

**ASSESSMENT OF A PROCESS-BASED MODEL TO PREDICT
THE GROWTH AND YIELD OF *EUCALYPTUS GRANDIS*
PLANTATIONS IN SOUTH AFRICA**

by

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DECLARATION

I

I hereby certify that this research is the result of my own investigation, except as acknowledged herein, and that it has not been submitted for a higher degree in any other university.

A handwritten signature in blue ink, appearing to read 'L J Esprey', with a large, sweeping flourish underneath.

L J ESPREY

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ABSTRACT

It is believed that the process-based model 3-PG (Physiological Principles Predicting Growth; Landsberg and Waring, 1997) can potentially play a useful role within South African forestry, both as an operational and a strategic tool. Strategic applications may include the prediction of potential productivity on a site-by-site basis; broad-scale productivity estimates based on remote sensing and the spatial application of 3-PG; identification of production constraints; and estimation of carbon fluxes to help address sustainability issues. Operationally, 3-PG could complement empirically-based models or be used in conjunction with them as a hybridised product.

The challenges of this study were therefore to see whether it is possible to adapt 3-PG to predict the growth and yield of *E. grandis* under South African conditions, test that model predictions are consistent with observed growth data and are biologically reasonable, and to assess the practicality of using 3-PG as either a strategic or operational tool. The main emphasis of this study was to understand the internal logic of 3-PG and how physiological processes are represented, and to develop methods to objectively parameterise and initialise the model. Thereafter a detailed model validation study was performed, ending off with selected potential applications of 3-PG within the South African context.

The sensitivity of predicted stand volume (SV) and leaf area index (LAI) to the values of the species-specific parameters in 3-PG was examined. These analyses enabled the development of three distinct parameter sensitivity classes: insensitive parameters (*i.e.* those that can be varied widely without affecting the outputs studied), sensitive parameters (*i.e.* those whose value strongly affects the outputs), and non-linear parameters (*i.e.* those for which the outputs depend in a non-linear manner on the parameter value).

Minimum data requirements for the parameterisation and initialisation of 3-PG are considered in detail. Conventional methods used for the parameterisation of models, specifically 3-PG, are reflected upon. An automated parameter estimation technique was examined and used for the estimation of selected parameters. Species-specific parameters were categorised according to data source estimation and sensitivity

classes. Parameters describing allometric and age-dependent relationships were assigned values using observed data from biomass harvests. Critical parameters that could not be directly assigned using observed data were the ratio of foliage to stem allocation (*i.e.* p_2 and p_{20}), allocation of net primary production (NPP) to roots (η_{Rr} and η_{Rn}), optimum temperature for growth (T_{opt}) and maximum canopy quantum efficiency ($\alpha_{C\alpha}$). These were estimated using Parameter ESTimation, by fitting model output to corresponding observed growth data.

As well as species-specific parameter values, mandatory inputs required by 3-PG include weather data, site-specific factors such as site fertility (FR) and physical properties of the soils, and stand initialisation data. Objective techniques to determine these site-specific factors and the initial values for the biomass pools were proposed. Most of these data are readily available for sites where experimental trials exist, or where monitoring networks are in place. However, this is the exception rather than the rule, so alternative data and information sources are required. These, together with the need for accurate weather inputs (especially monthly rainfall) and physical properties (especially soil texture, maximum available soil water and FR) of the sites being modelled were explored.

3-PG was validated using four simple tests by comparing predicted *versus* observed SV. Results showed that 3-PG predictions are relatively consistent with observed stand data. Analyses performed using time-series data showed model predictions accurately tracked observed growth in response to erratic and fluctuating weather conditions. Results from the initial model validation showed production on high and low productivity sites was under- and over-predicted, respectively. Further results presented here show a similar, but less marked trend (*i.e.* over- and under-predictions are not as extreme), and individual biases are less than those from predictions made using another locally developed parameter set.

The application of 3-PG showed that the model is able to make estimates of tree growth that are consistent with those used within the forestry site classification. This showed the considerable potential 3-PG has for strategic planning by the forest industry (*i.e.* projected wood supplies *etc*) and in research planning (refining existing site classifications). The model could be useful in predicting growth in various areas

where *E. grandis* is not grown, assisting in future decision making. 3-PG was able to identify growth constraints on a site-by-site basis and distinguish among them, and was able to identify environmental and site limitations to plantation growth, and how they vary in space and time. These results together with predictions of site productivity demonstrate the potential for 3-PG to be used to improve existing forest site classifications. The model comparison study between empirically-based models and 3-PG showed that although the empirical models made accurate predictions of volume under static climatic conditions, under fluctuating weather conditions empirical estimates of volume were less accurate than those made with 3-PG. 3-PG can therefore be used operationally with minimum input data to predict growth using enumeration data. This is useful in saving time and cutting costs.

The use of process-based models (PBMs) in general, and 3-PG in particular, needs to be "*championed*" to the South African forest industry. This is necessary for two reasons. Firstly, the model and the manner with which it describes physiological processes of growth need to be explained in layman's terms. This will demonstrate how and why a process-based model can work better in a fluctuating environment than empirically based models. Secondly the comparison between 3-PG and the local empirical models needs to be presented as an example of how 3-PG can be applied on an operational basis. It is accepted that much convincing is still required.

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LIST OF SYMBOLS

P_2	Ratio of foliage:stem partitioning at DBH = 2 cm	-
P_{20}	Ratio of foliage:stem partitioning at DBH = 20 cm	-
a_S	Constant in stem mass <i>versus</i> diameter relationship	-
n_S	Power in stem mass <i>versus</i> diameter relationship	-
η_S	Stem partitioning ratio	-
η_F	Foliage partitioning ratio	-
η_{Rc}	Maximum fraction of NPP to roots	-
η_{Rn}	Minimum fraction of NPP to roots	-
γ_{F0}	Litterfall rate at $t = 0$	month ⁻¹
γ_{Fx}	Litterfall rate for mature stands	month ⁻¹
T_{min}	Minimum temperature for growth	°C
T_{opt}	Optimum temperature for growth	°C
T_{max}	Maximum temperature for growth	°C
f_{N0}	Value of f_N when FR = 0	-
k_D	Defines stomatal response to VPD	mbar
t_x	Maximum stand age used to compute relative age	yr
g_{Cx}	Maximum canopy conductance	m ² s ⁻¹
L_{Cx}	Canopy LAI for maximum canopy conductance	m ² m ⁻²
g_B	Canopy boundary layer conductance	m s ⁻¹
γ_{N0}	Seedling mortality rate ($t = 0$)	yr ⁻¹
γ_{N1}	Mortality rate for older stands (large t)	yr ⁻¹
σ_0	Specific leaf area at stand age 0	m ² kg ⁻¹
σ_1	Specific leaf area for mature aged stands	m ² kg ⁻¹
k	Extinction coefficient for PAR absorption by canopy	-
t_c	Age at full canopy cover	yr
α_{Cx}	Maximum canopy quantum efficiency	-
α_C	Modified canopy quantum efficiency	-
Y	Ratio NPP/GPP	-
P_{BB}	Branch and bark fraction	-
P_{BB0}	Branch and bark fraction at stand age 0	-
P_{BB1}	Branch and bark fraction for mature aged stands	-
P_{FS}	Foliage stem partitioning ratio	-
P_R	Percentage NPP allocated to root biomass	-
P_S	Percentage NPP allocated to stem biomass	-
t_{BP}	Age at which $P_{BB} = \frac{1}{2}(P_{BB0} + P_{BB1})$	yr
ρ	Average basic wood density	t m ⁻³
a_H	Constant in stem height relationship	-
n_{HB}	Power of mean DBH in stem height relationship	-
n_{HN}	Power of stocking in stem height relationship	-
a_V	Constant in stem volume relationship	-
n_{VB}	Power of DBH in stem volume relationship	-
n_{VN}	Power of stocking in stem volume relationship	-
f_{age}	Age modifier	-
f_D	Vapour pressure deficit modifier	-
f_θ	Soil water modifier	-
f_T	Temperature modifier	-
f_N	Nutrition modifier	-
ϕ	Physiological modifier	-
θ_S	Available soil water	mm
θ_{Si}	Initial available soil water	mm
θ_{Sx}	Maximum available soil water	mm
θ_{Sn}	Minimum available soil water	mm

T_{AV}	Monthly mean temperature	$^{\circ}\text{C}$
T_X	Monthly mean daily maximum temperature	$^{\circ}\text{C}$
T_N	Monthly mean daily minimum temperature	$^{\circ}\text{C}$
W_F	Foliage biomass	$\text{t}_{\text{DM}} \text{ha}^{-1}$
W_S	Stem biomass	$\text{t}_{\text{DM}} \text{ha}^{-1}$
w_S	Single tree biomass	kg tree^{-1}
W_R	Root biomass	$\text{t}_{\text{DM}} \text{ha}^{-1}$
W_{F1}	Initial foliage biomass	$\text{t}_{\text{DM}} \text{ha}^{-1}$
W_{S1}	Initial stem biomass	$\text{t}_{\text{DM}} \text{ha}^{-1}$
W_{R1}	Initial root biomass	$\text{t}_{\text{DM}} \text{ha}^{-1}$
p_{BB}	Branch and bark fraction	
X	A selected model output with respect to sensitivity analysis	
p	A selected model parameter with respect to sensitivity analysis	
δ_X, δ_p	This is the change δ_X in X produced by a change δ_p in p relative to the original values of X and p .	
$\lambda_1(X, p)$	Relative sensitivity of a specific model output with respect to a specific parameter on a per site basis	
$\lambda_2(X, p)$	Relative non-linearity of a specific model output with respect to a specific parameter on a per site basis	
μ_1	Mean sensitivity across all sites	
μ_2	Mean non-linearity across all sites	
$(\mu_1 \times E)$	Environmental or between-site variation	
I	Flux density below canopy	
I_0	Flux density above canopy	
β_0 to β_5	Coefficients used in empirical models	

LIST OF ABBREVIATIONS AND ACRONYMS

3-PG	Physiological Principles in Predicting Growth	
3-PG _{PJS}	Excel-based version of 3-PG developed by Dr Peter Sands	
3-PGS	Spatial version of 3-PG	
ANOVA	Analysis of variance	
CRC-SPF	Co-operative Research Centre for Sustainable Production Forestry	
CSIR	Council for Scientific and Industrial Research	
CSIRO	Commonwealth Scientific and Industrial Research Organisation	
ICFR	Institute for Commercial Forestry Research	
IFP	Innovation Fund Project	
AWC	Available water capacity	mm m ⁻¹
B	Data source class: Biomass harvest	-
BA	Basal area	m ² ha ⁻¹
C	Carbon	
CAI	Current annual increment	m ³ ha ⁻¹ y ⁻¹
CEC	Cation exchange capacity	-
C-J	Clutter Jones mortality function	-
D	Estimation class: Default	-
DBH	Diameter at breast height	cm
dHT	Dominant height	m
E	Estimation class: Estimation	-
EBM	Empirically-based model	-
Emp _{SA}	Locally developed empirical model	-
Emp _{SA} ^{first}	Empirical model initialised using first inventory observations (2-4 years)	-
Emp _{SA} ^{enum}	Empirical model initialised using enumeration data (4-6 years)	-
ET	Evapo-transpiration	mm
F	Data source class: Field data	-
FC	Field capacity	mm m ⁻¹
FR	Site fertility rating	-
FSC	Forestry site classification	-
GC	<i>E. grandis</i> x <i>camaldulensis</i>	-
GE	Growth efficiency, light, or radiation use efficiency	g MJ ⁻¹
GPP	Gross primary production	t _{DM} ha ⁻¹
GW	Groundwater	-
GW (1)	Full groundwater access is activated	-
GW (2)	Groundwater access permitted only during periods of water stress.	-
GU	<i>E. grandis</i> x <i>urophylla</i>	-
G&Y	Growth and yield	-
H	Sensitivity: High	-
HT	Mean tree height	m
K	Potassium	-
L	Sensitivity: Low	-
L	Data source class: Literature	-
LAI	Leaf area index	m ² m ⁻²
M	Data source class: Mensuration	-
M	Sensitivity: Medium	-
MAI	Mean annual increment	m ³ ha ⁻¹ y ⁻¹
MAI _x	Peak mean annual increment	m ³ ha ⁻¹ y ⁻¹
MAI _x ^{range}	Range in peak mean annual increment	-
MAI _x ^{age}	Stand age at which MAI peaked	-
MAP	Mean annual precipitation	mm
MAT	Mean annual temperature	°C
MMRC	Modelling mensuration research consortium	
N	Nitrogen	-
NPP	Net primary production	t _{DM} ha ⁻¹

O	Estimation class: Observed	-
OBD	Over-bark diameter	cm
P	Data source class: Physiological	-
PAI	Plant area index	$\text{m}^2 \text{m}^{-2}$
PAR	Photosynthetically active radiation	$\text{MJ m}^{-2} \text{d}^{-1}$
PEST	Parameter ESTimation	-
PEST_{XL}	Excel version of PEST	-
PBM	Process-based model	-
pFs	Foliage: stem partitioning ratio	-
PSP	Permanent sample plot	-
qDBH	Quadratic mean diameter	cm
R	Monthly rainfall	mm month^{-1}
RMSE	Statistic root mean square error	-
RMSE_U	Unsystematic RMSE	-
RMSE_S	Systematic RMSE	-
SC	Soil class comprising c, cl, s, sl (clay, clay-loam, sand, sand-;loam)	-
S-H	Schumaker-Hall volume equation	-
SLA	Specific leaf area	$\text{m}^2 \text{kg}^{-1}$
SSP	Site-species productivity trials	-
SI	Site index	m
SI₅	Mean tree height of top 20% trees at five years	m
SR	Solar radiation	$\text{MJ m}^{-2} \text{d}^{-1}$
SPH	Stems per hectare	trees ha^{-1}
SPHi	Initial stems per hectare	trees ha^{-1}
SV	Stand volume	$\text{m}^3 \text{ha}^{-1}$
V	Stem volume	$\text{m}^3 \text{tree}^{-1}$
VPD	Vapour pressure deficit	mbar
WP	Wilting point	mm m^{-1}

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CHAPTER 1

INTRODUCTION

1.1 GROWTH AND YIELD MODELLING IN FORESTRY: AN OVERVIEW

The type of information required by forest managers and planners to make important decisions is becoming increasingly complex and presents a new challenge to these managers. This together with the ability to understand tree growth dynamics and to make reasonable predictions of growth and site productivity underpins sustainable forest management (Louw, 2003). Such knowledge can be gained through the use of process-based models (PBMs) that will provide new solutions to these complex problems. However, these models are a relatively new concept and have not yet been widely accepted in South Africa. Empirical models on the other hand are currently used to aid in such decisions.

Empirically based growth and yield (G&Y) models are central to plantation management and planning (Vanclay, 1994; Korzukhin *et al.*, 1996; Mäkelä *et al.*, 2000; Johnsen *et al.*, 2001). In general estimates of plantation G&Y and forecasts of stand inventory have traditionally been obtained through the use of statistically derived or empirically based stand-level models. Such methods provide acceptable predictions but lack generality in that they are limited to regions and management scenarios for which they were originally developed. Furthermore, these conventional methods cannot respond to dynamic changes in the environment, especially with respect to predicting growth in response to fluctuating weather patterns and the impacts of implementing site-specific management. Another approach to forest ecosystem management is process-based modelling which allows the detailed description of the various components in the ecosystem to be defined and modelled (Korzukhin *et al.*, 1996; Landsberg and Waring, 1997), along with their interaction with the environment. Until recently, these models have not been widely adopted as management tools due to the complex nature of the required input information. However, the last few years have seen

the development and more widespread application of PBMs specifically developed as part of forest management strategies.

Process-based forest growth models range in resolution, complexity, generality and applicability (Battaglia and Sands, 1998a) from highly detailed models embracing many processes to quite simple models developed primarily to calculate forest productivity. Generally, the structure (*i.e.* spatial and temporal resolution, physiological detail, and the nature of the input data and model outputs) of PBMs is largely related to the intended use of the model (Stapper, 1986; Sands, 1988). Highly parameterised models describing physiological processes in great detail are often used purely as research tools to understand the cause and effect of changes in the system. The development of such complex models requires theoretical and applied research spanning several years, and the models do not directly address questions of interest to forest managers. CABALA is a possible exception to the lack of application amongst this class of model (Battaglia *et al.*, 2004). Consequently, much simpler PBM's have been developed, *e.g.* 3-PG (Physiological Principles Predicting Growth; Landsberg and Waring, 1997) and PROMOD (Battaglia and Sands, 1997). Each of these has been used to complement traditional forest management tools by various agencies (research, government, commercial forestry and private consultants, especially in Australia) for diagnostic services, decision making and economic analysis (Sands, 2003).

The books authored by Landsberg (1986), and Landsberg and Gower (1997) provide a detailed overview of physiological knowledge and understanding of processes involved in tree growth, cover aspects of modelling tree growth, and the application of ecosystem process models to forest management. Detailed appraisals surrounding the role of PBMs in forest management are covered by Battaglia and Sands (1998a) and Mäkelä *et al.*, (2000). Publications specific to the development and description of the 3-PG model include those written by Landsberg and Waring (1997); Sands and Landsberg (2002) and Landsberg *et al.* (2003). Later chapters provide a more in depth review of relevant literature.

1.2 BACKGROUND TO CURRENT RESEARCH

3-PG is a relatively simple PBM requiring easily obtained input data and species-specific parameter values. The model calculates total carbon (C) produced from photosynthetically active radiation (PAR) intercepted by the canopy of the plantation whilst simultaneously accounting for temperature, water, vapour pressure deficits and nutritional constraints on tree growth. 3-PG was initially developed with the end user (forester and plantation manager) in mind and is accompanied by extensive documentation and a user manual which are freely available, as is the model code. The main reasons for the success of 3-PG are that firstly, the model and code are freely available on the internet and secondly, being a simple model its use was promoted. The model has been extensively used in countries other than its country of development and tested on a wide range of eucalypt and pine species. These countries include Australia, Canada, Great Britain, Brazil, Chile, Vietnam, China, New Zealand and South Africa (e.g. Almeida *et al.*, 2003; Coops and Waring, 2001a; Dye, 2001; Dye *et al.*, 2004; Landsberg *et al.*, 2001; Sands and Landsberg, 2002; Waring, 2000). The potential and usefulness of 3-PG has been shown at Aracruz Celulose, Brazil where it is currently being implemented as the central component of a new GIS-based management system (Almeida *et al.*, 2003; Almeida *et al.*, 2004a). Locally, besides the testing within the Institute for Commercial Forestry Research (ICFR), 3-PG is also being implemented as a forest management tool through the South African Government Innovation Fund Project (NRF, 2002).

Based on these facts it is envisaged that 3-PG is a potentially useful tool for strategic (e.g. potential site productivity, growth constraints *etc.*) and operational (e.g. growth prediction and projection) applications. The main challenges are therefore: (i) to see whether it is possible to adapt 3-PG to predict growth and yield of *Eucalyptus grandis* under South African conditions; (ii) to check that model predictions are biologically reasonable and accurate; and (iii) to compare predictions of stand volume with those made using locally developed empirical models. With these problems in mind, the following project objectives were formulated:

- Identify species-specific parameters in the model that need to be accurately determined;
- Develop standard techniques to parameterise and initialise 3-PG;
- Evaluate the predictive ability of 3-PG and test whether predictions are biologically realistic;
- Consider several strategic and operational applications of 3-PG for use in South Africa.

The aim of this project is to assess whether 3-PG is a useful tool for understanding tree growth dynamics, to interpret between-site productivity differences, to identify constraints which limit growth and how these change seasonally, and assess whether it can be used to complement empirical models, and aid in forest planning and scheduling harvest operations.

1.3. THESIS STRUCTURE

The thesis comprises eight chapters. An assessment of existing process-based G&Y models is carried out in Chapter 2, followed by a comparison of several PBMs and justification for the selection of the 3-PG model. A brief description of 3-PG is presented. For the unfamiliar reader, the publication by Sands and Landsberg (2002) is included in the Appendix. Using a preliminary set of parameters for *E. grandis*, the performance of 3-PG is evaluated. This evaluation of the model performance is preliminary and is expanded upon in later chapters.

A sensitivity analysis of model outputs with respect to changes in model parameters is presented in Chapter 3. This analysis helped in the understanding of tree growth dynamics and how complicated physiological processes have been simplified and depicted within the 3-PG model. Parameters that must be accurately determined if 3-PG is to make accurate predictions of tree growth are also identified. Guidelines necessary for the parameterisation of 3-PG were developed in Chapter 4. Issues surrounding data availability, parameter estimation techniques and the parameterisation of 3-PG for *E. grandis* are also covered in Chapter 4.

The use of inadequate weather data, site factors and stand data for initialising the model are explored in Chapter 5. Methods to assign values to the site fertility rating (FR) are investigated, and techniques to initialise 3-PG are developed. These techniques are based on the availability of observed inventory data.

Using the parameter set developed for *E. grandis* and the methods developed to initialise 3-PG, a detailed model validation is presented in Chapter 6. The validation is performed using data distinct from those used in the parameterisation, and the biological realism of predictions is examined. Model predictions in response to fluctuating weather conditions are also tested.

Chapter 7 looks at some strategic and operational applications within the South African context. A comparison between 3-PG and locally developed empirical models is included.

Chapter 8 is the final discussion and conclusion in which an overview of preceding chapters is presented.

1.4 GROWTH AND YIELD MODELLING TERMINOLOGY

An explanation of some common terminology and abbreviations used throughout this thesis are summarised below.

3-PG (Physiological Principles Predicting Growth; Landsberg and Waring, 1997) is the PBM used in this research.

3PGPJS is the implementation of 3-PG as a Microsoft Excel workbook that supplies all 3-PG input data and to which results are written, and an Excel add-in containing the 3PGPJS and 3-PG code.

Model parameters are constants in equations and in the case of 3-PG they are species and site-specific. With respect to empirical models the parameters referred to here are called model coefficients.

Model inputs, also known as driving variables, refer to inputs such as temperature, rainfall, vapour pressure deficit and solar radiation.

State variables refer to model components whose values are predicted over time and they characterise the condition of the system being modelled. The foliage, root and stem biomass, and the soil water content make up the state variables in 3-PG.

Empirically-based models (EBMs) are statistically based and developed using observed tree growth data, with the emphasis on statistical relationships rather than physical ones (Jeffers, 1988).

Process-based models (PBMs) are defined as a representation of a system and their behaviour at various levels of complexity (Landsberg, 1986; Landsberg, 2003), describing levels of organisation and processes in terms of mechanisms (Sands, 1988) underlying the responses of the system under study to changes in environmental factors or management interventions (Landsberg and Gower, 1997).

Model validation/verification, and *model parameterisation/calibration* are pairs of terms that are used interchangeably in modelling literature. Sections 6.1.1 and 6.1.2 are therefore dedicated to these terms where they are defined and elaborated upon in a great deal of detail.

CHAPTER 2

FOREST GROWTH AND YIELD MODELS

2.1 INTRODUCTION

A “*model*” describes any system comprising a collection of interrelated objects, which themselves are elemental units upon which observations can be made (Haefner, 1996). More specifically Landsberg (1986) defines models as “*formal and precise statements, or set of statements, embodying our current knowledge or hypothesis about the workings of a particular system and its responses to stimuli*”. Models have been classified according to the types of relationships depicted (Stapper, 1986; Sands, 1988), the level of detail incorporated (Vanclay, 1994; Gadow and Hui, 2001), the internal structure and type of problem to be solved (Haefner, 1996), and intended model users (Landsberg, 2003). In a similar fashion to Landsberg (1986), Haefner (1996) places models in a conceptual, diagrammatic and mathematical framework, with the latter used to make quantitative predictions surrounding the behaviour of the system. From the perspective of forestry and forest management, such mathematical representations of a system are generally classified as: empirical models (whole stand, size class or single tree models) used to predict growth and yield (G&Y) of plantations; process models used to predict patterns of growth as a function of weather inputs and physiological processes (Korzukhin *et al.*, 1996); hybrid simulation approaches, which are a combination of the latter two model types (Kimmins *et al.*, 1990); and succession models used to simulate species succession (Vanclay, 1994). Hybrid and succession models are beyond the scope of this study and will not be discussed further.

Empirically-based models (EBMs), or traditional G&Y models, as they are often called, are statistically based and developed using observed tree growth data, with the emphasis on statistical relationships rather than physical ones (Jeffers, 1988). Empirical models describe tree growth in relation to age, site index (SI) and other easily observed variables or stand treatments (Ek *et al.*, 2003). As long as the conditions under which these models are applied are similar to those under which the basic data were collected, these models are robust tools for the prediction of future yield (Mohren and Burkhardt,

1994; Corona *et al.*, 2002). However, they are not generic across all sites, are not dynamic, and lack flexibility especially with respect to predicting growth in response to fluctuating weather patterns and the impacts of site-specific management. In particular, statistical models cannot provide “*more knowledge about a system than is contained in the data and even the most cunning manipulation will not extract additional information from the data sets*” (Landsberg, 1986). Despite these disadvantages, EBMs are very widely used, and from the point of view of the forest manager they are simple and practical tools. For instance, stand level empirical models are used for planning, estimating timber volumes and tree size distribution, organising harvest scheduling and optimising timber supplies to mills (Almeida, 2003), and in South Africa they are extensively used in the forecasting of stand inventory. The books by Vanclay (1994) and Landsberg and Gower (1997) have very good overviews of methods for the modelling of forest G&Y. Empirically-based models are elucidated upon further in Section 7.4 where a comparison of growth predictions between empirical and process models is presented.

