appears that in a single-species stand, biomass growth is linked to LAI and intercepted PAR.

²The number of parameters used in 3PG+ is based on a figure provided in a presentation by Dr. Paul Feikema at the 3PG+/CAT workshop on 12 March 2010 at the University of Melbourne.

³The ALMANAC_{BF} publication does not provide details of how the modifiers are actually integrated into the potential biomass production, other than noting that nutrient limitations were not included in the model runs due to the complexity of representing nutrient feedback mechanisms in forest soils. Notably, they cite the original 3PG publication (Landsberg and Waring 1997) in support of this decision.

Seasonal leaf area growth is a sigmoidal function of growing degree days, attenuated by water stress. This is modified in mixed-species stands by accounting for differences in height growth among species and then reducing the amount of light a species intercepts as a function of its relative position within the vertical canopy profile. Both height growth and biomass accretion follow sigmoidal growth curves as well. So, where 3PG+ (correctly) imposes a functional relationship between the accretion of biomass in various components of the stand, $ALMANAC_{BF}$ induces it by using alike functions.

Both models estimate average stand DBH as a function of stand biomass and total number of trees. There is very little to separate them on this point.

Mortality

$ALMANAC_{BF}$ and 3PG+ use a similar approach to estimating mortality in stands of trees. However, there is a key difference between them in what drives mortality. In $ALMANAC_{BF}$ stem density is calculated from a species-specific, time-based empirical curve that is functionally independent of biomass but mimics self-thinning. The algorithm is parameterised using forest inventory data by setting the minimum and maximum possible densities in $ALMANAC_{BF}$ to the minimum and maximum observed densities in the inventory database. Stem density in each year is calculated as a function of years since stand initiation. Mortality is the difference in stem density between years t and $t - 1$. The rate of mortality varies among species as a function of a species-specific parameter that controls the steepness of the decline in stem density.

3PG+ uses a self-thinning approach: whereas changes in stem density are a function of time in $ALMANAC_{BF}$, they are a function of a theoretical biomass ‘carrying capacity’ in 3PG+. The approach used by 3PG+ has a long history in the theoretical plant ecology literature (Harper 1977). For a given stand there is a species-specific biomass maximum that can be achieved. If the biomass increment of the stand, when added to the standing biomass, is less than this maximum, then the individual trees can grow. If the combination of biomass increment and standing biomass exceeds this maximum, then mortality must occur (allowing the surviving trees to grow). In 3PG+ this approach does not handle early mortality in plantations well, so it has been modified to use a two-stage mortality function that has one form for early stand development and another form for older stands.

These differences in handling of mortality are important because they may lead to very different outcomes for the same stands. The fixed-mortality approach of $ALMANAC_{BF}$ forces mortality on a stand as a function of time. It assumes that the species-specific functions fit to observed minimum and maximum stem densities are not modified by the internal dynamics of stand development. In contrast, if growth near the self-thinning boundary is sufficiently low, 3PG+ should theoretically allow the stand to persist in a state of suspended animation, in which little to no mortality (or growth) may occur over

long periods. Although the approach of 3PG+ is more theoretically appealing, it may lead to a slower pace of mortality in this instance. In contrast, the approach of ALMANAC_{BF} may force mortality to occur more quickly than it does in natural stands for this scenario.

How ALMANAC_{BF} and 3PG+ deal with uncertainty and variability

Based on the available literature for both models, neither model appears to explicitly deal with parameter uncertainty. The ALMANAC_{BF} approach seems to focus on using relatively simple functional forms that are bounded by observed conditions, realising that the dynamics of the stand may depart somewhat from those conditions. In contrast, while 3PG+ sets boundary conditions for most of the processes being represented, the functional forms of the various processes are much more flexible. This has the benefit of perhaps mimicking reality more closely and allowing for greater flexibility in response, but it comes at the cost of greatly expanded uncertainties associated with interactions among processes and their parameterisations.