2.2 PROCESS-BASED MODELS

Process-based models (PBMs), on the other hand, have the potential to be far more flexible than empirical relationships, and can be used in the heuristic sense to understand the workings of a system and the response thereof to stimuli (*i.e.* forest management; Landsberg and Gower, 1997). Bossel (1991) has described PBMs as explanatory, in contrast to EBMs which are descriptive by nature. Furthermore, Bunnell (1989), cited by Vanclay (1994), distinguishes between models for prediction (empirical) and models for understanding (process-based). In light of these statements a PBM can be defined as a representation of a system and its behaviour at various levels of complexity (Landsberg, 1986; Landsberg, 2003), describing levels of organisation and processes in terms of mechanisms (Sands, 1988) underlying the responses to change of the system under study (Landsberg and Gower, 1997).

Effects of environmental factors on plantation distribution, canopy structure, biomass relationships and physiological processes are well documented. This knowledge of processes has, in the past two decades, led to the development of more mechanistic

forest growth models designed to couple water, C and nutrient cycles (Waring, 2000). There are two families of mechanistic models: “*bottom-up*” and “*top-down*” models. The bottom-up type of model is essentially a research tool which simulates growth using the actions and interactions of the physiological processes contributing to it (Landsberg, 1986). In contrast, top-down models use simplifications and assumptions to account for complex physiological processes and the response thereof to one or more of the driving variables. Such top-down models make up a full spectrum of forest PBMs ranging in resolution, complexity, generality and applicability (Battaglia and Sands, 1998a). Central to these models are common elements linking the atmosphere, vegetation and soils (Waring, 2000). Climatic variables and factors describing the site and initial state of the vegetation are required to drive the models. Such models were primarily developed to calculate forest productivity (Landsberg and Waring, 1997), but are also used as research and management tools (Johnsen *et al.*, 2001). Figure 2.1 is a schematic representation of a mechanistic model of tree growth. The different physiological/physical processes may vary in complexity and would be represented as sub-models or routines.

The structure (*i.e.* spatial and temporal resolution, physiological detail, and the nature of the input data and model outputs) of PBMs is largely related to the intended use of the model (Stapper, 1986; Sands, 1988). Many highly parameterised models describing physiological processes in great detail are used purely as research tools to understand the cause and effect of changes in the system. The development of such complex models requires theoretical and applied research spanning several years, and often these models do not directly address questions of interest to forest managers.

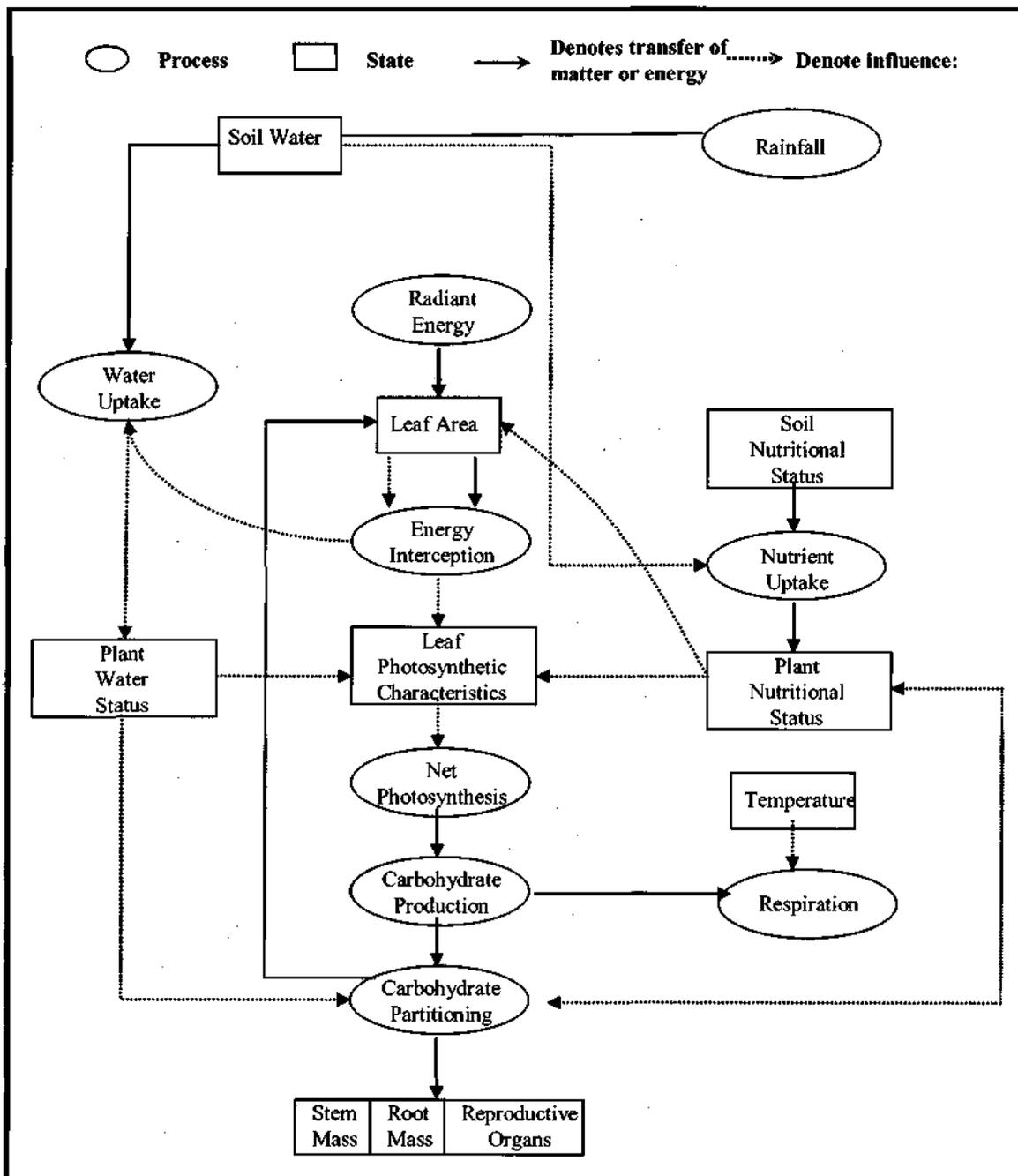


Figure 2.1. Schematic representation of detailed mechanistic model of tree growth (Landsberg, 1986).

Recently developed, simpler models capture the essential components of the system and allow for the quantification of system fluxes over a range of conditions. Required parameters are easily measurable either directly or indirectly. Such models are used as both research and management tools (Johnsen *et al.*, 2001) and therefore assist decision-making. In a bench-mark publication, Battaglia and Sands (1998a) discuss the potential

usefulness of these models in forest management as follows: (1) the prediction of G&Y from existing plantations; (2) selection of plantation sites or site-specific species; (3) identification of site limitations to productivity; (4) risk assessment, and (5) answers to questions for which “*real time*” experiments are not feasible, such as long-term impacts of climatic change on plantation production. Examples of simple PBMs include 3-PG (Physiological Principles Predicting Growth; Landsberg and Waring, 1997), ProMod (Battaglia and Sands, 1997) and Cabala (Battaglia *et al.*, 2004). Each of these has been used to complement traditional forest management tools by various agencies (research, government, commercial forestry and private consultants) and also, especially in Australia, for diagnostic services, decision making and economic analysis. (Sands, 2003).

Many PBMs have not been implemented as management tools by the forest industry because they were developed as research tools. Such models are complex, difficult to parameterise and not easy to validate. Furthermore, these models do not address questions of interest to forest managers, their implementation and documentation are incompatible with the needs of the manager, and model development usually takes too long (Sands *et al.*, 2000). Sands (1988) laid out the following guidelines which enhance the probability of the model being used by those other than the model developer: the model (i) is constructed in collaboration with intended end users; (ii) has a simple transparent structure; (iii) is simple to operate and appropriately documented; (iv) uses readily available input data; and (v) is supported by expert advice and services. Similarly, Landsberg (2003) proposed that operational models (used by forest managers), need to be scientifically sound and relatively simple with few input parameters. The primary aim of such models is to produce information needed by managers, and they must be easy to calibrate and test against readily available data. With these points in mind, models developed in the past decade are simpler, easier to operate and are therefore more practical tools (for example ProMod (Battaglia and Sands, 1997) and 3-PG (Landsberg and Waring (1997))).

2.2.1 Overview of existing process-based models

The most appropriate model to meet the project objectives was sought (Chapter 1). The model needs to be simple, yet physiologically sound and able to determine plantation growth, yield and water use. Furthermore, the model should exhibit flexibility allowing modifications to be easily made. Current PBMs were reviewed and inspected with respect to two sets of criteria defined below.

An overview of models ranging in resolution (spatial and temporal scale), complexity (environmental variables and processes reflected in model) and generality (situations and systems to which model can be applied) are presented in Table 2.1. The models are categorised in terms of intended model users and grouped according to the forest industry, broader public community, and academic and scientific communities (Landsberg, 2003). Forest industries include individuals and organisations concerned with the management of plantations, the broader public community related to community groups and politicians (both regional and local governments), and academic communities consisting of research institutions. Generally speaking, the models developed for research and public use are complex and operate on smaller temporal and spatial scales than those developed specifically as forest industry management tools. It is therefore reasonable to say that models developed primarily for either research or public-related purposes would be of limited use in this project.

Table 2.1. Tabulation of models reviewed showing the intended users (R= Research, P= Broader public community and I= Forest industry. Abbreviations are as follows: net primary production (NPP, $t_{DM} \text{ ha}^{-1}$); gross primary production (GPP, $t_{DM} \text{ ha}^{-1}$); leaf area index (LAI, $\text{m}^2 \text{ m}^{-2}$), diameter at breast height (DBH, cm) and mean annual increment (MAI, $\text{m}^3 \text{ ha}^{-1} \text{ y}^{-1}$); stand volume (SV, $\text{m}^3 \text{ ha}^{-1} \text{ y}^{-1}$), nitrogen (N), and carbon (C).

Model	Intended user	Brief model overview	References
CENTURY Parton <i>et al.</i> (1987)	P	Monthly time-step, simple procedures to handle plant growth, soil organic matter dynamics in response to climate and management. Inputs: soil texture / depth, rainfall and temperature, vegetation types and CO ₂ levels. Outputs: C and N fluxes, NPP and soil organic matter.	Landsberg and Gower (1997); Gabele (1998)
Mäkelä & Hari model Mäkelä and Hari (1986)	I	Hybrid model developed for <i>Pinus sylvestris</i> , simulates stand growth and competition between trees focusing on needle biomass and canopy closure.	Landsberg (2003)
ForGro Mohren (1987)	R	Daily time-step, detailed C-balance model, includes photosynthesis, respiration, phenology, hydrology (detailed and partly empirical), nutrient cycling (mechanistic), forest growth (detailed and partly empirical), and forest structure development. Inputs: tree physiology, site characteristics, stand structure. Outputs: potential growth in managed forests.	Titak and Grisven (1995); Gabele (1997)
FOREST-BGC Running and Coughlan (1988)	I, P	Daily and annual time-step, can be linked to remote sensing systems, simulates the flow of water, C and N, complete stand water balances (canopy interception, evaporation, transpiration, drainage). Inputs: temperature, radiation and rainfall. Outputs: C balance, photosynthesis, respiration, above and below ground NPP, litterfall, decomposition and LAI.	Running and Coughlan (1988); Landsberg and Gower (1997); Hoff <i>et al.</i> (2002); Landsberg (2003)
BIOMASS McMurtrie <i>et al.</i> (1990)	R	Daily time-step, C balance model, describes radiation absorption, canopy photosynthesis, allocation of photosynthate, litterfall and stand water balance. Inputs: LAI, temperature, humidity, radiation and rainfall, vegetation. Outputs: C, water and nutrient fluxes, NPP and yield.	Landsberg and Gower (1997); Bergh <i>et al.</i> (1998); McMurtrie <i>et al.</i> (1990)
Bex Bonan (1991)	R	Daily time-step, simulates fluxes of C, water and C in boreal forests. Inputs: averages of temperature, humidity, air pressure, wind speed, cloudiness, 27 physiological parameters. Outputs: above ground NPP.	Landsberg and Gower (1997)
MAESTRO Wang and Jarvis (1990)	R	Daily / seasonal time-steps, determines photosynthesis and transpiration for individual trees, effects of climate and canopy architecture on canopy photosynthesis. Great detail of input data and parameters required.	Landsberg and Gower (1997); Sonntag (1997a); Medlyn (2001); Landsberg (2003)

Model	Intended user	Brief model overview	References
FORCYTE Kimmins <i>et al.</i> (1990)	I	Intended to be of value for forest managers; immensely complicated. Inputs: very detailed. Outputs: impact of harvesting and fire. FORCYTE II determines stand yield prediction and long term impacts of management on site productivity.	Kimmins <i>et al.</i> (1990); Landsberg (2003)
TreeGro Weinstein <i>et al.</i> (1991)	P	Hourly time-step, explicit representation of photosynthesis processes, predicts growth and patterns of C allocation expected for an isolated tree exposed to various levels of ozone, nutrient stress, and water availability.	Titak and Grisven (1995); Sonntag (1997b)
G'DAY Comins and McMurtrie (1993)	P	Annual time-step, describes how photosynthesis and nutritional factors interact in determining the productivity of forests growing under N-limited conditions, insights into relationships between N and atmospheric CO ₂ .	Sonntag (1997c); Landsberg (2003)
TREENYD3 Bossel (1996)	R	Daily, weekly or annual time-step, simulates tree growth, C and N dynamics. Inputs: photosynthesis, respiration, climatic data (air temperature, radiation); Outputs: height, DBH, leaf biomass, number of trees.	Sonntag (1997d)
3-PG Landsberg and Waring (1997)	I, P, R	Monthly time-step, dynamic in that stand and canopy development predicted. Inputs: soil water capacity, texture and fertility ranking, monthly climatic data, stand initialisation values. Latitude. Outputs: dynamic variation of LAI, DBH, SV, other outputs of use to forest managers.	Landsberg and Waring (1997); Sands (2000); Sands and Landsberg (2002); Landsberg <i>et al.</i> (2001); Landsberg (2003)
ProMod Battaglia and Sands (1997)	I, P	Daily and monthly time-step, range outputs relevant to management scenarios. Inputs: soil water capacity, soil factors, latitude, daily or monthly climatic data. Outputs: peak MAI and canopy LAI, water use and limiting factors, NPP.	Battaglia and Sands (1997); Sands <i>et al.</i> (1999); Landsberg <i>et al.</i> (2001)
HYBRID Friend <i>et al.</i> (1997)	R	Daily / annual time-step, part of gap family of models, predicts impact of climate change in terms of GPP, NPP, soil respiration, latent heat flux, C biomass and maximum LAI, regeneration and mortality of individual trees that differ in age and size.	Sonntag (1997e); Landsberg (2003)
CenW Kirschbaum (1999)	R	Daily time-step, links flows of C, energy, nutrients and water in trees and soil organic matter; C gain simulated considering physiological factors, biomass pools, site factors, and soil organic matter; simulates the effects of silvicultural treatments	Kirschbaum (1999); Landsberg (2003)
CABALA Battaglia <i>et al.</i> (2004)	I, P, R	Daily and monthly time-step; provides silvicultural decision support for managers. Inputs: daily or monthly weather data, soil factors, tree spacing. Outputs: SV, LAI	Battaglia <i>et al.</i> (2004)
TRIPLEX Peng <i>et al.</i> (2002)	P	Hybrid monthly time-step model of forest growth and C dynamics; Integrates 3-PG, TREENYD3 and CENTURY; used for G&Y prediction; quantifying C budgets, climate change.	Peng <i>et al.</i> (2002)

Consequently the Mäkelä and Hari model (Mäkelä and Hari, 1986), Forest-BGC (Running and Coughlan, 1988), Forcyte (Kimmins *et al.*, 1990), 3-PG (Landsberg and Waring, 1997), ProMod (Battaglia and Sands, 1997) and CenW (Kirschbaum, 1999) models appeared to be acceptable choices. A more detailed critique was performed based on the following criteria aligned with those presented in Sands (1988):

- Intended model user;
- Forest management tool;
- Ability to simulate water use;
- Should preferably operate on a monthly time-step (daily time-step increases model complexity and the number of parameters required by the model);
- Easy to use, with a transparent structure and simple input data and parameters;
- Tested and evaluated on pine and eucalypt stands (as opposed to boreal forests).

Models satisfying these criteria were further subjected to a second set of criteria:

- Model used in countries other to the one in which it was developed (*i.e.* a measure of its popularity);
- Source code is freely available with adequate, scientifically-based and easy to understand documentation;
- User support is available;
- Model was developed in collaboration with intended end users.

Of the 17 models rigorously scrutinised only four (ProMod, CABALA, TRIPLEX and 3-PG) have been tested on eucalypt species. As expected, the remainder of the models comprise those predominantly developed for research purposes and of limited value to this project. Despite the simple input data mandatory to the operation of ProMod and CABALA, and the representation of detailed physiological processes and silvicultural regimes depicted, an inherent shortcoming of these models is that they are parameter intensive. TRIPLEX, on the other hand, shows some promise since the strengths of

three different models (of which two are complex models) is exploited. This is achieved by integrating the forest production model of 3-PG, G&Y model of TREENYD3 and the soil-carbon-nitrogen model of CENTURY which is highly complex to parameterise. However, TRIPLEX is of limited value as it has been specifically developed to simulate climate change scenarios (although it can also predict G&Y) and in addition has only been tested in Canadian boreal pine forests.

Of all these models, only 3-PG has been extensively used in countries other than its country of development and tested on a wide range of eucalypt and pine species. These countries include Australia, Canada, Great Britain, Brazil, Vietnam, China, New Zealand and South Africa (e.g. Almeida *et al.*, 2003; Coops and Waring, 2001a; Dye, 2001; Dye *et al.*, 2004; Landsberg *et al.*, 2001; Sands and Landsberg, 2002; Waring, 2000). Moreover, not only was 3-PG developed with the end user in mind, but extensive documentation and a user manual are freely available, as is the model code. A good foundation for communication exists between the Institute for Commercial Forestry Research (ICFR)/Council for Scientific and Industrial Research (CSIR) and Dr J. Landsberg (original developer of 3-PG), and with Dr P. Sands of the Commonwealth Scientific and Industrial Research Organisation/Co-operative Research Centre for Sustainable Production Forestry (CSIRO/CRC-SPF) with which the ICFR has a formal collaborative agreement. The main reasons for the success of 3-PG are that firstly, the model and code were made freely available on the internet (<http://www.ffp.csiro.au/fap/3pg/index.htm>), and secondly, the fact that it is a simple model encourages its use. This, in turn has encouraged model users to give feedback to its developers who in response have made appropriate corrections and additions. For these reasons 3-PG has gone through many transformations with a beta version 2.4 having been released in May 2004 (Sands, 2004b). It was therefore decided that the 3-PG model could be used to fulfil the objectives of this project.

2.3 THE 3-PG MODEL

3-PG (Landsberg and Waring, 1997) is a “*simple*” PBM of forest growth based on a number of well-established principles and requires as inputs, parameter values and readily available data. It is claimed that the model is generic and should not be site-

specific, but it does need to be parameterised for individual species and is applicable only to plantations of even aged trees (Landsberg *et al.*, 2003). It was explicitly developed to bridge the gap between conventional empirical, mensuration-based G&Y models, and process-based C balance models (Landsberg and Waring, 1997). Sands (2004a) has reported that 3-PG “*appears to be the de facto PBM for use as a forest management tool, not because it is technically superior to other models, but because (a) it is simple, and (b) it is freely available*”. As such 3-PG has been widely applied to various species within several forest/plantation types across a range of climate regions.

Since the initial publication of 3-PG (Landsberg and Waring 1997), several structural modifications have been made, and the manner in which various relationships between parameters are depicted has been changed to make the parameters more intuitively meaningful (Sands and Landsberg, 2002). 3-PG has been implemented as a Microsoft workbook (3PGpjs) that supplies all 3-PG input data and to which results are written, and an Excel add-in containing the 3PGpjs and 3-PG code. The input spreadsheets facilitate easy modification of site and climatic data, parameter values and run-time options. Guidelines to parameterise the model were developed (see Sections 4.2.1 and 4.2.2) and further model updates and modifications were made and included in 3PGpjs version 2.4 (Sands, 2004b). These include a mortality function (described as a probability of death function), improvements in the prediction of SV and the prediction of mean tree height (HT, m). The improved mortality function assumes a small probability that any tree will die, which generally depends on stand conditions, stand age, or climatic or other stress factors. Both SV and HT are based on an allometric relationship with either the mean DBH or the quadratic mean DBH (qDBH, cm) and stocking or stems per hectare (SPH, stems ha⁻¹). The qDBH refers to the diameter of the tree of mean basal area (BA, m² ha⁻¹) and is a stand attribute. The DBH on the other hand pertains to individual trees. For the purpose of this work these allometric relationships are parameterised with respect to the qDBH.

To date, there has been a total of 31 publications in peer-reviewed journals concerning the application of 3-PG, in one form or the other. The potential and usefulness of 3-PG has been shown at Aracruz Celulose, Brazil where it is currently being implemented as

the central component of a new GIS-based management system (Almeida *et al.*, 2003; Almeida *et al.*, 2004a; Almeida *et al.*, 2004b). 3-PG is also being evaluated as a forest management tool in South Africa to predict the productivity of several commercially important species (NRF, 2002). Locally, the model has also been used to predict growth and water use of *Pinus patula* (Dye, 2001) and *Eucalyptus* plantations (Dye *et al.*, 2004). Other benchmark studies include spatial applications of 3-PG using remotely sensed inputs and GIS (Coops *et al.*, 1998, Coops *et al.*, 2001; Coops and Waring, 2001a, Coops and Waring, 2001b; Tickle *et al.*, 2001 and White *et al.*, 2000). Sands and Landsberg (2002) present a methodology detailing the parameterisation of the model. This has been updated (Sands, 2004a) following the linking of the Parameter ESTimation (PEST) software with 3PGpjs (see Sections 4.2.2 and 4.3.2). Rigorous model validations have been performed using experimental data in Australia, New Zealand, Britain, USA, South Africa and Sweden (Landsberg *et al.*, 2001; Landsberg *et al.*, 2003). The comparison between 3-PG and a classical empirical approach for predicting stand G&Y has also been carried out in Brazil (Stape *et al.*, 2004).

2.3.1 Model inputs and outputs

Mandatory inputs required by 3-PG include weather data, site factors, a description of the initial conditions (Table 2.2) and species-specific parameters (Table 2.3). Weather inputs (see Sections 5.1, 5.2 and 5.4) required by 3-PG are monthly average values of daily solar radiation (SR, MJ m⁻² d⁻¹), monthly mean temperature (T_{AV} , °C) separated into monthly mean daily maximum and minimum temperature (T_X and T_N , °C), vapour pressure deficit (VPD, mbar), total monthly rainfall (R, mm month⁻¹) and frost days per month. The model can be run for any number of years, using actual monthly weather data or long-term monthly averages. Using historical long-term averages is the normal procedure unless there is particular interest in specific events, such as droughts (Landsberg *et al.*, 2003). In this case 3-PG can account for changing and fluctuating growth patterns as a result of climatic variability. This makes 3-PG a powerful tool, allowing the user to set up various scenarios to ask “*what if*” questions (see Sections 6.4.4, 7.2 and 7.3).

Table 2.2. Mandatory inputs of weather data, site factors and initial stand conditions required by 3-PG.

Inputs	Type of input	Units	Description
Weather data	Temperature (T_x, T_N)	$^{\circ}\text{C}$	Long term monthly mean or actual monthly
	Solar radiation (SR)	$\text{MJ m}^{-2} \text{d}^{-1}$	
	Rainfall (R)	mm	
	Vapour pressure deficit (VPD)	mbar	
Site factors	Latitude	deg	Used to determine day length
	Available soil water ($\theta_{Sx} / \theta_{Sn}$)	mm m^{-1}	Field capacity - wilting point
	Soil class	-	Soil texture
	Fertility rating (FR)	-	Nutrition of site
Stand Initial conditions	Year planted, first and last age		Stem, foliage and root biomass
	Biomass pools (W_{Ri}, W_{Fi}, W_{Si})	$\text{t}_{\text{DM}} \text{ha}^{-1}$	
	Initial soil water (θ_{Si})	mm	Number of trees
	Stems per hectare (SPHi)	stems ha^{-1}	

Site factors (see Section 5.3) describing the physical properties of the site include latitude, a site fertility rating (FR), maximum and minimum plant-available soil water capacity (θ_{Sx} and θ_{Sn} , mm) and a general descriptor of soil texture. The FR accounts for the nutrition of the site, and varies between “*poor*” (FR = 0) and “*optimal*” (FR = 1). Landsberg *et al.* (2001) further qualify the FR and explain that FR = 0 is a baseline condition and does not imply that the soil is devoid of nutrients. This baseline value will impact on the modified canopy quantum efficiency (a_C) to a relatively large extent leading to a low value of a_C . Not only will this reduce the GPP, but a high proportion of the NPP will be allocated below ground rather than to the above ground components. Increasing the FR will increase a_C (increasing the fertility modifier and hence the GPP). These dynamics apply only if the fertility parameters are enabled to do so (see Sections 3.2.3, 3.4.4, 5.3.2, 6.4.4, 7.2 and 7.3). For example, when $f_{N0} = 1$, the effect of site nutrition on the canopy quantum efficiency is not accounted for. This modifier, f_N (FR), is proportional to the site FR and is represented in 3-PG as $f_N(\text{FR}) = f_{N0} + (1 - f_{N0}) \text{FR}$ where f_{N0} is the value of f_N when FR=0 (Sands and Landsberg, 2002). If these parameters are disabled then only root allocation is affected by the specified FR.

The stand initialisation data, also known as initial conditions (Table 2.2) include the year and month planted, and the first and last stand ages. Also required at the starting age, are the foliage, root and stem (W_{Fi} , W_{Ri} and W_{Si} , $\text{t}_{\text{DM}} \text{ha}^{-1}$) biomass, available soil water (θ_{Si}), and stand stocking (SPHi).

Species-specific parameters in 3-PG (Table 2.3, Appendix 1) characterise biomass partitioning and turnover, maximum NPP (via GPP and growth efficiency, light or radiation use efficiency (GE, g MJ⁻¹)), stomatal conductance and their environmental modifiers, stem mortality and thinning, canopy structure and processes, wood density and stand properties, and several conversion factors. These parameters affect 3-PG outputs in various ways: some affect only a sub-set of outputs; many affect most outputs, and in some cases combinations of parameters interact in their effects on an output (see Sections 3.2.1, 3.3.2, 3.4, 3.4.2, 3.4.3 and 3.4.4).

Table 2.3. Species-specific parameters of 3-PG. Numbers in parenthesis refer to the total number of parameters within the parameter sub-class (*e.g.* three parameters make up the specific leaf area parameters which form part of canopy structure and processes). The full list of parameters inherent to 3-PG is provided in Appendix 1.

Parameter class	Parameter sub-class
Biomass partitioning and turnover	Allometric relationships & partitioning (6)
	Litterfall & root turnover (4)
NPP & conductance modifiers	Temperature modifier (3)
	Frost modifier (1)
	Soil water modifier (2)
	Fertility effects (3)
	Age modifier (3)
Stem mortality & self-thinning	(9)
Canopy structure and processes	Specific leaf area (3)
	Light interception (4)
	Production and respiration (2)
	Conductance (4)
Wood density and volume growth	Branch and bark fraction (3)
	Basic wood density (3)
	Stem height allometric (3)
	Stem volume allometric (3)
Conversion factors	(4)

Some of the more common monthly or annual outputs generated by 3-PG comprise foliage, root and stem biomass (W_F , W_R , W_S , t ha⁻¹), LAI, available soil water (θ_S , mm), and stand attributes such as SV, BA, DBH and qDBH, stocking (SPH), and evapo-transpiration (ET, mm month⁻¹). The full list of 3-PG outputs is presented in Appendix

2. A full description of the 3-PG model inputs, outputs and parameters is given in Sands (2004b).

2.3.2 Main components of 3-PG

Many authors have presented detailed descriptions of 3-PG, processes represented and the manner in which calculations are performed (see Landsberg and Waring, 1997; Landsberg *et al.*, 2001; Sands and Landsberg, 2002; Landsberg *et al.*, 2003, Sands, 2004b). Rather than repeating these details, a simplified overview of the model structure is presented instead. However, with the permission of the authors, the publication by Sands and Landsberg (2002), which details the important relationships represented by 3-PG is included in Appendix 3. This publication has not been changed in any way. Where necessary, more detail pertaining to the structure of 3-PG and processes represented are outlined, especially where such details help in the explanation of results (*e.g.* Sections 6.4.3, 6.4.4, 6.4.5, 7.2 and 7.3). Essentially 3-PG comprises five main components (Landsberg *et al.*, 2001): biomass production, biomass partitioning, stem mortality, water balance and stand properties (Figure 2.2), with the main calculations pertaining to those processes that lead to biomass production and those that partition this biomass between the components of the tree which ultimately describes the tree growth.

Biomass production within 3-PG is based on the calculation of radiation interception, GPP via photosynthesis, the estimation of NPP and the allocation of the incremental biomass to the individual tree components. Gross primary production is reduced through the α_C , which is represented as the product of the theoretical maximum canopy quantum efficiency (α_{Cx}) and environmental modifiers which take into account growth limitations imposed by VPD, air temperature, soil water availability and nutritional status of the site (f_D , f_T , f_θ , f_N). The physiological multiplier, ϕ , is calculated as the minimum (or most limiting) of the modifiers f_D and f_θ and used to reduce both the maximum canopy conductance (g_{Cx} , m s^{-1}) and α_C . Net primary production is calculated as a constant fraction of GPP to account for respiration, and carbohydrate is then allocated on a mean-tree basis to roots, stem and foliage.

The coefficient that determines below ground allocation to the roots is calculated first and is influenced by soil water deficits and nutrient limitations. The remainder of the carbohydrate is allocated to the above ground biomass components in accordance with the ratio of derivatives of the allometric relationships describing leaf and stem mass in terms of DBH. This above ground allocation satisfies the condition that 3-PG is a conservation of mass model (Landsberg *et al.*, 2003) implying that no more carbohydrate is allocated than is produced. Using the current period SPH and the cumulative sum of all monthly stem biomass (W_S comprising bole, branches and bark), mean-tree stem mass (w_S , kg stem⁻¹), represented as an allometric relationship of qDBH, is determined. This allometric equation is algebraically rearranged so that the relationship between qDBH and w_S determines BA, SV and HT for any time.

Stem mortality in 3-PG is calculated using the self thinning rule (Landsberg and Gower, 1997) and a density independent probability of death function (Sands, 2004a; Sands, 2004b). The self thinning rule is a -3/2 power law based on the largest tree size (greatest individual stem mass) likely to be attained at the current stem populations (Landsberg, 1981 cited by Landsberg, 1986). The density independent mortality assumes a small probability that any tree will die, which generally depends on stand conditions, stand age, or climatic or other stress factors. Parameter values intrinsic to the mortality function were established by trial and error to reproduce the data modelled using the Clutter and Jones (C-J) model (Clutter and Jones, 1980). The C-J model represents tree survival per hectare for an age as a function of trees per hectare. An advantage of the 3-PG mortality function over the C-J function is that the parameters in the former have a more intuitive meaning and can be readily assigned from observed data (Sands, 2004a). Thus, the seedling mortality rate (γ_{N0}) and the mortality rate for older stands (γ_{N1}) are the mortality rates at planting and for mature trees, respectively.

Soil water balance is based on a single soil layer model with losses through ET determined from the Penman Monteith equation. Evapo-transpiration is directly affected by VPD and SR with the g_{Cx} determined by the LAI and VPD. Inputs of soil texture are required as they reflect differences in the hydraulic characteristics of the soil and are used to determine the f_{θ} .

Figure 2.2 shows the main structural and causal components described. Causal loops are essentially diagrams that portray the information feedback at work within the system being modelled (see Section 3.4.3). These representations are simple and powerful tools to examine conceptually the stability of any model, and the likely behaviour of the model's output to perturbations in parameters or other input data.

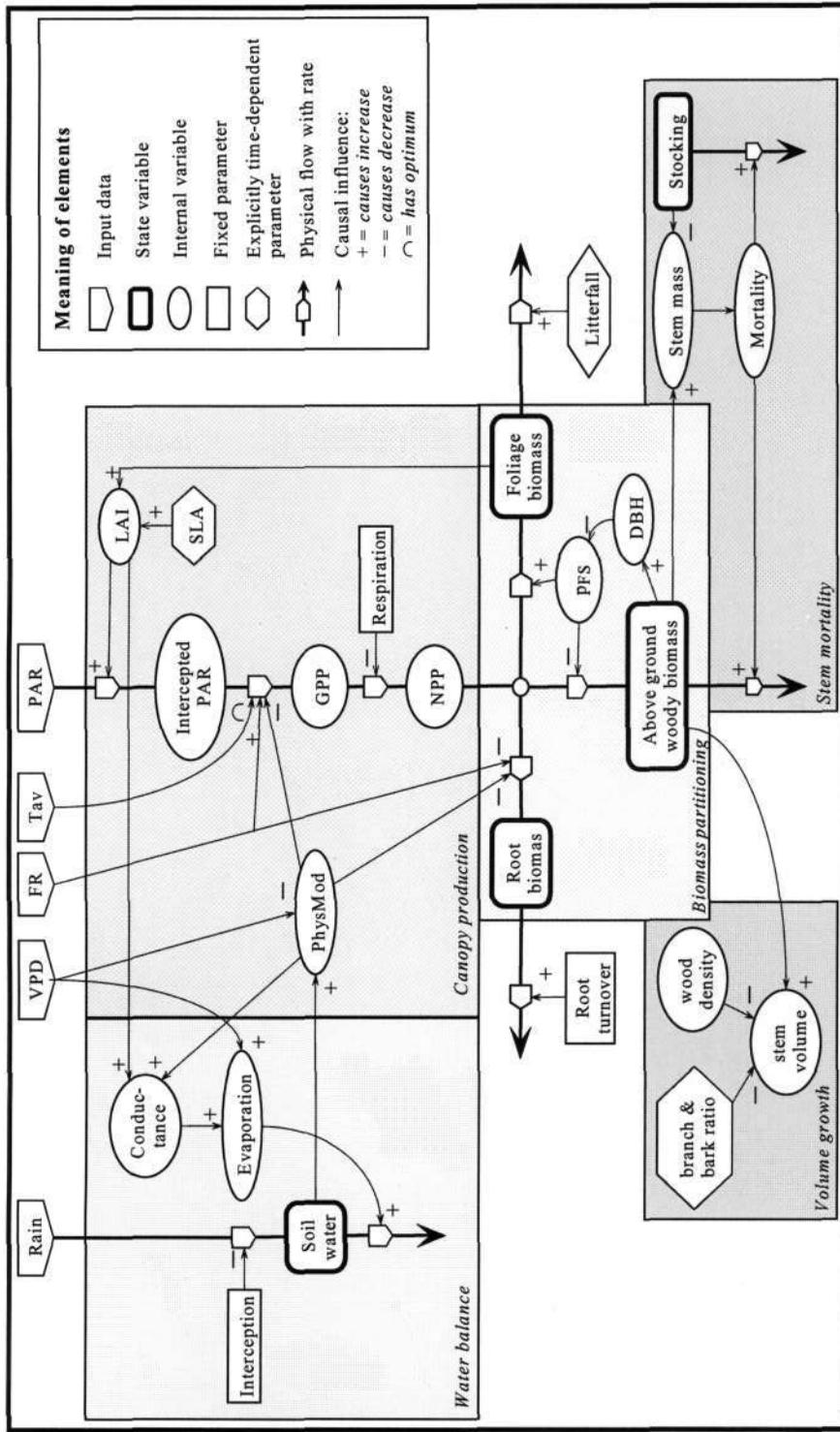


Figure 2.2. Schematic diagram showing the main structural and causal components of the 3-PG forest growth model (Sands, 2000), where the abbreviations are: VPD = vapour pressure deficit; FR = fertility rating; T_{AV} = average minimum and maximum temperature; LAI = leaf area index; σ = specific leaf area; GPP = gross primary production; NPP = net primary production; DBH = diameter at breast height; pFS = foliage:stem partitioning ratio, and ϕ referring to the physiological environmental modifiers (f_θ and f_D).

2.3.3 Assumptions, simplifications and limitations of 3-PG

Compared with most simple PBMs 3-PG is based on five important simplifications of relationships describing complex physiological processes as follows (Waring and McDowell, 2002; Waring, 2000):

- A constant ratio of net to gross primary production (NPP/GPP or Y);
- Canopy conductance approaches a maximum above a LAI of 3;
- The ratio of actual to potential photosynthesis decreases in response to the most restrictive environmental constraint (*i.e.* θ_s or VPD), represented in 3-PG as ϕ , which is also assumed to affect C allocation to the roots;
- The fraction of production not allocated to roots is partitioned between the above ground biomass in accordance with species-specific allometric relationships with $qDBH$;
- Canopy quantum efficiency increases linearly with soil fertility, implying that FR can be quantified.

A major limitation of the model is the simplistic fashion in which FR is represented. As already mentioned, fertility is a potentially important variable since it may affect a_C as well as C allocation to the below ground biomass. Landsberg *et al.* (2001) comment that “*despite many years of research effort all over the world, our ability to describe soil nutrient status in terms usable in quantitative models of plant growth is extremely limited. The FR, while based on the best information available, including expert opinion, therefore remains a somewhat problematical and unsatisfactory albeit pragmatic approach*”. They postulate that FR can also be used as a tuneable parameter in the model, and in this mode holds out some prospect of providing information about effective site fertility. Other model weaknesses include the manner in which C is allocated as a function of tree size and poor predictions of canopy development and mortality (Sands, 2003).

Several key model modifications have been identified, which if implemented should help improve the accuracy of 3-PG predictions (NRF, 2002). These modifications include: sub-models for stress related litterfall; improved modelling of canopy rainfall

interception and soil water balance on a daily time-step through a multiple-layer soil profile; access of groundwater (GW); a system for objectively assigning meaningful site fertility indices (see Section 5.3.2) and a system for assigning realistic stand initialisation data (see Section 5.4). In light of these proposed modifications it is pertinent to take cognisance of Occam's razor, also known as the principle of paucity, which is to not complicate things more than necessary (Landsberg, 2003). Secondly, Battaglia and Sands (1998a) comment that "*Every input or process added to a model increases the error in the model's predictions, particularly if the increased complexity is based on processes that are difficult to observe or requirements that are difficult to measure*".

Despite these limitations and shortcomings, strengths of 3-PG include the ease with which the model can be used, the simple inputs required, the range of species for which it can be used and the generation of outputs which are especially of interest to the forest manager (Appendix 2). The model can also be linked to spatial information, enabling broad scale predictions of productivity.

2.3.4 Preliminary evaluation of 3-PG for use in South Africa

The performance of 3-PG (see Chapter 6) was tested using a set of parameters developed for *E. grandis* in Kwa-Zulu Natal, South Africa, based on data from two contrasting sites (site index of 15.5 m and 26 m; Gush, 1999). Site index is used as a measure of site productivity and is determined as the top height at a particular reference age, which in this case is five years (SI₅, m). Model testing helps build user confidence and provides insights into the model outputs (Hamming, 1962 cited by Haefner, 1996). At the time of this evaluation, carried out by Esprey and Smith (2002), several other validation studies had been performed on *E. grandis* plantations in Espirito Santo, Brazil (Almeida, 2000) and Queensland, Australia (Williams and Ryan, 2000) and pine plantations in Oregon, USA (Keenan *et al.*, 2000) and parts of the United Kingdom (Waring, 2000). Results from all these studies demonstrated the ability of 3-PG to simulate observed data with useful accuracy.

Site information for these research trials used in this preliminary model evaluation are given in Table 2.4. The data from this model evaluation were drawn from various research trials conducted by the ICFR. The trials used vary in age from 4.5 to 11 years, and are located across a broad range of sites ranging in altitude from 15 to 1427 m and productivity from 14 to 51 m³ ha⁻¹ y⁻¹. They show a highly variable climate with mean annual precipitation (MAP, mm) ranging from 780 to 1400 mm, T_X from 22 to 27°C and T_N , from 9 to 17°C. Weather inputs, site factors and initial biomass pools used in the model validation are the same as those used in the parameter sensitivity analysis (see Section 3.2.1, Table 3.1).

Table 2.4. General site and climatic information for the 31 ICFR research trials used in the preliminary model evaluation and sensitivity analysis in Chapter 3. MAP and MAT refer to the mean annual precipitation and mean monthly temperature, respectively.

Site	Trial Number	Location	Final age (y)	Longitude	Latitude	Altitude (m)	MAP (mm)	MAT (°C)
1	K1	Shafton	8.58	30 ⁰ 12'	-29 ⁰ 27'	1192	1008	16.3
2	K2	Crofton	6.58	30 ⁰ 12'	-30 ⁰ 13'	979	784	16.5
3	K3	Nseleni	5.92	32 ⁰ 04'	-28 ⁰ 42'	54	1116	21.6
4	K4	Kwambonambi	5.83	32 ⁰ 12'	-28 ⁰ 34'	66	1174	21.6
5	T10	Shafton	10.75	30 ⁰ 16'	-29 ⁰ 25'	1076	1089	16.9
6	T12	Glenbain	-	30 ⁰ 04'	-29 ⁰ 35'	1300	946	15.8
7	T15	Baynesfield	10.25	30 ⁰ 19'	-29 ⁰ 46'	838	828	17.8
8	T24	Highflats	8.58	30 ⁰ 13'	-30 ⁰ 13'	1002	817	16.5
9	T2	New Hanover	-	30 ⁰ 30'	-29 ⁰ 15'	932	1031	18.3
10	T5	Glendale	10.50	30 ⁰ 40'	-29 ⁰ 01'	1145	1017	16.3
11	T8	Anhalt	-	30 ⁰ 45'	-27 ⁰ 04'	1231	900	17.1
12	T13	Bloemendal	10.75	30 ⁰ 28'	-29 ⁰ 33'	799	875	18.0
13	T17	Ifafa	8.67	30 ⁰ 37'	-30 ⁰ 25'	121	1011	20.4
14	SSP1	Glendale	5.08	30 ⁰ 40'	-29 ⁰ 00'	1243	814	15.9
15	SSP2	Shafton	5.92	30 ⁰ 14'	-29 ⁰ 24'	1226	920	16.1
16	SSP7	Ncalu	5.67	30 ⁰ 04'	-30 ⁰ 14'	955	874	17.2
17	SSP8	Mtunzini	4.83	31 ⁰ 51'	-28 ⁰ 52'	97	1403	21.1
18	SSP9	Kwambonambi	5.92	32 ⁰ 08'	-28 ⁰ 42'	32	1191	21.6
19	SSP10	Nyalazi	5.83	32 ⁰ 22'	-28 ⁰ 16'	39	1068	21.9
20	SSP13	Fernleas	5.83	32 ⁰ 16'	-28 ⁰ 16'	15	860	21.8
21	SSP15	Toverton	5.00	30 ⁰ 49'	-27 ⁰ 22'	1042	816	18.1
22	SSP17	Iswepe	4.50	30 ⁰ 30'	-26 ⁰ 45'	1427	859	16.3
23	SSP21	Frantzinus Rust	4.58	30 ⁰ 52'	-25 ⁰ 46'	960	921	18.8
24	SSP23	Venus	4.83	30 ⁰ 54'	-24 ⁰ 59'	889	1185	18.7
25	SSP24	Waterhoutboom	4.83	30 ⁰ 53'	-24 ⁰ 56'	1040	1347	18.1
26	SSP25	Sabie	3.83	30 ⁰ 46'	-25 ⁰ 06'	1132	1017	18.0
27	M2	Windy Hill	10.92	30 ⁰ 33'	-29 ⁰ 31'	884	1004	17.8
28	M3	Amangwe	9.83	32 ⁰ 05'	-28 ⁰ 39'	50	1050	21.6

Site	Trial Number	Location	Final age (y)	Longitude	Latitude	Altitude (m)	MAP (mm)	MAT (°C)
29	M4	Kia-Ora	9.75	30° 08'	-30° 06'	780	881	17.4
30	M5	Tanhurst	9.00	30° 26'	-30° 17'	610	917	18.1
31	M6	Baynesfield	11.00	30° 21'	-29° 45'	780	891	17.9

The performance of 3-PG as a tool for predicting SV was evaluated by comparing predicted and observed SV data for 28 of the sites shown in Table 2.4. Other data required for a proper validation, such as W_F and W_R biomass data (Sands and Landsberg, 2002), were not available. For each site, SV for the final stand age was predicted separately (a) with the stands initialised using W_{Fi} , W_{Ri} , W_{Si} , biomass typical of a two-year old stand, and (b) stands initialised at time zero using seedlings allocated a total mass 1 g. Figure 2.3 shows that the quality of fit is very similar in both cases, and that although the slope of the regression line is close to unity, 3-PG accounted for 65% of the variation in SV across all 28 sites. Generally these results are promising and demonstrate that 3-PG provides credible predictions of SV at 28 diverse sites, and over an observed range from 70 to 420 m³ ha⁻¹ (see Sections 6.2, 6.3 and 6.5).

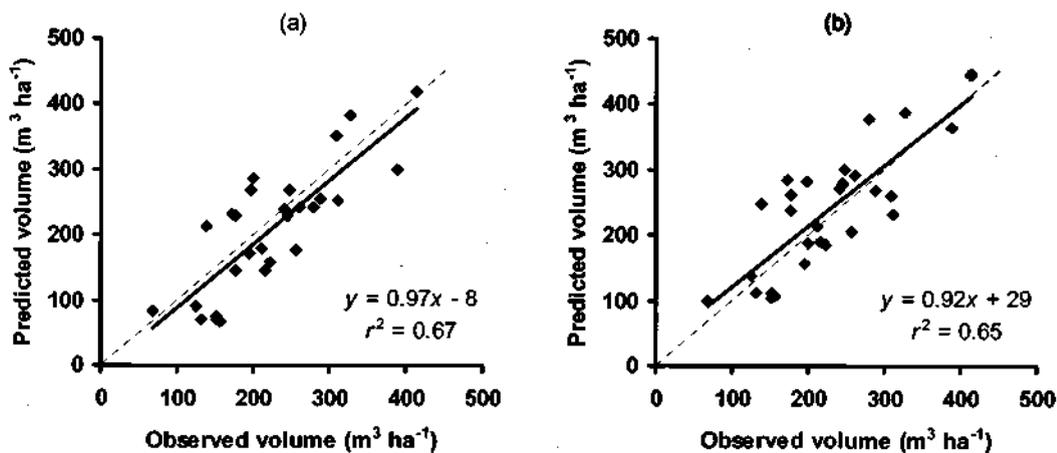


Figure 2.3. Comparison of the observed and predicted stand volume for 28 sites from Table 2.4 when simulated stand growth is initialised (a) using site-specific two-year biomass data and (b) seedlings with 1 g biomass. One-to-one line is shown as (---), and (—) is the regression line.

Other results (discussed fully in Chapter 6) show that:

- Residuals between predicted and observed SV are overpredicted on lower productivity ($<25 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$) sites with the reverse on medium productivity ($25 \text{ to } 45 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$) sites and to a lesser extent on high productivity ($>45 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$) sites. Of the 28 sites modelled, 13 sites fell within 20% of the observed data.
- Predicted current annual increment (CAI, $\text{m}^3 \text{ ha}^{-1} \text{ y}^{-1}$) tracks observed CAI reasonably well, especially during periods of drought (see Section 6.4.2). Such physiological dynamics in response to drought are well documented by Jones and Corlett (1992) showing that drought changes the efficiency of conversion of intercepted light into dry matter. Moreover, drought results in a significant decrease in plant biomass, LAI and specific leaf area (SLA, $\text{m}^2 \text{ kg}^{-1}$), resulting in drought-induced leaf shedding (Pita and Pardos, 2001).
- Predictions of peak LAI vary between 5 and 10 (see Section 6.4.3) for each of the 31 trial sites, compared with observed values of 2 and 3 for three and nine year old stands of *E. grandis* in South Africa, respectively (Dye, 1996). Although higher values of LAI have been reported by Myers *et al.* (1996) who measured values ranging from 4.9 to 5.7, these were taken in irrigated plantations at an age of 36 months. The over-prediction of LAI is important since LAI determines radiation interception which in turn affects C assimilation (GPP) and canopy transpiration. It is therefore essential to ensure that the maximum LAI produced and the time course of LAI are consistent with observations (Landsberg *et al.*, 2001). This is especially true when comparing observed and predicted data to ensure that model predictions are correct for the “right” reasons. Since SLA and W_F biomass (and litter-fall) are important determinants in the calculation of LAI, errors in estimation of these input parameters will seriously affect the estimation of LAI which “drives” the model.

2.4 DISCUSSION AND CONCLUSION

This chapter highlighted the types of growth and yield (G&Y) models that have been developed (*i.e.* empirical, process and hybrid models). Some background on process-based models (PBMs) is presented, followed by the appraisal of 16 models ranging in resolution, complexity and generality. The purpose of this exercise was to select the most appropriate model that would meet the objectives of this study. This selection process revolved around a set of 10 criteria, to which ratings or scores were associated (not shown). These criteria included, *inter alia*, the specific purpose of development, species to which the model is applicable, the international popularity, the availability of documentation and whether the model was developed with the end user in mind. 3-PG satisfied most of the criteria, followed closely by ProMod. This appraisal showed that the strength of 3-PG lies in the fact that the model has been used in 8 different countries (ProMod in 6) and has source code which is readily available, and has adequate and scientifically based documentation.

Using a set of parameter values developed for *E. grandis* (Gush, 1999), 3-PG was subjected to a preliminary model evaluation using observed data from 31 sites. Results of this evaluation show the considerable potential of 3-PG for predicting forest productivity. However, predictions of plantation productivity using 3-PG and the parameter set used in these calculations tend to over-predict productivity of *E. grandis* which may be due to an over-estimation of leaf area index (LAI). Thus there is a need to develop a more accurate and robust parameter set to increase the predictive ability of the model.

However, before doing so, it is imperative to perform a parameter sensitivity analysis (Chapter 3), which Jeffers (1978) states to be essential to discover how models behave within the full range of variation of their parameters. In order to understand the model and to identify those parameters and site factors that need to be accurately determined for reliable applications of the model to plantation-grown *E. grandis*, a detailed parameter sensitivity analysis of the 3-PG was performed.