Although the fixed-trajectory approach adopted by ALMANAC_{BF} has its theoretical limitations, the sole comparison of ALMANAC_{BF} modelled outputs against empirical data suggests that it provides a reasonable point estimate of key structural characteristics of boreal forests across a range of site quality (Fig. A.1). As with all models there is a fundamental challenge in balancing the complexity of the model against its fidelity to the observed processes. ALMANAC_{BF} sacrifices complexity in its representation of key processes, for greater flexibility in representing species-interactions, whereas 3PG+ takes the opposite approach.

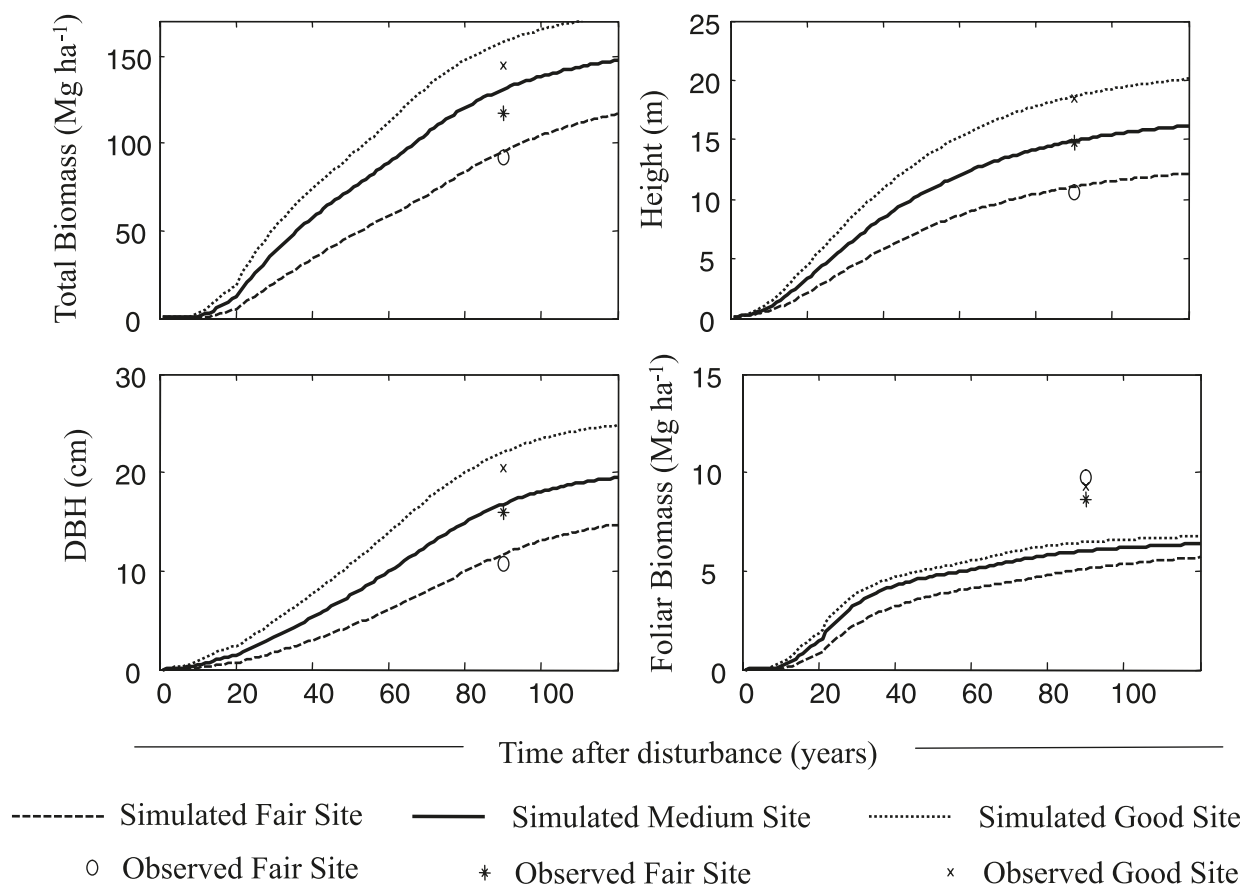


Figure A.1: ALMANAC: model outputs vs. observed data.