Another important issue in applying models such as 3-PG to predict the temporal pattern of growth is the availability of data that describes the initial state. Sands and Landsberg (2002) showed for *Eucalyptus globulus* that although stem growth rates for mature stands were independent of initial stand data over a reasonable range, early canopy growth and later-age stem volumes were affected by these data. Although in this preliminary evaluation a pragmatic approach to stand initialisation was adopted, it is necessary to develop a more robust method to assign initial values and site fertility rating (FR). These issues are revisited in Chapter 5.

CHAPTER 3

PARAMETER AND INPUT SENSITIVITY ANALYSIS

OF 3-PG¹

3.1 INTRODUCTION

Haefner (1996) postulates that the performance of a model can be assessed by actively manipulating input values or model components and observing the change in corresponding outputs. Such a manipulation is a sensitivity analysis and is defined as a systematic investigation of model responses to changes in model inputs and parameters (Huang *et al.*, 2003), and whether such changes produce large or small variations in the performance of the model (Jeffers, 1978). Sensitivity type analyses can also be used as a “*what-if*” analysis (Huang *et al.*, 2003) to decipher the “*black-box*” (model) and understand its behaviour under varying conditions. A distinction can be made between parameter sensitivity and component or structural sensitivity. McCuen (1973) defines parameter sensitivity as a measure of the change in output resulting from a change in a parameter value, whereas a component sensitivity analysis considers the effect of changing sub-routines, such as, for example, the biomass production, partitioning or water balance routines, on model output (Battaglia and Sands, 1998b). Non-linearity, on the other hand, is a change in response that is not proportional to the change in input, or equivalently, where the change in response to a given change in input depends on the value (level) of the input. Non-linear relationships are ones that show a strong positive feedback in one interval of the domain of the function and a strong negative feedback in another interval (Berryman and Millstein (1989), cited by Haefner (1996)). For example a non-linear response is one that shows a different sensitivity on increasing or decreasing the value of the parameter.

Knowledge of the sensitivity of model outputs to parameters, and of the non-linearity of output with respect to these parameters, is useful for modellers to better understand the correspondence between the model and the processes being modelled (McCuen, 1973).

¹ Major sections of this chapter are published in Esprey *et al.* (2004), Appendix 4.

A sensitivity analysis gives an appreciation of the role and significance of input and parameters in the transformation of the model input to output (Bacchi *et al.*, 1989), and provides a powerful method of exploring issues surrounding uncertainties in model structure and parameters (Battaglia and Sands, 1998b). It is also possible to determine the degree to which inaccuracies in assumed parameter values can lead to serious errors in prediction. The sensitivity analysis requires a set of model runs where values of the model input variables and parameters are changed. The resulting output is carefully evaluated especially when it varies for input variations that are within the bounds of realism (Huang *et al.*, 2003). Many techniques employed to perform a sensitivity analyses are highly mathematical and theoretical in nature. Huang *et al.* (2003) suggests using a sensitivity index and graphical techniques to conduct a sensitivity analysis.

The objective of this chapter is to perform an analysis in which the sensitivities of selected model outputs (SV and LAI) to variations of each parameter or input are calculated and used to assess the sensitivity of 3-PG to changes in its parameter and input values. Such an analysis helps the user/modeller understand individual parameters and how processes are modelled, identifies those parameters that need to be accurately determined, provides insight into the limitations of the model, and most importantly, builds confidence in the use of a model. This analysis enables guidelines, necessary for the subsequent model parameterisation, to be formulated.

The site data used in the sensitivity analysis were from 31 *E. grandis* research trials in regions where commercial plantations have been established in two provinces in South Africa. The analysis examined the sensitivity of SV and LAI (arbitrarily chosen) to 24 3-PG parameters. In addition, the sensitivity of SV and W_R to R and T_{AV} , FR and θ_{Sx} were tested. Non-linearity of model outputs with respect to the parameters was also investigated.

3.2 METHODS

3.2.1 Data used for sensitivity analysis

The data used in the sensitivity analysis were from 31 ICFR *E. grandis* research trials, grown either as a single species or in combination with other eucalypt species, at distinct sites in South Africa. Each trial received high quality silvicultural management comprising full weed control, fertilisation and blanking (*i.e.* replanting of areas where seedlings had died) to maximise survival during the early establishment phase. Details of the sites and trials are given in Table 2.4 (see Section 2.3.4) and Table 3.1. Mandatory climatic inputs, site factors and parameter values required for 3-PG were obtained as follows:

Long-term T_X , T_N , and SR data were obtained from the 1' x 1' latitude by longitude digital database developed by Schulze (1997a). Actual R data for the duration of each trial was used in the 3-PG model predictions. Where such data were missing or unavailable, representative rainfall data was selected using the “*driver station approach*” outlined in Schulze *et al.* (1994). According to this approach four criteria are used in the selection of the most representative data set as follows: (a) the driver station is as close as possible or within the catchment; (b) its altitude is close to the mean altitude of the catchment; (c) it has a long continuous record with a minimum of missing data; and (d) where data are missing, the next best driver station is used to estimate the missing rainfall.

Of the required site factors, latitude and soil texture were directly available for each site. Maximum available soil water was derived as the product of available soil water capacity (AWC, mm m^{-1}) and soil depth (m). The former was based on relationships between soil water holding capacity and soil texture (or soil class (SC): clay (c); clay-loam (cl); sand (s); and sand-loam (sl)) for South African forest soils (Smith *et al.*, 2001), and soil depth was based on a broad correlation between parent material and depth (Smith *et al.*, 2005).

Table 3.1. Details of 3-PG inputs (see Section 2.3.1, Table 2.2) for the sites used in the sensitivity analysis, and observed and predicted volumes for the stand ages given. See Section 2.3.4, Table 2.4 for additional site information. Sites 17 and 21 are Mfunzini and Toverton respectively and are referred to in Section 3.2.4. Abbreviations are as follows: θ_{sx} – maximum available soil water capacity; SC – soil class (c – clay; cl – clay loam; s – sand; sl – sand loam); FR – fertility rating; SPHi – initial stems per hectare; W_{Fi} , W_{Ri} , W_{Si} – initial foliage, root and stem biomass pools; MAI – mean annual increment; and SV – stand volume.

Site	Stand age y	Site Factors			Initial conditions				Observed MAI ($m^3 ha^{-1} y^{-1}$)	Observed SV ($m^3 ha^{-1}$)	Predicted SV ($m^3 ha^{-1}$)
		θ_{sx} (mm)	SC	FR	SPHi (stems ha^{-1})	W_{Fi} ($t ha^{-1}$)	W_{Ri} ($t ha^{-1}$)	W_{Si} ($t ha^{-1}$)			
1	8.6	325	c	0.6	1667	2.56	4.10	13.86	24	201	287
2	6.6	130	cl	0.6	1667	1.79	5.18	10.30	27	178	146
3	5.9	300	s	0.6	1482	8.97	16.59	40.81	49	289	256
4	5.8	300	s	0.6	1369	6.41	12.23	30.28	48	279	243
5	10.6	325	c	0.6	1667	5.12	7.52	24.94	29	310	351
6	-	300	cl	0.6	1667	2.56	4.10	13.86	-	-	-
7	10.3	260	c	0.6	1667	1.79	5.18	10.30	17	177	230
8	8.6	130	cl	0.6	1667	1.79	5.18	10.30	16	139	215
9	-	195	c	0.6	1667	5.12	7.52	24.94	-	-	-
10	10.5	455	c	0.6	1667	5.12	7.52	24.94	31	327	384
11	-	260	cl	0.6	1667	2.56	4.10	13.86	-	-	-
12	10.8	130	c	0.6	1667	2.56	4.10	13.86	22	242	239
13	8.7	130	c	0.6	1667	5.12	7.52	24.94	23	198	268
14	5.1	325	c	0.4	1600	1.79	5.18	10.30	29	152	75
15	5.9	195	c	0.4	1600	2.56	4.10	13.86	29	222	158
16	5.7	104	cl	0.4	1600	2.56	4.10	13.86	26	124	91
17	4.8	400	sl	0.4	1600	8.97	16.59	40.81	51	256	177
18	5.9	300	s	0.4	1600	6.41	12.23	30.28	42	247	267
19	5.8	300	s	0.4	1600	8.97	16.59	40.81	50	312	253
20	5.8	400	sl	0.4	1600	6.41	12.23	30.28	35	194	171
21	5.0	260	cl	0.4	1600	1.79	5.18	10.30	14	68	84
22	4.5	260	cl	0.4	1600	2.56	4.10	13.86	28	132	70
23	4.6	260	cl	0.4	1600	2.56	4.10	13.86	31	158	67
24	4.8	650	cl	0.4	1600	5.12	7.52	24.94	43	216	147
25	4.8	650	cl	0.4	1600	6.41	12.23	30.28	40	212	180
26	3.8	195	cl	0.4	1600	2.56	4.10	13.86	71	151	71
27	10.9	390	cl	0.6	1667	2.56	4.10	13.86	35	389	299
28	9.8	300	s	0.6	1667	6.41	12.23	30.28	42	414	419
29	9.6	130	cl	0.6	1667	1.79	5.18	10.30	25	245	230
30	9.0	195	cl	0.6	1667	2.56	4.10	13.86	29	260	241
31	11.0	130	c	0.6	1667	1.79	5.18	10.30	16	173	231

The assignment of site FR was based on whether the trial had received fertiliser or not. Trials 14 to 26 were not fertilised since the original objectives of these trials were to elucidate climatic and site factors important in driving productivity. All the other trials received fertiliser applications based on existing ICFR recommendations for *E. grandis* for the respective site conditions. In general, optimum economic response in South African eucalypt plantations is achieved with a single fertiliser dose at the time of planting (du Toit, 1998). Because of this, and since preliminary work has demonstrated 3-PG outputs to be highly sensitive to FR (Esprey and Smith, 2002), values of 0.6 and 0.4 were assigned for trials that had been fertilised and un-fertilised respectively (Table 3.1, see Section 5.3.2).

Species-specific parameters in 3-PG characterise canopy structure and canopy quantum efficiency, allometric relationships and biomass partitioning, branch and bark fractions, basic wood density, litterfall and root turnover rates, and various environmental modifiers (see Appendix 1 and Section 2.3.1). Table 3.2 lists the parameters studied in this analysis, along with their initial ascribed values. These parameters affect 3-PG outputs in various ways: some affect only a sub-set of outputs, many affect most outputs, and in some cases combinations of parameters interact in their effects on an output. In general, 3-PG outputs are non-linear functions of the species-specific parameters. At the time of this study parameter values had already been developed for *E. grandis* in Kwa-Zulu Natal, South Africa, using data from two contrasting trial sites having a SI_5 of 15.5 m and 26 m (Gush, 1999). Parameters related to the allometric and other biomass relationships were derived from data from destructive harvests over an age sequence at both sites. Parameters that had not been, or could not be directly measured for *E. grandis* were gleaned from a range of literature sources, many of which pertain to Australian plantations (Bray and Gorham, 1964; Shepherd, 1985; Coetzee *et al.*, 1996; Landsberg and Waring, 1997; Coetzee, 1998). Full details of this preliminary parameterisation of 3-PG for *E. grandis* are outlined in Gush (1999).

3-PG was applied at an age of two years with typical biomass data at that age. All runs were made to the ages given in Table 3.1. The biomass data required to initialise the stand at age two years were assigned using a pragmatic approach, as follows. (a) Each

stand was allocated one of five productivity classes according to its site index estimated using a SI_5 model for *E. grandis* at age five years (Coetzee, 1999) developed independently from the data presented here. (b) This model also allowed an approximate W_S at age two years to be assigned. (c) Data from various sources (Bradstock, 1981; Turner, 1986; Christie and Button, 1991; Cromer *et al.*, 1993; CSIRO, 1995; Myers *et al.*, 1996; Binkley *et al.*, 1997; du Toit *et al.*, 1999; Gush, 1999) indicated that partitioning of biomass between W_F , W_R and W_S was related to site quality, *e.g.*, on better sites the foliage:stem ratio was lower than on poor sites. (d) Once initial W_{Si} was assigned, W_{Fi} and W_{Ri} were estimated from these typical biomass ratios observed for stands aged about two years.

Table 3.2. Meaning and reference values for the 3-PG *E. grandis* parameters subjected to the sensitivity analysis. See Appendix 1 for the full list of parameters.

Name	Value	Units	Definition
a_S	0.095	-	Constant in stem allometric relationship
n_S	2.4	-	Power in stem allometric relationship
p_2	1	-	Foliage:stem partitioning ratio for DBH = 2 cm
p_{20}	0.15	-	Foliage:stem partitioning ratio for DBH = 20 cm
η_{Rx}	0.6	-	Maximum fraction of NPP to roots
η_{Rn}	0.25	-	Minimum fraction of NPP to roots
T_{min}	3	°C	Minimum temperature for growth
T_{opt}	23	°C	Optimum temperature for growth
T_{max}	35	°C	Maximum temperature for growth
f_{N0}	1	-	Parameter that controls the effects of FR on α_C
t_x	30	years	Maximum stand age as used in age modifier
γ_{Fx}	0.035	month ⁻¹	Maximum litterfall rate
g_{Cx}	0.02	m s ⁻¹	Maximum canopy conductance
L_{Cx}	3.33	-	LAI for max. canopy conductance
kg	0.05	mbar ⁻¹	Stomatal response to vapour pressure deficit
g_B	0.2	m s ⁻¹	Canopy boundary layer conductance
σ_0	12	m ² kg ⁻¹	Specific leaf area at age 0
σ_1	6	m ² kg ⁻¹	Specific leaf area for mature leaves
k	0.5	-	Extinction coefficient
α_{Cx}	0.06	-	Maximum canopy quantum efficiency
Y	0.47	-	Ratio of NPP: GPP
p_{BB0}	0.15	-	Branch and bark fraction at age 0
p_{BB1}	0.15	-	Branch and bark fraction for mature stands
ρ^*	0.5	t m ⁻³	Mean stemwood basic density

3.2.2 Calculation of sensitivity measures

The relative sensitivity $\lambda_1(X, p)$ of a given model output X with respect to a parameter, site factor or model input p , was defined by Brylinsky (1972) as:

$$\lambda_1(X, p) = \frac{p}{X} \frac{\partial X}{\partial p} \quad (3.1)$$

This is the change δ_X in X produced by a change δ_p in p relative to the original values of X and p . Relative sensitivity is zero if X is independent of p , and is positive or negative depending on whether an increase in p results in an increase or a decrease, respectively, in X . By analogy with Equation 3.1 the relative non-linearity λ_2 of X with respect to p is defined by:

$$\lambda_2(X, p) = \frac{p^2}{X} \frac{\partial^2 X}{\partial p^2} \quad (3.2)$$

and this is zero if the variable X depends linearly on p . Finite-difference approximations to λ_1 and λ_2 are obtained using:

$$\lambda_1(X, p) = \frac{p_0}{X_0} \frac{X_+ - X_-}{2\delta_p}$$
$$\lambda_2(X, p) = \frac{p_0^2}{X_0} \frac{X_+ - 2X_0 + X_-}{\delta_p^2}, \quad (3.3)$$

where δ_p is a change in p , and $X_- = X(p_0 - \delta_p)$, $X_0 = X(p_0)$ and $X_+ = X(p_0 + \delta_p)$.

3.2.3 Parameter sensitivity analysis

The relative sensitivity and non-linearity of SV and LAI were determined for each site in Table 3.1 by running the model with the reference values of each parameter (p) from Table 3.2, and with each p varied 30% either side of its reference value. The variation of p by $\pm 30\%$ was arbitrarily chosen and, except for variables that are strong non-linear functions of p , it has no affect on λ_1 and λ_2 . The resulting 3-PG outputs were then used

in Equations 3.3 to approximate λ_1 and λ_2 , and general measures of mean sensitivity (μ_1) and mean non-linearity (μ_2) of SV and LAI to each parameter were calculated by averaging λ_1 and λ_2 , respectively, over all sites. The coefficient of variation, expressed as a percentage, of the λ_1 around their site-mean (μ_1) was calculated as an indication of the environmental or between-site variation ($\mu_1 \times E$) of sensitivity.

When the default parameter set is used, the effects of FR on α_C are disabled because the parameter defining f_N when FR = 0 (f_{N0}) is set to 1, but FR does nonetheless affect biomass partitioning to roots. However, possible effects of FR on α_C were taken into account in the sensitivity analysis because the analysis of sensitivity to f_{N0} was based on $f_{N0} = 0.7$ and 1.3 as well as $f_{N0} = 1$.

Predicted values of SV and LAI at two contrasting sites were also plotted as a function of selected parameters. These sites are: Mtunzini (high productivity, deep soils, low water stress and high temperatures) and Toverton (low productivity, high water stress and cooler temperatures); see sites 17 and 21 in Table 3.1. The parameters considered in this way were: f_{N0} , which controls the effects of FR on α_C ; the optimum (T_{opt} , °C) temperature for growth; α_{Cx} which affects the radiation use efficiency (GE, g MJ⁻¹); η_{Rx} which regulates the maximum fraction of NPP allocated to roots; the foliage: stem partitioning ratio for mature trees (p_{20}); the LAI required for maximum canopy conductance (L_{Cx} , m² m⁻²); and the constant and power in the stem mass *versus* DBH allometric relationship (a_S and n_S).

3.2.4 Model outputs as a function of site factors

The sensitivities of SV and W_R , to the FR, θ_{Sx} , and MAP and MAT were also examined at the same two sites. Rainfall, temperature and θ_{Sx} were varied by $\pm 30\%$, and FR was assigned the values 0, 0.3, 0.6 and 0.9. In each case, SV and W_R were plotted as a function of these site factors at contrasting sites, Mtunzini and Toverton.

3.3 RESULTS

3.3.1 Model outputs as a function of parameter values and site factors

Predicted SV and LAI at Mtunzini and Toverton (Table 3.1, sites 17 and 21, respectively) are shown as a function of selected parameters in Figure 3.1. This illustrates the various degrees of sensitivity found in this study. The slope of the plot of output *versus* parameter increases with increasing sensitivity, e.g. at both sites LAI, but not SV, is sensitive to the foliage:stem partitioning ratio (p_{20}) at a mean stem diameter of 20 cm. In general, if the plot of output (X) *versus* parameter (p) is not a straight line, then X is non-linearly related to p . Figure 3.1b shows that both LAI and SV are non-linear with respect to T_{opt} .

Figures 3.2a and 3.2b show that increasing FR increases biomass partitioning to the stem and decreases partitioning to roots. Figures 3.2c and 3.2d show that at both sites there is only a slight response of SV and W_R to changes in θ_{sx} . Figures 3.3a and 3.3b show that increasing R increases both SV and W_R at both sites, and that the increase in SV is greater at the more productive site, Mtunzini, than at Toverton. Figures 3.3c and 3.3d show that increasing the mean temperature reduces both SV and W_R , and that the reduction is greater at the warmer site (Mtunzini).

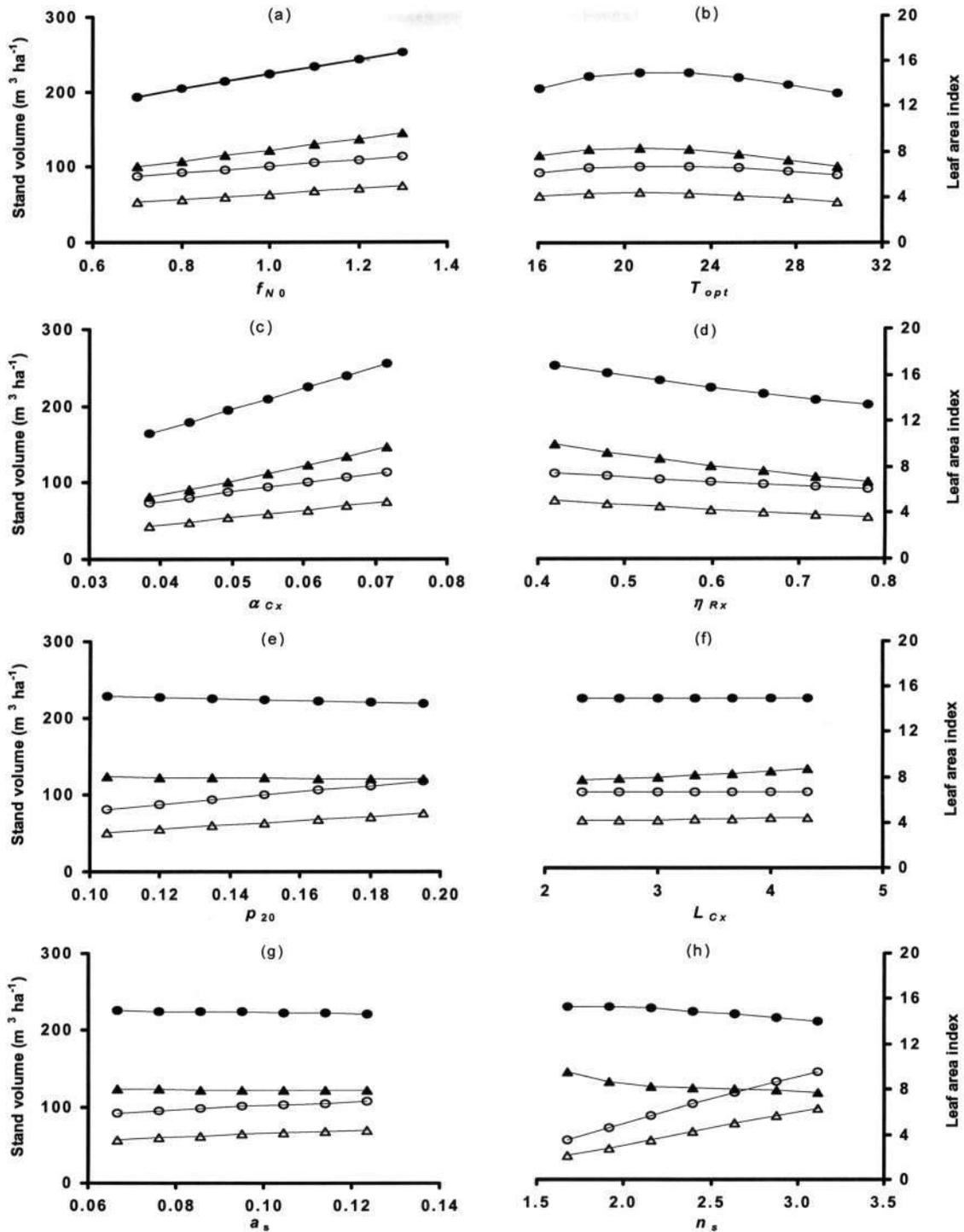


Figure 3.1. Predicted stand volume (\bullet , \blacktriangle ; left-hand scale) and LAI (\circ , \triangle ; right-hand scale) as a function of parameters: (a) effect of FR on α_C (f_{N0}), (b) optimum growth temperature (T_{opt}), (c) maximum canopy quantum efficiency (α_{Cx}), (d) maximum root partitioning ratio (η_{Rx}), (e) foliage:stem partitioning ratio of large trees (p_{20}), (f) LAI required for maximum canopy conductance (L_{Cx}), (g) constant (a_s) in stem allometric relationship, and (h) power (n_s) in stem allometric relationship. Sites are Mtunzini (\bullet , \circ) and Toverton (\blacktriangle , \triangle).

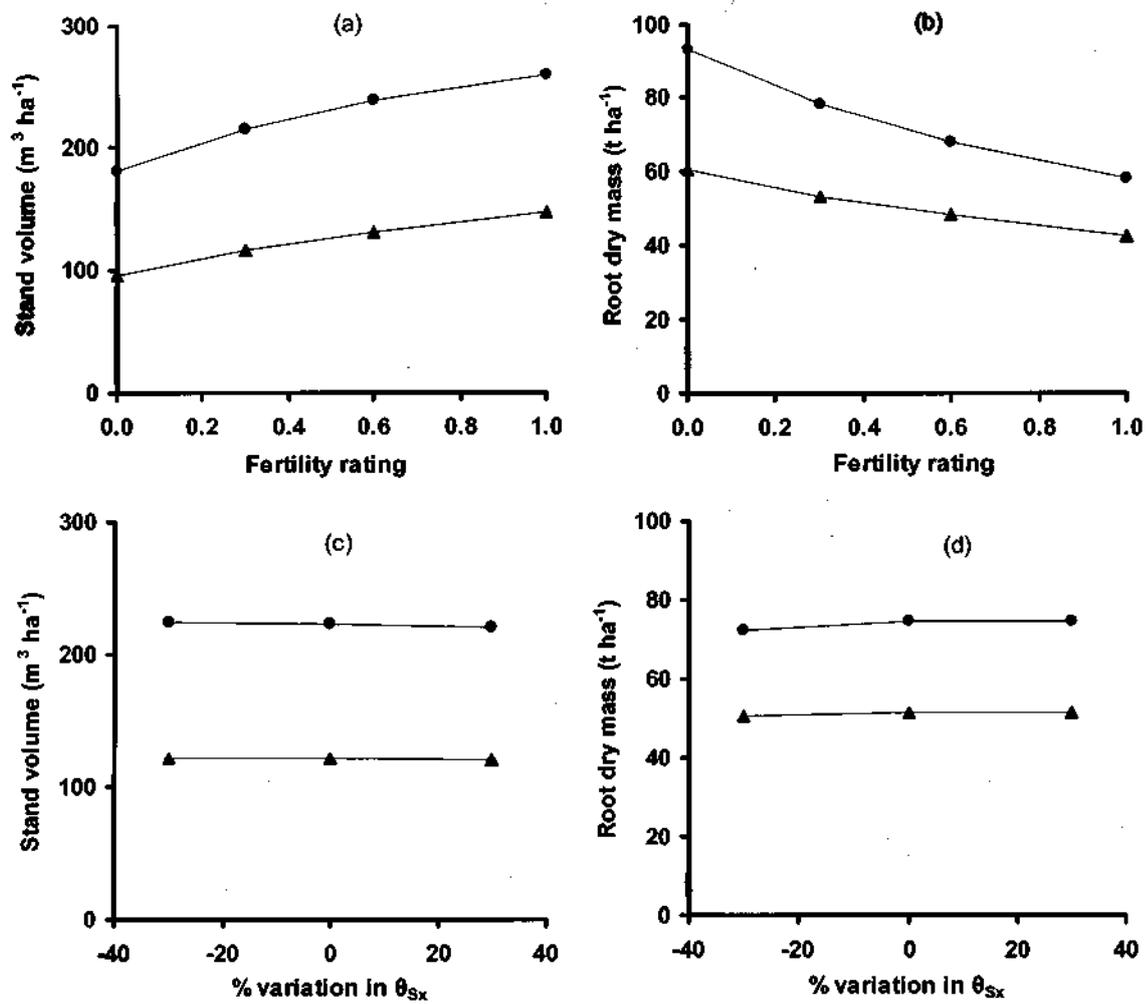


Figure 3.2 Predicted stand volume and root dry mass as a function of the site factors: (a and b) fertility rating (FR) and (c and d) maximum available soil water (θ_{sx}) for sites Mtunzini (●) and Toverton (▲).

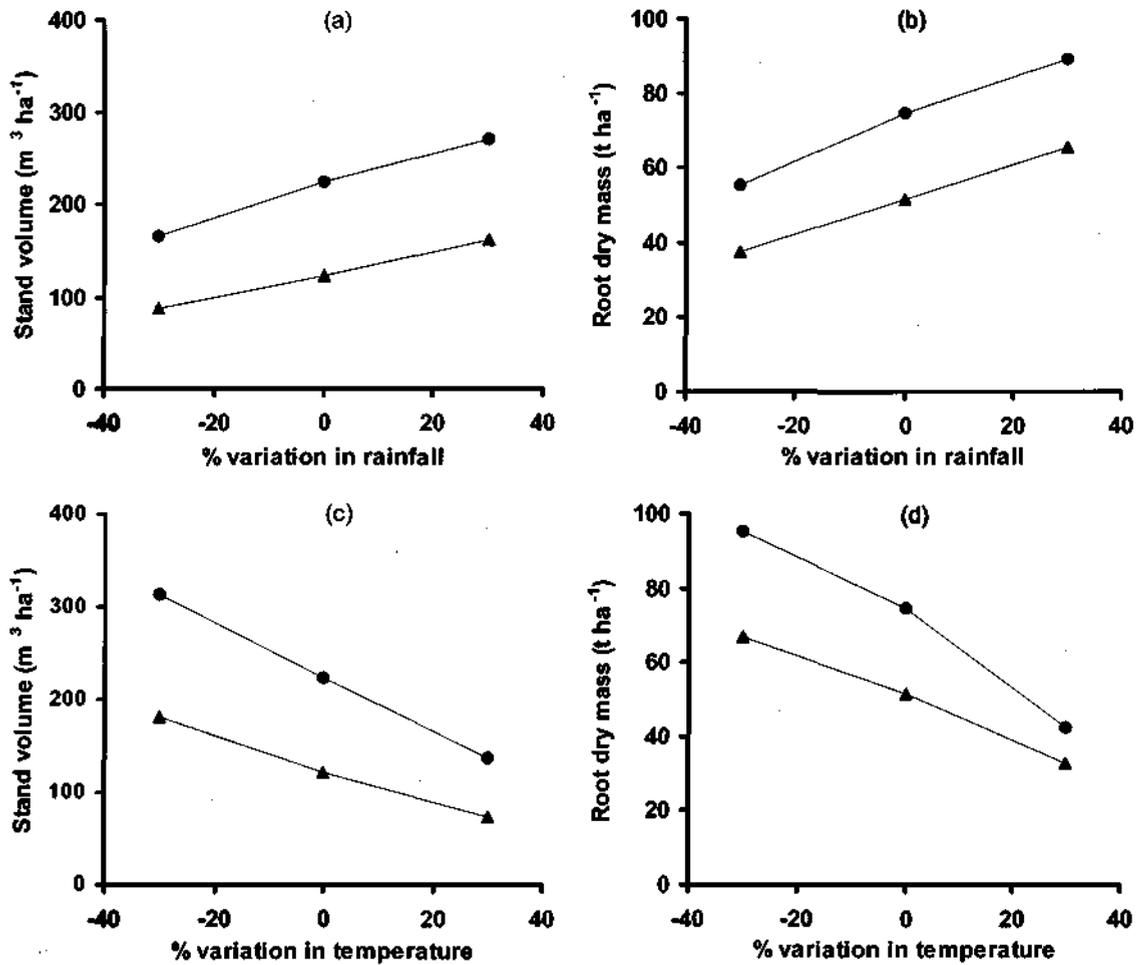


Figure 3.3. Predicted SV and root dry mass as a function of climatic factors: (a-b) rainfall and (c-d) mean temperature for sites Mtunzini (●) and Toverton (▲).

In their application of 3-PG to *E. globulus*, Sands and Landsberg (2002) showed that although variation of initial stand biomass data could strongly affect early stand development, it often had little effect on predicted stem growth rates. This finding was confirmed here. It was also found that variation in available soil water at the time of stand initialisation had little effect on SV, W_R and LAI at the stand ages given in Table 3.1. Neither of these results is shown in detail.

3.3.2 Relative sensitivity and environmental variation

A comprehensive summary of the results from the parameter sensitivity analysis is given in Table 3.3. This shows the mean sensitivity (μ_1) and non-linearity (μ_2), and

environmental variation of sensitivity ($\mu_1 \times E$) for both SV and LAI predicted at the stand ages given in Table 3.1. Sensitivity has also been ranked using a simple scheme based on the distribution of individual values (Battaglia and Sands, 1998b), thus isolating those parameters to which SV and LAI are or are not sensitive. Ranked values (0 to 3) indicate the range from insensitive to highly sensitive.

Table 3.3 Results from sensitivity analysis of SV and LAI predicted by 3-PG. ^aRanking refers to the ranking scheme used by Battaglia and Sands (1998b) and is appended to this table.

Parameter	Sensitivity (μ_1)		Non-linearity (μ_2)		Between-site variation ($\mu_1 \times E$)		Ranking ^a			
	SV	LAI	SV	LAI	SV	LAI	μ_1		$\mu_1 \times E$	
	SV	LAI	SV	LAI	SV	LAI	SV	LAI	SV	LAI
g_B	0.05	0.04	-0.02	-0.02	52	57	0	0	1	1
T_{min}	-0.02	-0.01	0.00	0.00	-55	-59	0	0	1	1
t_x	0.01	0.01	-0.01	-0.02	93	99	0	0	2	2
P_{BB0}	-0.01	0.00	0.00	0.00	-83	0	0	0	2	0
L_{Cx}	0.06	0.02	0.02	0.01	133	262	0	0	2	3
σ_0	0.01	0.01	0.00	0.00	162	176	0	0	3	3
P_{BB1}	-0.17	0.00	0.00	0.00	-8	0	1	0	0	0
kg	-0.16	-0.14	-0.01	-0.01	-44	-48	1	1	1	1
T_{max}	0.21	0.18	-0.26	-0.24	89	89	1	1	2	2
p_2	0.00	0.17	0.00	-0.03	-312	48	0	1	3	1
f_{N0}	0.50	0.43	0.00	-0.02	17	19	2	2	0	0
η_{Rn}	-0.36	-0.30	0.09	0.06	-18	-8	2	2	0	0
η_{Rx}	-0.45	-0.37	0.10	0.06	-26	-31	2	2	1	1
k	0.26	0.21	-0.17	-0.15	40	41	2	1	1	1
a_S	-0.01	0.33	0.01	-0.06	-126	11	0	2	2	0
T_{opt}	-0.26	-0.24	-0.63	-0.57	-109	-78	2	1	2	2
α_{Cx}	0.98	0.85	0.04	-0.04	12	7	3	3	0	0
ρ^*	-1.14	0.00	0.55	0.00	-21	0	3	0	0	0
Y	0.98	0.84	0.00	-0.07	11	7	3	3	0	0
g_{Cx}	-0.76	-0.62	0.23	0.14	-25	-27	3	3	1	1
γ_{F0}	-0.10	-1.02	-0.01	0.35	-46	-21	1	3	1	0
n_S	-0.16	1.85	-0.01	-0.04	-67	13	1	3	1	0
σ_1	0.14	1.13	-0.04	0.01	39	4	1	3	1	0
p_{20}	-0.03	0.79	-0.03	-0.08	-102	17	0	3	2	0

Ranking value	0	1	2	3
μ_1	$ \mu_1 < 0.075$	$0.075 \leq \mu_1 < 0.25$	$0.25 \leq \mu_1 < 0.4$	$0.4 \leq \mu_1 $
$\mu_1 \times E$	$ \mu_1 \times E < 25$	$25 \leq \mu_1 \times E < 75$	$75 \leq \mu_1 \times E < 150$	$150 \leq \mu_1 \times E $

For each parameter the mean sensitivity μ_1 and non-linearity μ_2 are the average of the relative sensitivity λ_1 and non-linearity λ_2 across 31 sites. The environmental variation ($\mu_1 \times E$) is the coefficient of variation (expressed as a percentage) of λ_1 across all sites. The parameters have been ordered in increasing maximum ranking of μ_1 for SV and LAI, and then in order of increasing maximum ranking of $\mu_1 \times E$ for SV and LAI.

Stand volume is seen (Table 3.3) to be highly sensitive to the ratio (Y) of NPP: GPP, α_{Cx} , maximum canopy conductance (g_{Cx}) and basic wood density (ρ^*), with a moderate sensitivity to the maximum (η_{Rx}) and minimum (η_{Rn}) fractions of biomass allocated to roots, the effect of site fertility on canopy quantum efficiency (f_{N0}), the optimum growth temperature (T_{opt}), and the extinction coefficient (k). The remaining parameters in Table 3.3 have a sensitivity ranking of 0 or 1, and as such are not influential in the determination of SV. The sensitivity of SV displays a large environmental variation to the foliage:stem partitioning ratio (p_2) and specific leaf area of seedlings (σ_0), but the actual sensitivities are very low. However, the sensitivity of SV displays moderate environmental variation to the foliage:stem partitioning ratio (p_{20}) and specific leaf area of mature trees (σ_1).

On the other hand, Table 3.3 shows that LAI is highly sensitive to a subset of these parameters (Y , g_{Cx} and α_{Cx}), to the power (n_S) in the allometric relationship between stem mass and mean diameter, and to the maximum litterfall rate (γ_{Fx}), specific leaf area (σ_1) and foliage:stem partitioning ratio (p_{20}) of mature trees. LAI is moderately sensitive to f_{N0} , η_{Rx} and η_{Rn} , and also to n_S . Stand volume and LAI are seen to have a high ($\mu_2 \approx 0.6$) degree of non-linearity with respect to T_{opt} and moderate ($\mu_2 \approx 0.15-0.25$) non-linearity with respect to k , g_{Cx} and T_{max} .

3.4 DISCUSSION

The results presented above constitute a comprehensive analysis of the sensitivity of 3-PG output to species-specific parameters of the model. The sensitivity of 3-PG outputs to stand initialisation data and to site and climatic factors was also studied. The results are invaluable in aiding the parameterisation of 3-PG for new species, and in particular, in a subsequent re-parameterisation of 3-PG for *E. grandis* in South Africa (See Chapter 4). The 3-PG output variables on which the sensitivity analysis was based were a key determinant of stand growth (canopy LAI), a key economic output (SV) and root biomass (W_R). However, effects on soil water or stand water use were not considered. The discussion below refers in particular to two contrasting sites (Mtunzini and Toverton), but the conclusions are typical for all sites.

An important issue in applying models such as 3-PG to predict the temporal pattern of growth is the availability of data that describes the initial state. Sands and Landsberg (2002) showed for *Eucalyptus globulus* that although stem growth rates for mature stands were independent of initial stand data over a reasonable range, early canopy growth and later-age stem volumes were affected by these data. This finding was confirmed here, so a pragmatic approach to stand initialisation was adopted (see Section 3.2) that allowed the allocation of site-dependent foliage, stem and root biomass (W_{Fi} , W_{Si} and W_{Ri}) data for a two year old stand that was realistic, but dependent on a pre-existing assessment of site quality. However, despite differences at individual sites, there was little difference between the overall agreement between predicted and observed SV at the stand ages listed in Table 3.1 when stands were initialised with realistic biomass data at age two years. This, and the fact that sensitivity is calculated from differences between predicted outputs, means that the sensitivity measures are relatively insensitive to initial stand conditions. Although the approach used here to initialise the model and assign the fertility rating (FR) is pragmatic, more objective methods are required (see Section 5.3.2)..

Of the potential applications outlined in Sections 2.1 and 7.1 the most useful within the South African context is to estimate final standing volume towards the end of the rotation. Such predictions are required for harvest scheduling, planning and to estimate the potential supply to the mill and are generally made using either empirically-based models (EBMs) or using inventory information immediately before clear-felling.

Empirically-based models are circular and work reasonably well but are limited to areas and conditions under which they were developed and performing inventory assessments are labour intensive, time consuming and expensive. Process-based models (PBMs) have, therefore a potentially important role to play. Under these circumstances model initialisation is relatively straightforward especially since inventory data is collected at some point during the rotation. Using such information, simple methods have been devised to initialise 3-PG (*i.e.* FR and biomass pools); these are presented in Chapter 5.

This study also showed that initial available soil water (θ_{si}) had no effect on simulated mature-age stands. This was because the amount of water used in early stand growth, did not exceed inputs from monthly rainfall (R) and hence available soil water (θ_s) quickly attained a state independent of θ_{si} . However, this might not be the case at very dry sites and at sites at which there is significant competition by weeds for water.

3.4.1 Sensitivity measures

Definition of relative sensitivity and non-linearity by Equations 3.1 and 3.2 ensures that λ_1 and λ_2 are independent of the units employed for both X and p . They are thus suitable measures for comparing sensitivity and non-linearity of different outputs to a range of different parameters or factors, and even between distinct models. However, their values do depend on the value of both X and p . Thus, even if X is a linear function of p , λ_1 is not constant and varies slightly with X and p . For this reason λ_2 , which is zero when $X(p)$ is linear, was introduced as a measure of non-linearity.

For models that are inherently non-linear, such as 3-PG, λ_1 may vary from site to site (and with the value of p) and therefore the averages μ_1 and μ_2 of λ_1 and λ_2 over all 31 sites have been used as indicators of the inherent sensitivity and non-linearity of an output with respect to a parameter. In addition, the coefficient of variation ($\mu_1 \times E$) of λ_1 about its mean μ_1 is an effective indicator of the environmental variation of sensitivity *i.e.* of how sensitivity varies between sites.

The results presented in Table 3.3 are powerful guides to the accuracy with which parameters need to be determined when 3-PG is adapted to a new species. The basic rules are as follows:

- Parameters with a low ranking in sensitivity can be assigned generic values.
- Parameters with a high ranking in sensitivity must be assigned species-specific values.
- Parameters with a moderate sensitivity ranking but with a high non-linearity or site variation, require special attention as particular circumstances of the

current parameter values or site factors might be hiding potential high sensitivity.

The accuracy δp with which a parameter or factor must be assigned so as to obtain a particular accuracy δ_X in the output variable can be obtained from the relevant relative sensitivity through the relation $\delta p < (p\delta_X/X)\lambda_I$. Conversely, if a parameter can only be determined to the accuracy δp , the likely error δ_X in the output variable is $\delta_X \approx (X\delta p/p)\lambda_I$.

3.4.2 Parameter sensitivity analysis

The parameter sensitivity analysis highlighted the existence of classes of: insensitive parameters, *i.e.* those that can be varied widely without affecting the outputs studied; sensitive parameters, *i.e.* those whose value strongly affects the predicted outputs; and non-linear parameters, *i.e.* those for which the outputs depend in a non-linear manner on the parameter value. Because this study considered the variation of sensitivity of each parameter across a wide range of sites, it also identified potential site-dependence of parameter sensitivity.

Parameters in Table 3.3 are listed in order of increasing maximum ranking of μ_I for SV and LAI, and then in order of increasing maximum ranking of $\mu_I \times E$ for SV and LAI. Ranking on the basis of both outputs reflects the understanding that although SV is an output of economic importance, LAI is a major determinant of growth and productivity. The following discussion, therefore, focuses on both outputs.

It is expected that the values currently assigned to insensitive parameters (*i.e.* those ranked 0-1: g_B to p_2 in Table 3.3), with the possible exception of T_{max} , can be used in a subsequent re-parameterisation of 3-PG, especially for *E. grandis*. However, closer attention will need to be paid to those parameters with moderate sensitivity (*i.e.* those ranked 2: f_{N0} to T_{opt}), and especially to those with the highest ranking (*i.e.* those ranked 3: α_{C_X} to p_{20}). In addition, attention needs to be paid to non-linear parameters with low to moderate sensitivity, as a change in their value could make an insensitive parameter sensitive, and conversely: *e.g.* T_{opt} and T_{max} , and to a lesser extent k . Parameters of moderate sensitivity, but with strong site-dependence also need close attention if the

parameter set is to be applied across a wide range of site conditions. The relevant parameters here are T_{opt} and T_{max} , but not parameters such as L_{Cx} , σ_0 and p_2 because although they have a very high $\mu_j \times E$, their sensitivity is very low.

It is also important to note that some parameters have different sensitivity rankings depending on the particular output variable considered. For instance, basic density (ρ^*) directly and strongly affects SV, but has no effect on the biomass components or canopy LAI. Both the allometric parameters a_S and n_S strongly affect LAI, and in all environments, whereas they have little effect on SV. On the other hand the maximum litterfall rate (γ_{Fx}) and the mature-age specific leaf area (σ_1) directly and strongly affect LAI, and because this affects primary production and hence overall growth, these parameters also affect SV.

In summary, the following parameters will require accurate determination because they have a moderate or high sensitivity ranking for SV or LAI: f_{M0} , a_S , n_S , η_{Rn_x} , η_{Rx} , a_{Cx} , ρ^* , Y , g_{Cx} , γ_{Fx} , σ_1 and p_{20} . In addition T_{max} and T_{opt} require close attention because they are highly non-linear and have a moderate sensitivity ranking. The light extinction coefficient (k) can probably be assigned a generic value (typically 0.5), although its sensitivity ranking is moderate. This is because inaccuracies in k affect light capture for all stands at all times and will be absorbed into inaccuracies inherent in the assignment of a value to other parameters, e.g. a_{Cx} .

Sands and Landsberg (2002) noted that many of the parameters in the list requiring close attention essentially affect primary production and stem growth multiplicatively, and hence uncertainties in one affect the determination of values for the others. The only resolution to this problem is to estimate parameters by fitting observed time-series data for W_F , W_R and W_S biomass to data predicted by 3-PG. In the case of Sands and Landsberg (2002) such data were available for foliage and stem biomass but not root biomass, whereas Almeida *et al.* (2004b) also had access to coarse root biomass. In our case, no time-series data were available.

3.4.3 Dependence of outputs on parameter values

The values of SV and LAI shown in Figure 3.1 as a function of selected parameters can be explained by considering how each parameter affects the calculation of SV and LAI. Net primary production (NPP) is the product of Y (a constant), α_C and intercepted radiation, and hence is indirectly related to the parameters T_{opt} , T_{max} and f_{N0} through the temperature and nutrient modifiers used in the calculation of α_C . Because biomass increments are proportional to primary production, these parameters affect both SV and LAI, (Figures 3.1a-b), and in particular SV and LAI are strongly influenced by α_C (Figure 3.1c), and Y . However, since the temperature modifier also depends on the site temperature, the sensitivity of SV or LAI to the value of T_{opt} can vary significantly from site to site, and as T_{opt} is within the annual range of site temperature, outputs such as SV and LAI vary non-linearly with T_{opt} (Figure 3.1b).

Increasing the biomass partitioned to roots reduces both LAI and SV at all sites. Figure 3.1d shows the sensitivity of LAI and SV to η_{Rx} , and similar results pertain for η_{Rn} . The ranking of environmental variation for these two parameters found in this study (*i.e.* 1 and 0, Table 3.3) may be under-estimated because the variation of FR and the range of mean annual precipitation (MAP) are limited at the study sites (Table 3.2). The foliage:stem partitioning ratio affects the balance between canopy development and accumulation of stem volume (V). But because, in 3-PG, foliage biomass is a balance between growth and litterfall, whereas stem growth is purely accumulative, the foliage:stem partitioning ratios p_2 and p_{20} have more effect on foliage biomass, and hence on LAI, than on SV (Figure 3.1e).

Leaf area is a function of the specific leaf area (SLA), and hence LAI would be expected to vary with parameters that affect SLA. However, SLA essentially attains a constant value (*i.e.* σ_1) by a stand age of four years so LAI is insensitive to seedling specific leaf area (σ_0) but is strongly affected by SLA in mature trees, σ_1 (Table 3.3). L_{Cx} is used in the calculation of canopy conductance and transpiration and hence affects available soil water. It follows that SV and LAI could be sensitive to L_{Cx} when soil water is limiting production. However, sensitivity with respect to L_{Cx} is inherently low (Table 3.3 and Figure 3.1f).

Both stem allometric parameters a_S and n_S affect LAI, and the effect of n_S is quite marked (Figures 3.1g-h), but their effects on SV are small or negligible. These effects are mediated through the effects the allometric relationship has on stem diameter, and hence on biomass partitioning to stems and foliage. It might be surprising that the effect on LAI is so strong, especially in the case of n_S , while that on SV is so weak. This can be explained by considering the causal links between a_S and n_S on the one hand and LAI and SV on the other (Figure 3.4).

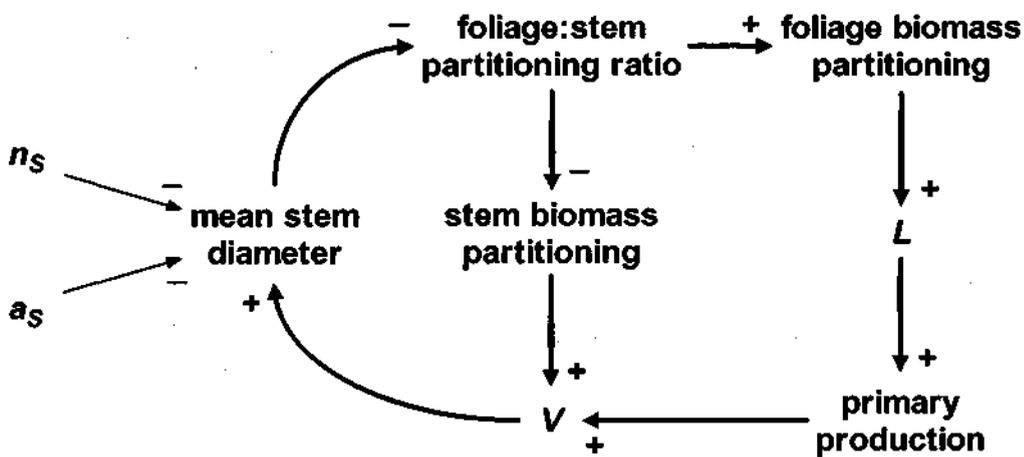


Figure 3.4. Causal loop diagram showing influence of the stem allometric parameters (a_S and n_S) on stem volume (V , $\text{m}^3 \text{ tree}^{-1}$) and LAI. $A \rightarrow B$ indicates that variable A has an influence on variable B, and the sign (+, -) indicates a positive or enhancing effect (+), or a negative or diminishing effect (-).

In a causal loop diagram such as Figure 3.4, $A \rightarrow B$ indicates that variable A has a direct influence on variable B, and the sign (+, -) indicates a positive or enhancing effect (+), or a negative or diminishing effect (-). Closed loops such as $A \rightarrow B \rightarrow A$ (and where B may comprise several steps) are known as feedback loops and are important controls on the dynamics of the system. Loops such that an increase in A feeds around the loop to further increase A comprise positive feedback, and loops such that an increase in A feeds around the loop to cause a decrease in A comprise negative feedback.

First, for a given V , an increase in a_S or n_S causes a decrease in DBH because V is proportional to $a_S B^{n_S}$ and $n_S > 1$. Next, it can be seen from Figure 3.4 that an increase in DBH will increase stem biomass partitioning (η_S) and hence increase SV and DBH; this

is a positive feedback loop. On the other hand, an increase in DBH will also decrease foliage biomass partitioning (ηF) and hence decrease LAI, which in turn leads to a decrease in NPP and hence in V and ultimately in DBH; this is a negative feedback loop. So an increase in a_S or n_S causes an increase in LAI, as is seen in Figures 3.1g-h. However, an increase in a_S or n_S can cause either an increase or a decrease in V , depending on the loop followed in Figure 3.4, and the two effects cancel or result in a milder response.

3.4.4 Sensitivity to site and climatic factors

The sensitivity of 3-PG stand-level outputs to site and climatic factors was also studied, and results are summarised in Figures 3.2 and 3.3. Increased fertility increases SV , and decreases W_R (Figure 3.2a and 3.2b). It is generally agreed that biomass partitioning to roots declines with increasing site fertility (Vogt *et al.*, 1997), and this is seen here. However, since $f_{N0} = 1$ in the parameter set used here, FR has no effect on canopy quantum efficiency, and so NPP and total stand biomass are not directly affected by FR. This situation differs from that found for effects of site R (see below) because the latter does increase production. Changes in the maximum available soil water (θ_{Sx} , see Figures 3.2c and 3.2d) have no effect on SV or W_R .

Both SV and W_R show a substantial response to increasing site R (Figures 3.3a and 3.3b). Because water stress reduces α_C and hence growth, this response suggests that at these sites NPP is limited to some extent by soil water. Water stress also increases partitioning to roots, but this effect is much less than the effects of increased R on NPP and hence both SV and W_R increase with increasing R, but at different rates. However, an increase in monthly mean temperature results in a reduction of SV and W_R at both sites (Figures 3.3c and 3.3d), and the effect is more pronounced at the warmer site (Mtunzini). A decrease in SV and W_R is predicted because temperatures generally exceed the optimum temperature (T_{opt}) for growth and hence increased temperature reduces α_C . However, increased transpiration rates and the subsequent onset of tree water stress may also play a role in reducing NPP and hence overall growth.

3.5 CONCLUSION

The analysis presented is a comprehensive sensitivity analysis for the forest growth model 3-PG. The results have identified parameters that need to be accurately determined if 3-PG is to be used with confidence as a management tool for *E. grandis* in South Africa. They also provide general information that will facilitate a sound parameterisation of 3-PG for other species or under other conditions. This work therefore satisfies the first objective (see Section 1.2). The analysis also examined the sensitivity of the model to site initialisation data, and to site and climatic factors. These results illustrate the accuracy with which site and climatic factors need to be determined, and the general impacts of these on stand growth. A useful by-product of this study is greater understanding of the functioning of 3-PG, and of its strengths and weaknesses. This will enhance its potential as a tool to predict plantation productivity and to identify factors that limit growth, leading ultimately to its use as a component of a management system for commercial forestry.

CHAPTER 4

ADAPTATION OF 3-PG TO *EUCALYPTUS GRANDIS* – SPECIES-SPECIFIC PARAMETERS

4.1 INTRODUCTION

3-PG parameters comprise site and species-specific parameters which characterise the canopy structure and canopy quantum efficiency, allometric relationships and biomass partitioning, branch and bark fractions (p_{BB}), basic wood density (ρ^* , $t\ m^{-3}$), litterfall and root turnover rates, and various environmental modifiers. This chapter describes the development of a parameter set for *E. grandis* for 3-PG.

Model parameterisation or calibration (see Section 6.1.2) is the process whereby selected parameters of the model are adjusted so that model outputs match observations (Schulze, 2003). Several studies outlining the parameterisation of 3-PG for a range of species and regions have recently been published (Table 4.1). Parameter estimation in many of these studies was achieved using a stepwise approach where parameter values were adjusted until the fit of model predictions to experimental data was no longer improved. Hopkins and Leipold (1996) argue that such parameter adjustments can be defended by the following: (i) the circumstances under which the original parameter values were determined might not be similar or consistent with the system being modelled; (ii) if the parameter values have been determined over several locations there could well be a range of values; and (iii) if a model is to be used in management and planning it should at least reproduce some reasonable results.

Table 4.1. Methods used to assign parameter values for several tree species based on a series of publications regarding the parameterisation of 3-PG. Abbreviations for species are: GU – *E. grandis* x *urophylla*; and GC – *E. grandis* x *camaldulensis*.

Methods to assign parameter values	Species	Author
Generic default parameter values based on a range of studies and publications.	many species	Landsberg and Waring (1997)
Progressive adjustment of parameter values within biological realistic bounds + default values.	<i>E. globulus</i> <i>E. grandis</i>	Morris (2000)
Benchmark paper in which parameters made more intuitively meaningful. These were adjusted in stepwise fashion to give best fit to observed data.	<i>E. globulus</i>	Sands and Landsberg (2002)
Assigned using destructively harvested data, physiological measurements and default values.	GU	Stape <i>et al.</i> (2004)
Assigned from direct observation. Remainder of parameters estimated through manual adjustments until best fit obtained.	<i>E. grandis</i> hybrids	Almeida <i>et al.</i> (2004b)
Selected parameters assigned using field measurements and default values for <i>E. globulus</i> .	GC	Dye <i>et al.</i> (2004)

However, Hopkins and Leipold (1996) caution against such logic giving reasons why such parameter adjustments should not be done. *“At the root of this belief is the assumption that substantial disagreement between model predictions and experimental data indicates a serious error. Such an error could be in the parameter values, the model equations, or the experimental results. If the error is in one or more of the parameter values, it is not clear how one would choose the right parameter value(s) to adjust. Particularly with complex models characterised by many parameters, it is likely that values other than the incorrect one(s) could be adjusted to improve the fit. If the error is in the model equations or the experimental data, it might still be possible to adjust away the lack of fit. And finally, parameter values optimised for a particular set of experimental conditions might give worse model predictions than the unadjusted parameters when an attempt is made to model a different set of experimental conditions.”* These cautions are noted and accepted. Nevertheless, in most practical applications parameter adjustments may well be necessary because of a lack of data, problems of scaling, and/or a poor understanding of processes (Mäkelä *et al.*, 2000). Sands (2004a) maintains that manually assigning parameter values can provide initial values suitable for the automated process, and aids in understanding the process.

4.2 DATA SOURCES AND CLASSIFICATION OF PARAMETERS

To parameterise and test the 3-PG model, data should preferably come from sites covering a range of site qualities (*e.g.* low, medium and high productivity). It is highly desirable that good biomass data come from one or more sites that are not limited by either fertility or θ_s , as this averts the need to be concerned with the soil and nutrient modifiers, and also from sites limited by water only or fertility only. At least some of the individual items of data should comprise a significant time-series and should include foliage (W_F and/or LAI), stem (W_S and/or SV) and/or DBH/qDBH, and W_R and leaf litter-fall over a period of time (Sands, 2004a). In general, age-series data are not as suitable as time-series data as they come from different sites often having distinct management and climatic histories. The data typically required to parameterise and test 3-PG can be classified as biomass harvest, field, literature, mensuration and physiological data (B, F, L, M or P) as shown in Table 4.2.

Table 4.2. Data source classes for data required for parameterisation.

Data source class		Description
Biomass harvest	B	Data from direct measurement of harvested trees, <i>e.g.</i> biomass data (foliage, stem, root), leaf area, wood density
Field data	F	Data not routinely obtained from an inventory assessment, <i>e.g.</i> soil samples, litterfall, soil water, specific leaf area, leaf area index
Literature	L	Data obtained from the literature
Mensuration	M	Data from an inventory assessment, <i>e.g.</i> measured stem height and diameter, volume or other data inferred from statistical relationships
Physiological	P	Results of physiological experiments, <i>e.g.</i> gas-exchange analyses

Individual species to which 3-PG is applied are characterised by a set of species-specific parameters. The use of 3-PG for forest management depends on the ability to obtain reliable values for parameters characterising several eucalypt, acacia, pine and other species. Although 3-PG has been applied to a wide range of species and clones, in only a few cases have the species-specific parameters been rigorously determined, and this has been largely by a process of trial and error (*e.g.* Morris (2000); Sands and Landsberg (2002); Almeida *et al.* (2004b) and Table 4.1). Therefore, a systematic protocol for assigning species-specific parameters was required. This was made possible by understanding the meaning of the model parameters, and the sensitivity of 3-PG outputs to these parameters (Chapter 3).

As a general rule, parameter values should always be assigned by direct measurement, either as the direct result of some experimental measurement, or indirectly by regression analysis of experimental data, or by analogy with other species (Sands, 2004a). Failing this, parameters can be estimated by adjusting their values to optimise the fit of 3-PG output to observed data. For this case, software for fitting model output to observed data is available. Estimation by adjusting parameter values to optimise the fit between observed and predicted data is effective, but should be the last choice. These observations are reflected in the classification of parameters by their estimation class (Table 4.3). This classification serves only as a formal guide of how a particular parameter might be assigned a value. Sensitivity analysis of key model outputs (*e.g.* LAI, SV) to the species-specific parameters in a model (see Section 3.4.2; Battaglia and Sands, 1998b) provides a classification of parameters according to the accuracy with which they must be assigned. These estimation and sensitivity classes are presented for 3-PG in Table 4.3. The estimation classes are default, observed, estimated (D, O or E), and the sensitivity classes are low, medium and high (L, M or H). This classification, and the data source classes (Table 4.2) were applied to the 3-PG parameters as shown in Table 4.4. These reflect current judgement for *E. globulus* (Sands and Landsberg, 2002) and provide guidance for parameter estimation for a range of species.

Table 4.3. Parameter estimation and sensitivity classes (see Section 3.3.2, Table 3.3).

Estimation class		Description
Default	D	The parameter can be assigned some generic value, <i>e.g.</i> based on work with other species, or from <i>a priori</i> knowledge
Observed	O	The parameter can be directly measured, <i>e.g.</i> via gas-exchange analysis, or determined by analysis of experimental data, <i>e.g.</i> by regression analysis
Estimated	E	The parameter can only be estimated indirectly, <i>e.g.</i> by adjusting its value to optimise the fit of some output to observed data
Sensitivity class		Description
Low	L	Outputs are essentially independent of the parameter value
Medium	M	Outputs depend moderately on the parameter value
High	H	Outputs depend strongly on the parameter value, or their sensitivity varies significantly across sites

Default parameter values (D), comprise, *inter alia*, environmental modifiers and conversion factors such as the molecular weight for wood and the conversion of SR to photosynthetically active radiation (PAR, MJ m⁻² d⁻¹). Examples of sensitivity class L are parameters related to the canopy boundary layer conductance (g_B , m s⁻¹), specific

leaf area for young stands, and branch and bark fraction (p_{BB0} and p_{BB1}) (see Section 3.4.2, Table 3.3). Such insensitive parameters can be assigned a value common to other species, which is especially helpful when parameters are not experimentally accessible (Sands, 2004a). However, parameters representing processes that are experimentally accessible should be assigned values using observed data (estimation class O), *e.g.* allometric parameters. Where such parameters cannot be assigned values directly (estimation class E), values have to be estimated (*e.g.* α_{Cv} , p_2 and p_{20}).

A distinction between parameter assignment and parameter estimation is made as follows: Assigning parameter values is done through direct measurement. In contrast, parameter estimation is the process whereby parameter values indirectly ascribed or adjusted according to some observed data or by analogy with other species.

TABLE 4.4. CLASSIFICATION OF PFT PARAMETERS (SANDS 2004a) IN TERMS OF SENSITIVITY CLASSES WHICH ARE LOW, MEDIUM AND HIGH (L, M AND H), estimation classes given as Default, Observed and Estimated (D, O and E), and data source class classified as Biomass harvest, Field data, Literature, Mensuration and Physiological (B, F, L, M and P) as described in Tables 4.2 and 4.3.

Description	Units	Symbol	Site / species specific ^a	Sensitivity class	Estimation class	Data source class	Data requirements and comments
Allometric relationships & partitioning							
Ratio of foliage:stem partitioning at DBH = 2 cm	-	P_2	Species	H	E	B	Foliage biomass or LAI, stem biomass or DBH
Ratio of foliage:stem partitioning at DBH = 20 cm	-	P_{20}	Species	H	E		
Constant in stem mass v diameter relationship	kg	a_S	Species	M	O		
Power in stem mass v diameter relationship	-	n_S	Species	H	O		Stem biomass and DBH at contrasting sites
Maximum fraction of NPP to roots	-	η_{Rx}	Species	M	O/E		
Minimum fraction of NPP to roots	-	η_{Rn}	Species	M	O/E		Below and above ground biomass
Litterfall & root turnover							
Litterfall rate at $t = 0$	month ⁻¹	f_{r0}	Both	L	D		
Litterfall rate for mature stands	month ⁻¹	f_{rx}	Both	H	O	F	Observed litterfall, SLA and LAI
Age at which litterfall rate has median value	month	t_{rf}	Both	L	E/D		
Average monthly root turnover rate	month ⁻¹	γ_R	Both	L	D	L	Understanding of root turnover rates
Environmental modifiers							
Minimum temperature for growth	°C	T_{min}	Species	L	D		
Optimum temperature for growth		T_{opt}	Species	M	E	B/M	Growth data from contrasting sites
Maximum temperature for growth		T_{max}	Species	L	D		
Number of days production lost for each frost day	-	kF	Species	L	D	B/M	Growth data from cold sites
Value of m when FR = 0	-	m_0	Species	-	O		
Value of f_N when FR = 0	-	f_{N0}	Species	M	O	M/B	Growth data from sites unlimited by fertility and soil water stress AND sites limited by fertility
Power of (1-FR) in f_N	-	fNn	Species	L	O		
Defines stomatal response to VPD	mbar	k_D	Species	L	D	P	Conductance data
Moisture ratio deficit which gives $f_D = 0.5$	-	c_D	Site	H	D	F	Soil water retention characteristics
Power of moisture ratio deficit in f_D	-	n_D	Site	L	D		
Maximum stand age used to computer relative age	years	t_x	Species	L	D		
Power of relative age in f_{age}	-	n_{age}	Species	L	D	B/M	Growth data over long time periods
Relative age to give $f_{age} = 0.5$	-	Γ_{Age}	Species	L	D		
Conductance							
Maximum canopy conductance	m s ⁻¹	g_{Cx}	Species	H	O/E	P	
Canopy LAI for maximum canopy conductance	-	L_{Cx}	Species	L	D	L	Conductance data
Canopy boundary layer conductance	m s ⁻¹	g_B	Both	L	D	L	
Stem mortality^{bc}							
Seedling mortality rate ($t = 0$)	% yr	γ_{s0}	Species	-	O	M	Time series of SPH
Mortality rate for older stands (large t)	% yr	γ_{sx}	Species		O		
Age where mortality = 1/2 seedlings and older stands	years	$t_{1/2}$	Species		O		

Description	Units	Symbol	species specific ^a	Sensitivity class	Estimation class	data source class	Data requirements and comments
Shape of mortality response	-	n_{FN}	Species		O		
Specific leaf area							
Specific leaf area at stand age 0	$m^2 kg^{-1}$	σ_0	Species	L	O		
Specific leaf area for mature aged stands	$m^2 kg^{-1}$	σ_1	Species	H	O	B	Observed SLA over a range of sites
Age where SLA = 1/2 young & older stands	years	t_σ	Species	L	O		
Rainfall interception							
Maximum fraction of rainfall intercepted by canopy	-	i_{RX}	Both	M	D		
LAI for maximum rainfall interception	-	L_{ik}	Species	L	D	F/L	Rainfall interception data
Light interception, production and respiration							
Extinction coefficient for PAR absorption by canopy	-	k	Species	M	D	O	
Age at full canopy cover	years	t_c	Species	M	M	F	Light interception data
Maximum canopy quantum efficiency	$mol mol^{-1}$	α_{Cx}	Species	H	E	B/M	Growth data with no fertility or water limitation
Ratio NPP/GPP	-	Y	None	H	D	L	
Branch & bark fraction							
Branch and bark fraction at stand age 0	-	P_{BB0}	Species	L	O		
Branch and bark fraction for mature aged stands	-	P_{BB1}	Species	L	O	B	Observed biomass data
Age at which $P_{BB} = 1/2$ that for young & old trees	years	t_{BB}	Species	L	O		
Basic density							
Minimum basic density – for young trees	$t m^{-3}$	ρ_0	Both	H	O		
Maximum basic density – for older trees	$t m^{-3}$	ρ_1	Both	H	O	B	Observed biomass data
Age at which density = 1/2 density of old young trees	years	t_p	Both	M	O		
Stem height allometric relationship^f							
Constant in stem height relationship	m	a_H	Species	-	O		
Power of qBDH in stem height relationship	-	n_{HB}	Species	-	O	M	Observed height and diameter data
Power of stocking in stem height relationship	-	n_{HN}	Species	-	O		
Stem volume allometric relationship^e							
Constant in stem volume relationship	m^3	a_V	Species	-	O		
Power of qDBH in stem volume relationship	-	n_{VB}	Species	-	O	M	Observed height and diameter data
Power of stocking in stem volume relationship	-	n_{VN}	Species	-	O		
Conversion factors							
Intercept of net radiation v. solar radiation relationship	$W m^{-2}$	Qa		H	D	L/P	
Slope of net radiation v. solar radiation relationship	-	Qb		H	D		
Molecular weight of dry matter	$gm mol^{-1}$	$g_{DM, mol}$		H	D		Literature and physiological experiments
Conversion of solar radiation to PAR	$mol MJ^{-1}$	$molPAR_{-}$		H	D		

^aSite/species-specific information taken from Table 1 in Sands and Landsberg (2002).

^bSince improved mortality function used, self-thinning parameters omitted. It is noted that these parameters should be used for longer rotations.

^cModifications and new updates to 3PGpjs

4.2.1 Guidelines for assigning parameters values

The following guidelines, taken from Sands (2004a), were followed when assigning species-specific 3-PG parameters for *E. grandis*:

- First assign values to all parameters that can be directly observed, or can be given default values, or by analogy with other species.
- Of the remaining parameters, identify those that cannot be assigned, by fitting to observed data because suitable data are not available, and reconsider these with a view to assigning them default values.
- Estimate the remaining parameters by fitting model output to appropriate observed data, taking into account any *a priori* information, *e.g.* on the permissible range for the parameters. This may be by either manually adjusting parameter values, or by using appropriate software, or both, and it may be an iterative process.
- It is important that the fit be based on observations of as many distinct variables as possible, and from sites covering a wide range of conditions.
- There is no point in basing a fit on more than one set of observed data that are correlated, *e.g.* SV, W_s , DBH and qDBH are highly correlated.

When parameter values have been established, the following basic checks must be performed on both the parameters and the subsequent outputs of the model:

- Check that all parameter values are biophysically or biologically reasonable.
- Perform at least a basic sensitivity analysis of observed and assigned values in the context of the final parameter set (Chapter 3). If they are of low sensitivity, they should not need to be considered further; otherwise their values will have to be carefully examined for reasonableness (Chapter 3).
- Verify that the behavior of all outputs is reasonable, especially those not used in the estimation process, *e.g.* canopy LAI is often predicted to be very high within the first two years of canopy development. Should an output behave unreasonably, repeat the estimation with a bound placed on the output in question.

4.2.2 Guidelines for estimating parameter values

Parameter estimation is a systematic process in which the fit of model outputs to observed data is optimised either manually (stepwise adjustment) or automatically (estimation software). Optimisation is accomplished by minimising the merit function through the adjustment of selected parameters. The merit function, usually the residual sum of squares, measures the agreement between model predictions and observed data when changing the values of a subset of parameters, and is conventionally arranged so that small values represent a good agreement (Press *et al.*, 1992). Best-fit parameters are realised by iteratively adjusting model parameters until a minimum in the merit function is reached (Press *et al.*, 1992). Many algorithms exist to minimise the merit function (Sands, 2004a), with the Marquardt algorithm being one such example (*e.g.* Marquardt, 1963, and Draper and Smith, 1981 cited by Sands 2004a). This algorithm is implemented by the freeware package PEST (Parameter ESTimation, Doherty, 2002). PEST which is a non-linear parameter estimator, is widely used with hydrological models to infer aspects of reality that may not be amenable to direct measurement (Waterloo Hydrogeologic, 2002).

The primary purpose of PEST is to assist in data interpretation through the estimation of system properties from observed data sets, and for model parameterisation and predictive analysis (*i.e.* once a parameter set has been determined, it is reasonable to ask whether another parameter set exists). PEST operates by “*taking control*” of the model that is being parameterised and executes it as many times as is necessary to minimise the merit function and determine the optimal set of parameters. Using the Marquardt algorithm, PEST adjusts model parameters until the fit between model outputs and field observations are optimised in the least squares sense. An additional feature of PEST is the analysis of non-unique parameter values and the repercussions of these values on predictions made by the model.

Early attempts to use PEST to estimate 3-PG parameters were difficult because 3-PG_{PJS} as an Excel spreadsheet, had to be transformed into an executable file. This meant that the user no longer had the flexible access nor the power of the commonly used spreadsheet implementation of 3-PG (Sands, 2004a). A spreadsheet-based technique

that allows the use of PEST with spreadsheet-based models was developed (NRF, 2002). This tool allows parameter estimation for any Excel-based model and eliminates the tedious preparation of PEST control files. In addition, it gives confidence limits or standard errors on the parameter estimates, and the correlation between estimates. These are invaluable additional results from the estimation that are not readily available from manual estimations. Sands (2004a) took this spreadsheet technique a few steps further and developed PEST_{XL} which has a user-friendly interface and “*wizard*” that allows the 3PGpjs user to access and apply PEST without knowledge of, or the need to see PEST_{XL}, its self.

With respect to parameter estimation the following guidelines were therefore adhered to (Sands, 2004a):

- A successful estimation should be repeated with different initial parameter values. This will test the robustness of the estimated parameter set, and possibly avoid convergence to a local optimum.
- It is advisable to simultaneously use data spanning a wide range of site conditions. However, an initial estimation based on a single or few sites can quickly highlight problems such as correlation between parameters, or parameters or model output variables going out of range.
- Parameter estimation software packages also provide confidence intervals or standard errors for the estimated parameters. If the confidence interval is large it is often worth fixing the parameter mid-range to reduce the number of parameters being estimated.
- If the confidence interval encompasses the value of a parameter that in practice turns some process or effect off, consider repeating the estimation with the parameter fixed at that particular value.
- Software packages for estimation also provide the correlation matrix between parameter estimates. If two or more parameters are highly correlated, estimation can often be aided by holding one constant whilst estimating the others.

- A difficult estimation can often be aided by successively estimating groups of parameters. It is then worth trying to refine the entire parameter set by estimating all the parameters with their new values as initial values for the full estimation.

Several other important considerations, specific to the parameter estimation of 3-PG, are documented in Sands (2004a). Of these, two very important issues are firstly, the use of surrogate data in the absence of state variable measurements, and secondly, the importance of interacting parameter groups. As highlighted, parameter estimation should ideally be based on observed values of W_F , W_R and W_S biomass, SPH and soil water contents. The reasons for this, according to Sands (2004a), are because the primary variables predicted by 3-PG are strongly related to the internal structure of the model. Where these data are not available, surrogates may be used. There are no simple surrogates for W_R ; however, many exist for W_F (e.g. LAI) and for W_S (e.g. DBH, HT or SV).

Understanding the interaction effects of groups of parameters on the behaviour of 3-PG is essential, especially when using estimation packages such as PEST. This aspect of model parameterisation is highly complex and therefore an explanation around the parameter interactions in 3-PG is quoted from Sands (2004a). *“Three interacting parameter groups are (a) maximum canopy quantum efficiency (α_{Cx}), (b) parameters controlling biomass allocation (i.e. foliage stem partitioning ratios (p_2 and p_{20}) and below ground allocation (η_{Rx} and η_{Rn}) and (c) those controlling the growth modifiers. These groups interact because growth of each biomass pool is the product of NPP and the corresponding allocation ratio. The goal is to find values for α_{Cx} , p_2 , p_{20} , η_{Rx} and η_{Rn} that apply to all stands, irrespective of the degree of growth limitation, and for the parameters characterising the modifiers. Groups (a) and (b) strongly interact, and can be uniquely estimated if biomass data from all pools are available at sites free of major growth limitations. Group (c) interacts with the others to a lesser extent, and their estimation requires data from sites with significant growth limitations. However, site fertility usually does not vary significantly during a rotation, and unless growth data is available from a range of sites with widely varying fertility, including sites free of*

fertility limitations, the product a_{Cx} and fertility cannot be separated into a_{Cx} and the effect of fertility on NPP". As with other mechanistic models, selected parameter groupings affect model outputs (e.g. Sievanen and Burk, 1993; Sievanen and Burk, 1994; Sands and Landsberg, 2002).

Parameter estimation is a powerful but often abused technique, which can readily lead to erroneous results. To help avoid this, parameter estimations must be tempered by judgement and only be undertaken with a sound understanding of the model and the purpose of each parameter. Furthermore, final parameter values and model predictions must be checked for biological reality (see Section 6.4.3).

Accordingly, 3-PG was parameterised for *E. grandis* using a methodology similar to that of Sands and Landsberg (2002) except where they estimated parameters by "trial and error", PEST_{XL} was used to estimate optimum parameter values. Initially parameters that could be directly observed or given default values were assigned values. The remaining parameters comprised those that could not be assigned values because of limited or no data (e.g. root data), and those that cannot be directly estimated using observed data (e.g. p_2 and p_{20}). For these, either default values were used or values were estimated by fitting model output to observed data. When parameters were estimated it was important to set biologically reasonable ranges within which the parameters could vary. Parameter assignment and estimation specific to *E. grandis* is outlined next.

4.3 ASSIGNING/ESTIMATION OF PARAMETER VALUES FOR *E. GRANDIS*

Using the information presented in Table 4.2 and the parameterisation guidelines, default parameter values were gleaned from Landsberg and Waring (1997) and selected literature sources (e.g. Sands and Landsberg (2002); Gush (1999)). Since no physiological data were collected during this study appropriate values were gleaned from the literature.

Fourteen destructive harvesting studies were performed within South Africa. At each site only aboveground biomass data were collected. Of these sites, 10 came from the 31

research trials used in the model evaluation (see Section 2.3.4) and parameter sensitivity analysis (Chapter 3). These sites were selected according to the following criteria: (1) trees were originally planted as seedlings; (2) the stocking at harvest was at least 70% of the initial stems per hectare; (3) trials were situated relatively close to sites to be used in subsequent model verification studies; (4) the sites had contrasting water and climatic environments, and (5) climatic data were available. Furthermore, sites spanning a range of ages and productivities, measured as the MAI, were required. Four age classes (1-3 yr; 4-6 yr; 7-9 yr and >10 yr) and three MAI-based productivity classes namely low, <25 m³ ha⁻¹ y⁻¹, medium, 25-40 m³ ha⁻¹ y⁻¹, and high, >40 m³ ha⁻¹ y⁻¹ were therefore selected (Table 4.5). These trials had received high quality silvicultural management, particularly during the early establishment phase.

Table 4.5. Description of the *E. grandis* trials at which selected trees were destructively harvested for the collection of aboveground biomass components. Abbreviations are: T_X and T_N , - mean monthly maximum and minimum temperature; MAT - mean annual temperature; and MAP - mean annual precipitation.

Trial	Age (years)	Initial stocking	Final stocking	Altitude (m)	T_X (°C)	T_N (°C)	MAT (°C)	MAP (mm)	Productivity class
T15	12	1667	1302	780	24	11.6	17.8	891	Low
K1	11	1667	1480	1192	22.6	10.1	16.3	1008	Low
SSP7	7	1600	1328	955	23.3	11.1	17.2	874	Low
CSP1	3	1680	1680	1260	22.3	9.6	15.2	950	Low
B24	2	1667	1440	880	-	-	17.5	829	Low
K2	9	1667	1417	979	22.3	10.7	16.5	784	Medium
SSP1	6	1667	1242	1243	21.6	10.2	15.9	814	Medium
SSP13	7	1600	1342	15	27.2	16.4	21.8	860	Medium
A69	6	1666	1468	900	-	-	17.4	895	Medium
SSP23	6	1976	1304	889	25.1	12.3	18.7	1185	High
K4	8	1389	972	66	26.6	16.6	21.6	1174	High
SSP10	7	1600	1216	39	26.8	16.9	21.9	1068	High
SSP8	6	1600	1144	97	25.8	16.4	21.1	1403	High
W162	1.5	1333	1328	66	26.6	16.6	21.6	1174	High

The DBH of approximately 196 trees (14 rows by 14 trees) were measured within the control treatment of each trial. To ensure representative sampling, the measured DBHs were stratified from the largest to the smallest tree and divided into 12 size classes from which the median tree of each class was selected. The methodology described was replicated on all trees across all sites (*i.e.* approximately 14 sites x 12 trees). Each

selected tree was felled into cleared areas to minimise leaf and branch loss, then measured for total height to the first live branch and height to the canopy base. The over-bark diameter (OBD) at 1 m increments along the length of the bole to 5 cm OBD was recorded. The aboveground biomass components, *i.e.* foliage, capsules, branches (living and dead), bark and stemwood, were separated and the total wet mass of each determined. The wet masses of sub-samples from each component were determined before returning to the laboratory where additional measurements (stemwood volume and leaf area) were completed and samples were oven dried to a constant mass. The leaf area of the foliage sub-sample was determined using the LI-COR 3100 Leaf Area Scanner (LI-COR Inc, Lincon, Nebraska, USA) and together with the oven-dried mass, was used to calculate SLA. Application of the water displacement method to measure the volume of wood (TAPPI, 1985) enabled the inference of basic wood density. Using the ratio of wet:dry mass of each sub-sample, the total dry mass for each component at the tree scale was determined.

Data and information relating to the field data source class (Table 4.2) comprised LAI measurements, monthly litterfall collection and soil samples. At the time of harvesting the plant area index (PAI, $\text{m}^2 \text{m}^{-2}$) at 9 sites was measured using the LICOR 2000 Plant Canopy Analyser (PCA, LI-COR Inc, Lincon, Nebraska, USA). Using the calibration curve ($\text{LAI} = 1.54 \times \text{PAI}$) developed by Cherry *et al.* (1998), corresponding LAIs for each site were determined. Between May and August 2002 four litter-traps, each occupying 6 m^2 , were randomly established at 12 of the sites. Litter was collected at monthly intervals, taken to the laboratory and sorted into woody and leafy components prior to oven drying. Although litter traps at 5 of the sites were lost due to theft, the quality of the litter fall data was sufficient to estimate litterfall rates required by 3-PG. Soil samples from each of the harvested trial sites were analysed in the laboratory and characteristics describing the organic matter and soil texture were determined.

Stand-level mensuration data comprised qDBH, DBH and HT measurements from all the trials. Using these data and observed tree volume (based on the mass and density of each 1 m section of the bole) of all harvested trees, a generic set of coefficients applicable to the Schumacher-Hall (S-H) volume function as described in Coetzee

(1992) was derived. By applying this generic S-H function, annual time-series data of SV were calculated for six site-species-productivity (SSP) trials, and used for the parameter estimation work described in the following sections.

4.3.1 Parameter assignment

The 3-PG parameters and their values for *E. grandis* determined both by Gush (1999) and in this study, are presented in Table 4.6 (see Table 4.4 for accompanying symbols and units). Note that in some cases, where there were no data available, the suggested estimation class (Table 4.4) has been changed accordingly. Allometric and age-dependent relationships used in 3-PG_{PJS} are assigned values using biomass and field data. Unless otherwise specified, default parameter values are from Landsberg and Waring (1997).

Table 4.6. 3-PG parameter values for *E. grandis* (this chapter) and from Gush (1999). See Table 4.4 for accompanying symbols and units.

Description	Estimation class ^a	Gush (1999) ^b	This study ^c
Allometric relationships & partitioning			
Ratio of foliage:stem partitioning at DBH = 2 cm	E	1	0.75
Ratio of foliage:stem partitioning at DBH = 20 cm	E	0.15	0.11
Constant in stem mass v diameter relationship	O	0.095	0.044
Power in stem mass v diameter relationship	O	2.4	2.771
Maximum fraction of NPP to roots	D ¹	0.6	0.6
Minimum fraction of NPP to roots	D ¹	0.25	0.25
Litterfall and root turnover			
Litterfall rate at t = 0	D	0.001	0.001
Litterfall rate for mature stands	O/E	0.035	0.075
Age at which litterfall rate has median value	O	24	24
Average monthly root turnover rate	D	0.015	0.015
Environmental modifiers			
Minimum temperature for growth	D ¹	3	3
Optimum temperature for growth	E	23	23
Maximum temperature for growth	D ¹	35	35
Number of days production lost for each frost day	D	0	1
Value of m when FR = 0	D	0	0
Value of f_N when FR = 0	D	1	1
Power of (1-FR) in f_N	D	0	0
Defines stomatal response to VPD	L ²	0.05	0.05
Moisture ratio deficit which gives $f_\theta = 0.5$	D	0.7	0.7
Power of moisture ratio deficit in f_θ	D	9	9
Maximum stand age used to compute relative age	D ¹	30	30
Power of relative age in f_{age}	D	4	4
Relative age to give $f_{age} = 0.5$	D	0.95	0.95
Conductance			
Maximum canopy conductance	L ¹	0.02	0.02
Canopy LAI for maximum canopy conductance	D	3.33	3.33
Canopy boundary layer conductance	L ¹	0.2	0.2
Stem mortality			
Seedling mortality rate (t = 0)	O	na	2
Mortality rate for older stands (large t)	O	na	2
Age at which mortality = 1/2 that for seedlings and older stands	O	na	4
Shape of mortality response	O	na	1
Specific leaf area (SLA)			
Specific leaf area at stand age 0	O	12	13
Specific leaf area for mature aged stands	O	6	7.7
Age at which SLA = 1/2 that for young & older stands	O	2	2.25
Rainfall interception			
Maximum fraction of rainfall intercepted by canopy	D	0.15	0.15
LAI for maximum rainfall interception	D	0	0
Light interception, production and respiration			
Extinction coefficient for PAR absorption by canopy	O/D ²	0.5	0.5
Age at full canopy cover	D	0	2
Maximum canopy quantum efficiency	E	0.06	0.064
Ratio NPP/GPP	E/D	0.47	0.47
Branch and bark fraction			
Branch and bark fraction at stand age 0	O	0.15	0.6

Description	Estimation class ^a	Gush (1999) ^b	This study ^c
Branch and bark fraction for mature aged stands	O	0.15	0.131
Age at which $p_{BB} = \frac{1}{2}$ that for young & old trees	O	1.5	1.945
Basic density			
Minimum basic density – for young trees	O	0.5	0.53
Maximum basic density – for older trees	O	0.5	0.32
Age at which density = $\frac{1}{2}$ density of old and young trees	O	4	5.66
Stem height allometric relationship			
Constant in stem height relationship	O	na	0.84
Power of qDBH in stem height relationship	O	na	1.15
Power of stocking in stem height relationship	O	na	0
Stem volume allometric relationship			
Constant in stem volume relationship	O	na	3.1×10^{-5}
Power of qDBH in stem volume relationship	O	na	3.094
Power of stocking in stem volume relationship	O	na	1
Conversion factors			
Intercept of net radiation v solar radiation relationship	D	-90	-90
Slope of net radiation v solar radiation relationship	D	0.8	0.8
Molecular weight of dry matter	D	24	24
Conversion of solar radiation to PAR	D	2.3	2.3

^a Effective estimation class resulting from this study;

^b Parameter values developed in Gush (1999); ^c Parameter values developed in this study.

D: parameter values taken from Sands and Landsberg (2002) and Landsberg and Waring (1997);

D¹: parameter values taken from Gush (1999);

D²: Parameter exhibiting large environmental variation therefore default value used;

L¹ Parameter value taken from Dye (1987).

Allometric relationships

Three biomass allometric relationships with respect to qDBH are used in 3-PG. These are: (i) the mean single tree biomass (w_s , kg tree⁻¹) calculated from W_s /SPH, depicted as a function of qDBH; (ii and iii) SV and HT, both as functions of qDBH and SPH, shown in Equations 4.1, 4.2 and 4.3 respectively. These allometric relationships were parameterised with respect to the qDBH as follows:

$$w_s = a_s B^{n_s} \quad (4.1)$$

$$SV = a_v B^{n_{vb}} N^{n_{vn}} \quad (4.2)$$

$$HT = a_H B^{n_{hb}} N^{n_{hn}} \quad (4.3)$$

where the allometric parameters a_s , a_v and a_H are multipliers; n_s , n_{vb} , n_{hb} and n_{vn} , n_{hn} are the powers of B (referring to qDBH) and N (referring to SPH) respectively. Only parameter values parameterised with respect to qDBH are reported. For a given site, 3-

PG predicts woody biomass per hectare (W_S), from which w_S is calculated. Equation 4.1 is re-arranged and solved for B, which in this case is the DBH. This calculated qDBH is used to calculate BA, SV (Equation. 4.2) and HT (Equation. 4.3). The relationship depicted in Equation 4.1 is therefore an important one (of which the parameters have a moderate sensitivity rating; see Section 3.3.2, Table 3.3). As such, the allometric parameters, a_S and n_S need to be accurately determined.

Using the biomass data collected from the destructive harvests, Equation. 4.1 was parameterised by first applying the single-tree allometric relationship (based on w_S and DBH derived from each of the 12 harvested trees) to all the 196 trees measured at each site. For example, 14 site-dependent allometric relationships were developed using the 12 harvested trees at each of the 14 sites. These individual allometric relationships were used at their corresponding sites to calculate the individual tree mass as a function of the measured DBH for each of the 196 trees at each site. The average w_S and qDBH of the 196 trees at each site were calculated. These w_S and qDBH pairs (14 pairs of values, one pair for each site) were combined to develop a stand-based allometric relationship which is representative of all sites. In a similar fashion the allometric relationships shown in Equations 4.2 and 4.3 were developed. According to Duursama and Robinson (2003), the development of allometric relationships in this way (*i.e.* as a function of qDBH rather than arithmetic mean DBH, and by using stand level biomass data) circumvents two valid criticisms of the way 3-PG is used. Firstly, a_S and n_S are established using stand level relationships rather than on the basis of single tree data (which would be inconsistent with what 3-PG assumes and actually does), and secondly, the calculation of BA using qDBH is unbiased (whereas there is bias when BA is calculated from the arithmetic mean DBH). Across the 14 sites the derived relationship was $qDBH = 1.058 * DBH$ ($r^2 = 0.985$).

Parameters for the relationships given by Equations 4.1 to 4.3 were determined using Solver (a simple optimisation tool in Microsoft Excel) by minimising the sums of squares between observed and model predicted values. Calculations in Solver are performed using untransformed data compared with ln-transformations used in Excel's power function trend-lines.

Figure 4.1 shows tree stem biomass and height as a function of qDBH for *E. grandis* stands of differing ages and MAIs across all 14 harvested sites. The allometric parameter values estimated from these relationships and accompanying statistics are presented in Table 4.7.

The allometric parameters for the w_S and SV relationships give an excellent fit accounting for 96% of the variation of the observed data. Since stocking information was inadequate, neither n_{HN} nor n_{VN} were estimated and were set as 0 and 1 respectively. This relationship therefore applies to stands having a stocking of between 1000 and 1600 stems per hectare.

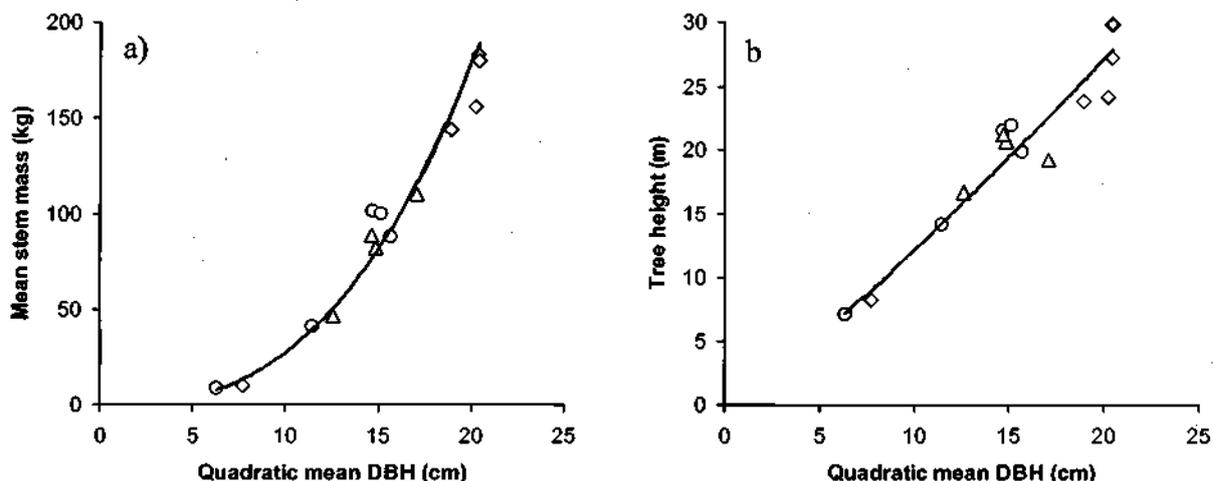


Figure 4.1 Allometric relationships between qDBH and (a) mean single-tree stem biomass (w_S), and (b) tree height, HT, for high (\diamond), medium (Δ) and low (\circ) productivity sites. The line (—) is the fitted relationship used in 3-PG where the parameters for mean single-tree biomass (w_S) are $a_S = 0.044$ and $n_S = 2.771$ and for HT are $a_H = 0.84$, $n_{HB} = 1.15$ and $n_{HN} = 0$.

Table 4.7. Parameter values assigned to the allometric relationships in 3-PG where the quadratic mean diameter (qDBH) is used as the measure of stem size. Statistics shown include the standard error (SE) and 95 % confidence intervals of parameter estimates, and the r^2 of the observed *versus* predicted data.

Relationships	Parameters	qDBH	SE	95% CI	r^2
Stem mass (kg tree ⁻¹)	a_s	0.044	0.016	± 0.031	0.96
	n_s	2.771	0.12	± 0.23	
Stand volume (m ³ ha ⁻¹)	a_V	3.1 x 10 ⁻⁵	1.1 x 10 ⁻⁵	± 2.1 x 10 ⁻⁵	0.96
	n_{VB}	3.094	0.116	± 0.23	
	n_{VN}	1	na	na	
Height (m)	a_H	0.84	0.17	± 0.33	0.91
	n_{HB}	1.15	0.076	± 0.15	
	n_{HN}	0	na	na	

Age-dependent relationships

Specific leaf area, p_{BB} , wood density and tree mortality are described in 3-PG by functions of stand age, and are represented as Gaussian functions having a non-zero asymptote (Sands and Landsberg, 2002). Using Solver, parameter values characterising SLA, p_{BB} and ρ^* relationships were determined in a similar fashion to the allometric parameter values.

Parameter values intrinsic to the mortality function were established by trial and error to reproduce the data modelled using the C-J model (Clutter and Jones, 1980). The C-J model represents tree survival per hectare for an age as a function of trees per hectare at an earlier age. An advantage of the 3-PG mortality function over the C-J function is that the parameters in the former have a more intuitive meaning and can be readily assigned from observed data, and these were therefore used (Sands, 2004a). Thus, the seedling mortality rate (γ_{N0}) and the mortality rate for older stands (γ_{NI}) are the mortality rates at planting and for mature trees respectively.

3-PG calculates monthly leaf litterfall per month using an age-dependent litterfall rate, which increases from a low value (γ_{F0}) to a maximum (γ_{Fx}) at approximately three years of age (Sands and Landsberg, 2002). Sands and Landsberg (2002) have shown that given observed litterfall, LAI and SLA, the monthly leaf litterfall rate can be approximated. Using observed litterfall rates, LAI and SLA, values for γ_{Fx} were

calculated for each of 10 sites. Values for the maximum litterfall rate were shown to vary (ranging between 0.04 and 0.13) from stand to stand in response to local conditions. An average value of 0.075 was therefore assigned. Since no litterfall information for young stands were available and γ_{F0} has a low sensitivity rating (see Sections 3.3.2 and 3.4), a default value of 0.001 was used. All parameter values assigned to the age-dependent relationships and r^2 between observed and predicted values are given in Table 4.8.

Table 4.8. Parameter values assigned to the specific leaf area (SLA), branch and bark fraction (p_{BB}), density, mortality and litterfall age-dependent relationships. The coefficient of determination (r^2) of the observed *versus* predicted data is given. Definitions of parameters are given in Table 4.6.

Relationships	Parameters	Value	r^2
SLA ($m^2 kg^{-1}$)	σ_0	13	0.85
	σ_1	7.7	
	t_σ	2.25	
Branch and bark fraction	p_{BB0}	0.6	0.92
	p_{BB1}	0.131	
	t_{BB}	1.945	
Wood Density ($t m^{-3}$)	ρ_1	0.53	0.71
	ρ_0	0.32	
	t_p	5.66	
Mortality	γ_{N0}	2	0.99
	γ_{N1}	2	
	$t_{\gamma N}$	4	
	$n_{\gamma N}$	1	
Litterfall (per month ⁻¹)	γ_{Fx}	0.075	-

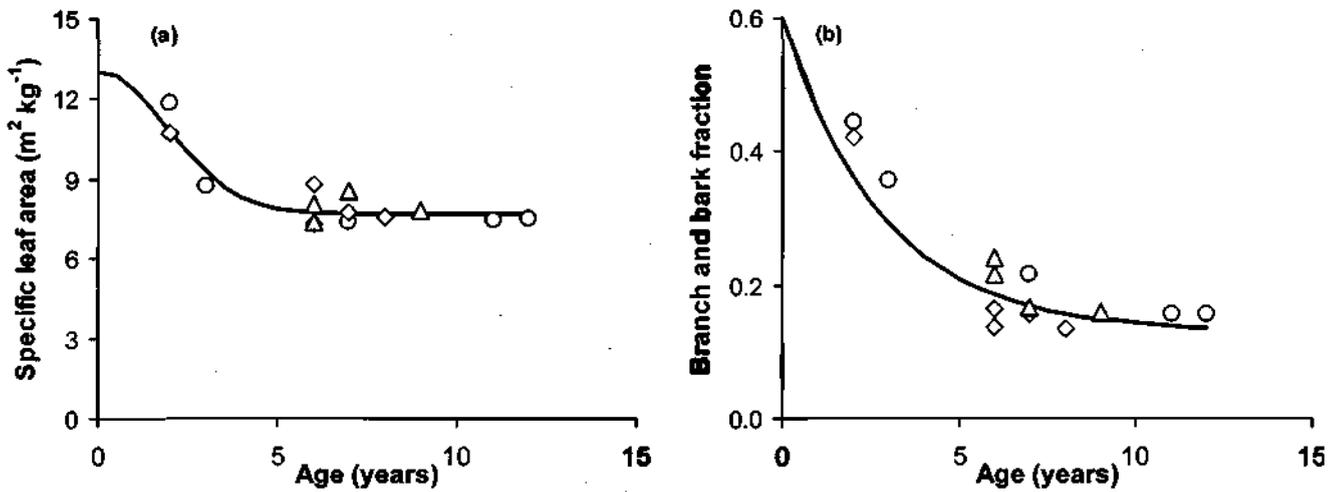


Figure 4.2 Age-dependence of (a) specific leaf area and (b) branch and bark fraction for all harvested sites. The symbols shown refer to high (\diamond), medium (Δ) and low (\circ) productivity sites with lines (—) depicting curves fitted.

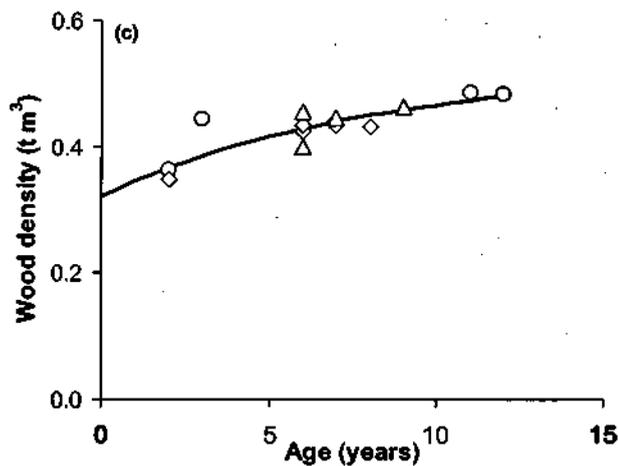


Figure 4.3. Observed and modelled variation in wood density with age across 14 sites of high (\diamond), medium (Δ) and low (\circ) productivity.

Figure 4.2 illustrates how SLA and p_{BB} decline with age. Figure 4.2a shows a decline from $10.8 \text{ m}^2 \text{ kg}^{-1}$ at age 2 years to $7.7 \pm 1.3 \text{ m}^2 \text{ kg}^{-1}$ for stands aged between 6 to 12 years and reproduces the observed SLA with $r^2 = 0.85$. Figure 4.2b shows p_{BB} declines from 0.36 at age 2 years to 0.14 for the older stands ($r^2 = 0.92$). On the other hand wood density, shown in Figure 4.3 increases with age (*i.e.* 0.36 t m^{-3} to 0.48 t m^{-3}) over a 10 year rotation and is also site-specific with densities ranging between 0.39 t m^{-3} and 0.42

t m^{-3} at age 6 years. Compared to observed values the predicted wood density has an r^2 of 0.71.

Figure 4.2b shows the values of p_{BB} to be highly variable between sites. This finding is similar to that of Sands and Landsberg (2002). Since SV is highly sensitive to p_{BB} (see Section 3.3.2, Table 3.3) and the between-site variation in p_{BB} is large, it is very easy to get erroneous predictions of SV. For instance, at four of the sites of age 6 years p_{BB} is observed to vary between 0.24 and 0.13, but using the parameter values in Table 4.8 it is predicted to be 0.17 at an age of 6 years. Using a wood density of 0.43 t m^{-3} at age 6 years (Figure 4.3) and a W_S of, say, 100 t ha^{-1} , predicted SV (calculated as $W_S \times (1 - p_{BB}) / \rho^*$) would be $193 \text{ m}^3 \text{ ha}^{-1}$. Using this prediction of p_{BB} at age 6 years would therefore over-estimate SV at the site where observed p_{BB} was 0.13 ($202 \text{ m}^3 \text{ ha}^{-1}$) and under-estimate SV at sites where observed p_{BB} values of 0.24 ($176 \text{ m}^3 \text{ ha}^{-1}$). Due to these inaccuracies in predicting p_{BB} and wood density, it is preferable to base predicted SV on the allometric relationship with qDBH and SPH (Equation 4.2).

The 3-PG mortality relationship with a probability of death (γ_{No}) set as 2% per annum was as accurate as the prediction when using the C-J function (e.g. a decline in SPH from 1666 to 1377 and to 1361 when using the C-J and 3-PG function respectively) over a 10-year period respectively.

Other parameters

Apart from the PAI determined using the LICOR 2000, additional measurements made by the instrument include the fraction of sky visible to the sensor (I/I_0 , where I and I_0 are the flux densities below and above the canopy, respectively). Using I/I_0 and the LAI of the stand, the light extinction coefficient (k) can be determined (Monsi and Saeki (1953) cited by Linder (1985)). By re-arranging $I = I_0 e^{-kLAI}$, values for k were determined across all nine measured sites. Results showed k to be site-specific with a mean value of 0.45 (SE = 0.04). Due to the site-specific nature of k and since values of k are well known from the literature, a default value of 0.5 was assumed.

It is known that canopy conductance can respond to VPD. Parameters characterising canopy conductance were gleaned from results of a study of transpiration in *E. grandis*: Dye (1987) estimated 0.0625 mbar^{-1} for proportional stomatal response to vapour pressure deficit (k_D), and found the ranges $0.01\text{--}0.025 \text{ m s}^{-1}$ for maximum canopy conductance (g_{Cx}) and $0.22\text{--}0.07 \text{ m s}^{-1}$ for the boundary layer conductance (g_B). Accordingly, the standard values of 0.02 m s^{-1} and 0.2 m s^{-1} were retained for these last two parameters.

Where parameters could not be assigned a value directly from observed data, either because suitable data were not available, or unnecessary due to low sensitivity ratings, default values were taken from Landsberg and Waring (1997), Sands and Landsberg (2002) and Gush (1999). Critical parameters that could not be directly assigned using observed data included foliage:stem partitioning ratios (p_2 and p_{20}), fractions of NPP to roots (η_{Rx} and η_{Rn}), optimum temperature for growth (T_{opt}) and maximum canopy quantum efficiency (α_{Cx}). These should then be estimated by fitting to observed growth data (see Almeida *et al.*, 2004b). However, since no root data were available, default values were used for η_{Rx} and η_{Rn} . A default value for T_{opt} was also used because of its high correlation with α_{Cx} . The final set of parameters is shown in Table 4.6, which includes those assigned by observation, given default values, or estimated using PEST as described below.

4.3.2 Estimation of parameter values for *E. grandis*

Parameter estimation was performed using PEST, in conjunction with PEST_{XL} (see Section 4.2.2). Sands (2004a) strongly recommends that parameter estimation should be based on observed values of W_F , W_R and W_S biomass and θ_S , as these are the state variables of the model and are implicitly associated with the internal dynamics and processes of the model. Since it is not always possible to have such observed data, acceptable surrogates such as qDBH and LAI can be used in the place of W_S and W_F . However root data necessary for the estimation of η_{Rx} and η_{Rn} were not available so default values were used for these parameters (Table 4.6)

Estimation of p_2 , p_{20} and α_{Cx} was based on a single measurement of LAI and time-series data for W_S at each of six selected sites. Of the sites presented in Table 4.5, two from each productivity class were selected: K1, K2, SSP1, SSP7, SSP8 and SSP10. A total of 29 observations across these sites made up the observed data used in the estimation process. Site information and weather data required for 3-PG simulations were the same as those used in Chapter 3. The stand was initialised with W_S and W_F data from the earliest observations at each site. Initial W_R was assumed to be 25% of the total tree biomass (Shephard, 1985).

As discussed in Section 4.2.2 several model parameters are correlated, *i.e.* a change in one parameter can be offset in terms of the quality of fit by a coordinated change in other parameters. Table 4.9 gives the correlation coefficients calculated using PEST for a number of parameters and based on the data available for use in parameter estimation. The values of the correlations depend on the combination of parameters included, the parameter values, and the quality of fit. This table shows that for the default parameter values used in this analysis, changes in α_{Cx} are very highly correlated with changes in T_{opt} , g_{Cx} and k_D , and moderately correlated with p_{20} , η_{Rx} and γ_{Fx} . These correlations can be readily explained with reference to a sound understanding of the model (see Sections 3.3 and 3.4; Sands, 2004a).

Table 4.9. Correlations between selected parameters calculated using PEST.

Parameter name	p_2	p_{20}	α_{Cx}	η_{Rx}	T_{opt}	γ_{Fx}	g_{Cx}	k_D
p_2	1.00							
p_{20}	0.20	1.00						
α_{Cx}	-0.14	-0.21	1.00					
η_{Rx}	-0.20	-0.13	0.31	1.00				
T_{opt}	0.01	-0.06	0.84	0.28	1.00			
γ_{Fx}	0.36	0.98	-0.22	-0.15	-0.06	1.00		
g_{Cx}	-0.40	-0.54	0.71	-0.07	0.27	-0.58	1.00	
k_D	-0.19	-0.43	0.96	-0.17	0.74	-0.44	0.84	1.00

Correlations such as these mean it is very difficult with the available data to simultaneously estimate certain groups of parameters. Accordingly, only p_2 , p_{20} and α_{Cx} were estimated by fitting predicted W_S and LAI to corresponding observed data, with

the other parameters given default values as in Table 4.6. Biologically plausible bounds were placed on each of these parameters in the estimation process. It was found that the resulting estimates of p_2 and p_{20} were highly correlated, and any value for p_2 between the imposed lower bound of 0.5 and the default value of 1 gave equivalent results; the value 0.75 was selected. Table 4.10 shows the resulting values for these parameters, and the standard error and correlation coefficients for each estimated value.

Table 4.10. Values, standard error and correlation coefficients of p_2 , p_{20} and α_{Cx} estimated using PEST.

Parameter name	Estimated value	Imposed range	Standard error	Correlation coefficients		
				p_2	p_{20}	α_{Cx}
p_2	0.75	0.05 to 5	1.4	1.00	-	-
p_{20}	0.11	0.01 to 1	0.03	-0.84	1.00	-
α_{Cx}	0.064	0.05 to 0.07	0.001	-0.14	-0.09	1.00

Canopy development is naturally sensitive to litterfall, which is controlled in 3-PG by the parameter γ_{Fx} : reducing γ_{Fx} will increase LAI. The observed value of γ_{Fx} used in these estimations was 0.075 and was based on data from a specific 12-month period of time, whereas Gush (1999) used 0.035 averaged over the life of the stand. Accordingly, γ_{Fx} was reduced to 0.035 and the estimation of the parameters in Table 4.10 was repeated. This leads to a slight improvement in the fit to observed LAI, but with a reduction of p_{20} to 0.043 (a rather low value) and α_{Cx} to 0.061. As a result, the apparent under-prediction of canopy LAI remains a concern.

At two sites (SSP1 and SSP10) stem growth rate was observed to decline markedly from age 6 years, but this decline was not reproduced in the simulations, irrespective of parameter values. It is expected this might be a site-specific effect, *e.g.* loss of fertility or low stored water that has not been taken into account in the site specification.

4.4 DISCUSSION AND CONCLUSIONS

This study established a more refined set of 3-PG parameter values to use in the prediction of stand attributes useful to the forest manager, and for use of the model as a research and management tool for Eucalypt plantations in South Africa. Many key parameters were assigned specific values based on sound data obtained from biomass

harvests. However, specific key parameters had to be estimated by fitting model outputs to observed data. The software tools Parameter ESTimation (PEST) and PEST_{XL} were invaluable aids in this process. A useful by-product, is the formulation of a set of guidelines for the successful parameterisation of 3-PG. These guidelines classify the model parameters according to their sensitivity class, data source class and estimation class. Greater appreciation of the quality and type of data required for model parameterisation was developed, and it is clear that further work is required to unravel some of the intricacies and unknowns associated with the data and sites used in this study. Additional analyses and data would be invaluable to guide refinement of parameters that had to be simply assigned default values by analogy with other species. Besides the improved parameter set for *E. grandis*, a major spin-off of this study was the development and application of PEST_{XL}, which has been shown to be a powerful parameter estimation tool. Using this tool, and given the availability of good observed data, parameterisation for additional species will be facilitated, allowing comparisons between eucalypt, pine and acacia species to be made. Using a knowledge of the physiological differences between these species, it is anticipated that inferences between parameter sets may be possible and help circumvent the requirement for “*difficult to obtain data*” such as root biomass, thus short-circuiting the parameterisation process.

The development of standard techniques to parameterise the 3-PG model satisfies part of the second project objective presented in Chapter 1. The second part of this objective is concerned with methods to set up and initialise 3-PG. These are explored next in Chapter 5

CHAPTER 5

SETTING UP 3-PG – MODEL INPUTS AND INITIALISATION

5.1 INTRODUCTION

Besides species-specific parameter values (Chapter 4), 3-PG requires three types of information as inputs (Table 5.1): (1) weather data; (2) site information, and (3) stand initialisation data. Ideally these data should come from the site(s) of interest, where experimental trials exist, and/or where monitoring networks are in place (see Almeida, 2004a). However, this is the exception rather than the rule, so alternative data and information sources are required. Table 5.1 shows suggested sources from which these data can be accessed.

Table 5.1. Mandatory inputs required by the 3-PG model showing ideal and alternative sources of data. Abbreviations are: T_X and T_N – mean monthly maximum and minimum temperature ($^{\circ}\text{C}$); R – Monthly rainfall (mm); SR – Solar radiation $\text{MJm}^{-2}\text{d}^{-1}$; θ_{Sx} – maximum available soil water (mm); GPS – geographic positioning system; FR – site fertility rating; W_{Si} , W_{Fi} , W_{Ri} – initial stem, foliage and root biomass ($\text{t}_{\text{DM}} \text{ha}^{-1}$); SPHi – initial stems per hectare; θ_{Si} – initial available soil water (mm); WP – wilting point (mm m^{-1}); and FC - Field capacity (mm m^{-1}).

	Mandatory Inputs	Ideal source	Alternative source
Weather data	T_X , T_N R SR	Observed/measured Observed/measured Observed/measured	Gridded mean monthly derived and interpolated from a network of stations Also gridded but as a function of temperature
Site factors	Latitude Soil texture θ_{Sx} FR	Trial register/GPS Soil survey WP- FC x soil depth Soil survey chemical	Geological and soil maps
Stand initial conditions	W_{Si} W_{Fi} W_{Ri} SPHi θ_{Si}	Observed Observed Observed Observed 50% of total θ_{Sx}	Different approaches dependent on data available Apply mortality to initial stocking 50% of θ_{Sx}

Fortunately, the ICFR is the custodian of extensive experimental trial information and weather data for major parts of southern Africa. This site information plus edaphic and topographical data have been disseminated into the ICFR forest site classification (FSC) documented in Smith *et al.*, (2005). The FSC is based on climate, geology and soils and comprises three levels. The first level is based on MAT, which influences the climatic and disease risks for a given species. This level comprises three climatic zones corresponding to general snow and frost risk across the landscape (cool temperate), frost risk confined to low-lying areas only (warm temperate), and frost-free (sub-tropical). Since rainfall is associated with productivity and drought risk, the second level of the classification incorporates MAP namely dry, moist and wet. Due to ET demands varying according to temperature, the MAP thresholds vary according to each MAT class. The third level of the classification relates to factors that affect soil water storage and soil resilience. The FSC serves as a useful framework and allows for several model inputs to be determined, especially when observed data are not available (*e.g.* site information and initial biomass pools).

This chapter considers objective techniques to determine values for the initial biomass pools and ways in which the model inputs can be derived. Several methods to estimate the site fertility are also explored.

5.2 WEATHER DATA INPUTS

A direct relationship between rainfall and growth has been shown in many species-site-growth studies in South Africa (Schönau and Wilhelmij, 1981; Schafer, 1988a; Schafer 1988b; Louw, 1995; Zwolinski *et al.*, 1998; Strydom, 2001; du Plessis and Zwolinski, 2003). Rainfall is also highly variable in its temporal and spatial distribution, which influences the temporal pattern of soil water content, canopy interception, infiltration, runoff and deep drainage (Mummery and Battaglia, 2004). The use of actual rainfall data is therefore recommended. Moreover, Almeida *et al.* (2004a) express the importance of using actual rather than average weather data so the impact of climatic fluctuations on stand productivity can be evaluated (*i.e.* retrospective modelling). For predictive purposes (or to answer “*what if*” questions) long term average mean data may be used.

Observed daily rainfall data for 14 000 stations across southern Africa are readily available from a locally developed database (Lynch, 2003). Where rainfall data are missing, the rainfall record is patched using representative rainfall, selected using the “*driver station approach*” outlined in Schulze *et al.* (1994). Four criteria are used in the selection of the most representative data set as follows: (a) the driver station is as close as possible to or within the catchment of interest, (b) its altitude is close to the mean altitude of the catchment, (c) it has a long continuous record with a minimum of missing data, and (d) where data are missing, the next best driver station is used to estimate the missing rainfall.

Long-term monthly average values of SR, T_X and T_N , and R, are also routinely available in a database comprising a minute of a degree latitude by longitude digital database developed by Schulze (1997a). However, extractable SR is not based on actual data but is calculated using the Clemence (1992) equation, based on extraterrestrial daily solar radiation, maximum air temperature and the daily temperature range.

5.3 INPUTS RELATED TO SITE INFORMATION

Site information required by 3-PG include the latitude of the site, soil class (*i.e.* clay, clay loam, sand loam or sand), the θ_{sx} and FR.

5.3.1 Maximum available soil water and soil texture

Johnston (1973), cited by Smith *et al.* (2005), defines the important factors determining the potential water supply as:

- The water retained by the soil that is available to a root system, commonly referred to as the available water capacity (AWC, mm m^{-1}) calculated as the difference between field capacity (FC, mm m^{-1}) and wilting point (WP, mm m^{-1}).
- The depth of soil available for root growth and the species rooting patterns.
- The ease with which roots may access that water which is influenced by soil structure and texture.
- Stoniness.

Therefore, the total potential soil water storage capacity or θ_{sx} as depicted in 3-PG, is calculated as the product of the AWC and the soil depth. If the observed soil depth and soil texture, from which the hydraulic characteristics (*i.e.* FC and WP) are derived, are not available, default values can be used. Defaults of AWC have been estimated for any soil using the soil form (soil horizon sequences), soil texture and organic C (Smith *et al.*, 2005). Alternatively, AWC can be determined directly from geological maps using the dominant lithology to derive the soil texture and soil depth (Smith *et al.*, 2005), which is then converted to θ_{sx} . Of course if soil survey information is available, observed values of texture and θ_{sx} should be used.

5.3.2 Site fertility rating (FR)

Forest nutrition is an important factor contributing to biomass production and plantation growth (Cromer *et al.*, 1993), and the maintenance of the nutrient supply is crucial for sustaining productivity (Folster and Khanna, 1997). According to Landsberg (2000) soil fertility affects tree growth by altering:

- Leaf photosynthetic rate;
- Biomass allocation to foliage (and roots), which affects the amount of energy captured and nutrient uptake;
- The efficiency of energy conversion to carbohydrates; and
- Patterns of internal re-translocation.

Quantifying site nutrition is very difficult (Landsberg and Waring, 1997), and according to Landsberg and Gower (1997) there is a plethora of fertiliser studies, yet understanding of nutrition dynamics and the ability to consistently predict these dynamics are very limited. Nutritional processes in 3-PG are therefore based on broad information about the soil chemistry and organic matter, and do not include nutrients in any mechanistic sense (Landsberg, 2003). They are depicted as a FR (0 to 1) where nutrients are either limiting ($FR < 1$) or non-limiting ($FR = 1$) to growth, which, “*while based on the best information available, including expert opinion, remains a somewhat problematical and unsatisfactory, albeit pragmatic approach*” (Landsberg *et al.*, 2001). Despite the empirical and subjective nature of this important model input, the parameter

and input sensitivity analysis showed FR to have a moderate to high sensitivity rating (see Section 3.3.2, Table 3.3). Consequently it is important that the FR is assigned realistic values; however, Landsberg (2000) reviewed the problem of estimating FR for 3-PG simulations, and concluded that there is still no objective way of measuring the FR in soils.

Landsberg and Waring (1997) acknowledged that the estimation of FR is very difficult and suggested that FR is assigned on the basis of litterfall N content or N mineralisation rates or soil phosphorous (P) content. N mineralisation is the process by which nutrients are released and made available through microbial action. Since that benchmark publication, numerous approaches have been suggested. These include:

- Landsberg (2000) considered observed *versus* simulated MAI for 19 Tasmanian sites. The FR for each stand was adjusted until the best fit to observed MAI was achieved. These “*estimated*” FR values showed a degree of correlation to the SI at an age of 20 years. Over a SI range of 10 to 25 m, FR varied from 0.1 to 0.9.
- Williams *et al.* (2002) created a FR as a weighted, linear combination of selected soil attributes known to directly influence soil fertility. These attributes are total P at 0 to 10cm, organic C at 0 to 10cm, subsoil cation exchange capacity (CEC) at 50 to 60cm and subsoil exchangeable sodium percentage at 50 to 60cm.
- Stape (2002) developed a soil fertility index based on CEC, P and potassium (K) concentrations based on growth responses to site fertilisation.
- Louw and Scholes (2002) developed an empirical model for predicting N mineralisation which can be used as a surrogate for FR.
- The SNAP model (Paul *et al.*, 2002) provides a practical means of assessing site fertility (Landsberg, 2003). SNAP uses a baseline N mineralisation value (determined by laboratory incubation), which is then modified by soil water and soil temperature to predict N availability.
- Almedia (2003) calculated the FR using a degree of soil limitation factors (natural fertility, potential fertility, water and oxygen limitation and

management impediment) which was further varied with respect to stand age and regeneration practice.

For this study several of these approaches were considered. These were (1) the use of a soil fertility score (Fey, 1993 cited by Schulze, 1997a; Kunz *et al.*, 1995) based on the clay content and base status of the soil; (2) the employment of litterfall N as an indicator of potential nutrient limitations and (3) the Louw and Scholes (2002) model to determine the N mineralisation potential from soil organic matter, and (4) a method which relates FR to the MAT and soil organic content of the site.

Assigning FR using the soil fertility score

The first method (*i.e.* the soil fertility score) is based on the base cation condition of soils and therefore does not consider N, P and K in the soil. It is a good general method and particularly useful for agricultural soils, but is not all that applicable to forestry soils (du Toit, pers. comm²). This approach was therefore not used.

Assigning FR using litterfall Nitrogen as an indicator

The second method considered was the potential to measure the concentration or content of limiting nutrients remaining in litterfall (after internal re-translocation has taken place). The latter has been shown to be a powerful indicator of potential nutrient limitations in the stand (du Toit, pers. comm²). However, few reliable data sets of litterfall exist for plantations in southern Africa; nevertheless, litterfall data collected in this project was thought to provide an ideal opportunity to determine litterfall N concentration as a surrogate for site fertility. However, the sites initially chosen were selected in accordance to key criteria (see Section 4.3), specific to the objectives of identifying litterfall parameters required by 3-PG. Consequently it was resolved that N concentration determination in this fashion (*i.e.* from this limited set of sites) would not be representative of the site productivities found in southern Africa and therefore would be of limited use.

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Assigning FR using the N-mineralisation potential

The third possibility was the application of the statistical model of Louw and Scholes (2002), developed for the higher altitude areas of the Mpumalanga Province, using *in situ* N mineralisation rates. The model uses easily measured and clearly defined independent variables, *i.e.* mean annual temperature, total N in the topsoil (as an optional variable) and geological substrate, to investigate N mineralisation patterns over a wide range of site conditions over which *P. patula* is planted. Although relatively robust, Louw and Scholes (2002) warn that specific environmental factors responsible for differential N supply are not clearly understood and, furthermore, the importance in seasonal variation in the N cycle needs to be addressed. Most N mineralisation models, such as SNAP (Paul *et al.*, 2002), use baseline (or potential) N mineralisation developed in the laboratory. This potential N mineralisation is modified for temperature and water to determine the actual N mineralisation. Since no actual *in situ* N mineralisation data were available (only laboratory incubated N mineralisation) this method was not of use.

Assigning FR using the MAT and organic carbon of the site

Site fertility, better described as the availability of nutrients to tree stands, is complex, and influenced by soil, climatic and site management factors. For example research has shown that early, intensive silvicultural operations have the potential to trigger short-term increases in nutrient availability to tree stands (Schönau, *et al.*, 1981; Schönau, 1989; du Toit *et al.*, 1999; Little *et al.*, 2002; du Toit and Dovey, 2005). Other studies have shown that:

- Nutrient requirements of forest plantations change with stand age (Goncalves, 1997).
- The availabilities of N, P and to a lesser extent, K are crucial determinants of soil fertility on most southern African plantations as other nutrients are seldom in short supply (Campion and du Toit, 2003; du Toit and Oscroft, 2003).
- Both the quantity of soil organic matter and the rate of nutrient release from this pool are important indicators of fertility (du Toit *et al.*, 2001).

- N and P availability to trees are strongly (but temporarily) increased by management practices, in particular surface soil tillage or disturbance, N-fixing species, slash burning and obviously fertilisation (du Toit and Dovey, 2005).

Using this knowledge and the premise that N mineralisation rate is strongly affected by temperature, a method linking FR values to MAT ranges and soil organic C content was considered. Both the MAT and organic content, accessible from the site classification (Smith *et al.*, 2005), makes it possible to assign FR values for each potential productivity zone. The link between FR and these variables is presented as a relationship between the nutrient status of a site, the size of the potentially available nutrient pool, and the rate of nutrient release (or N mineralisation). A slow turnover within a big nutrient pool may yield similar nutrient availabilities as compared to a rapid turnover within a small pool. Sandy soils with small pools of organic matter (less than 0.3% organic C in the topsoil) are likely to provide inadequate supply rates of nutrients to tree stands and warrants a very low rating (du Toit *et al.*, 2001). However, most sites with larger pool sizes are probably governed primarily by the rate of organic matter mineralisation rather than by the pool size. The method developed is a two-step approach as follows (du Toit and Esprey, 2005, unpublished results):

- A baseline FR based on MAT and organic C is determined;
- The modification of FR based on management influences.

A conceptual diagram shows the effect of silvicultural management inputs on the FR and how it may change over time (Figure 5.1).

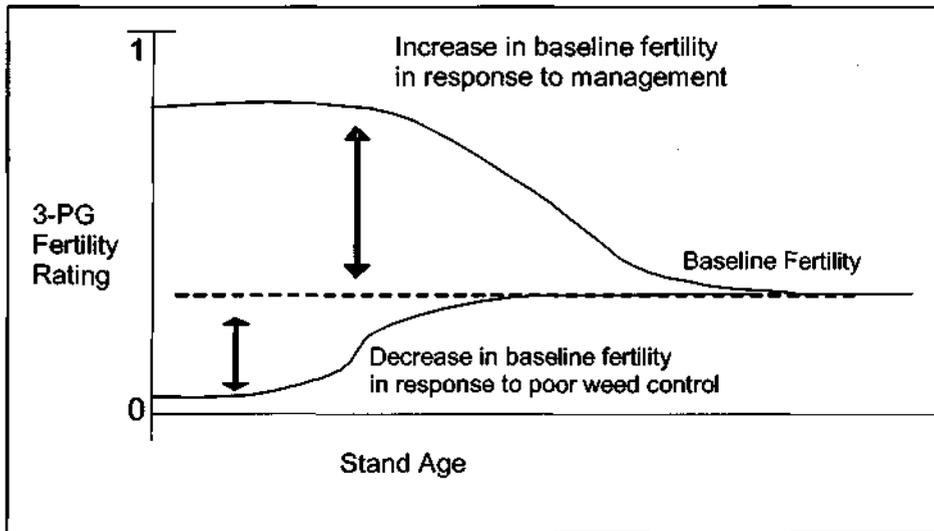


Figure 5.1. Conceptual diagram showing the baseline fertility rating of a site and the temporary modification thereof with respect to silvicultural operations or poor weed control (after du Toit and Esprey, 2005).

Although the method described here is not directly based on empirical data, it is founded on general findings and results of ICFR trials. Although this approach is conceptually correct, no evidence supporting these values can be provided. Without such a link it cannot be said with certainty what the range of FR is.

In light of the above discussion values for FR are pragmatically assigned and based on whether a trial has or has not received fertilisation: *i.e.* 0.4 and 0.6 respectively (see Section 2.3.4). This method is the same as that used in Section 2.3.4 and Chapter 3.

5.4 INITIALISATION DATA

Analogous to model parameterisation, model initialisation refers to the estimation of numerical values for the θ_{Si} , $SPHi$, as well as W_{Ri} , W_{Fi} and W_{Si} at some initial stand age. There are no publications in the public domain that document or develop approaches to initialise 3-PG. Generally, researchers using 3-PG have initialised the model with data from the first inventory assessment (Dye, 2001; Landsberg *et al.*, 2001; Landsberg *et al.*, 2003; Dye *et al.*, 2004; Almeida *et al.*, 2004b). Sands and Landsberg (2002) assigned values for $SPHi$ and W_{Si} using early observations. In the absence of observed W_F , values that reproduced the first observed canopy LAI were assigned. Root biomass

was given values corresponding to expected root biomass data. It is emphasised that there is no feedback from W_R to 3-PG processes which implies that the model is not sensitive to W_R . Almeida (2003) proposes that a strategy based on simple inventory data (either DBH or HT) be developed to estimate biomass distribution. However, such a method would require many destructive harvesting studies over a range of site and species types. Not only is this a laborious task but also time consuming and costly.

In sections 2.3.4 and 3.2, biomass data required to initialise the stand at age two years were assigned using a pragmatic approach. This approach used site index models and biomass ratios gleaned from the literature. This method worked well but placed too much emphasis on the biomass ratios. The lack of an objective method to assign values to initial biomass pools presents a huge gap in our knowledge and highlights the need to develop more practical methods.

The problem of model initialisation is addressed in two ways: (1) consideration of potential applications of 3-PG within the South African context, and (2) additional sources of observed growth data. Growth prediction from existing plantations and the understanding or exploration of growth constraints are probable applications of 3-PG in South Africa (see Sections 7.2, 7.3 and 7.4). If the model is to be used in these ways there is greater likelihood that early growth measurement data (*i.e.* DBH and HT, from which SV can be determined) will be available. Other sources of observed data useful to initialise the model are those available from via inventory or enumeration assessments. In South Africa three types of growth plots are distinguishable with respect to a measurement time frame.

- (i) Permanent sample plots (PSPs), also known as re-measured plots, are used to monitor G&Y over the rotation and form part of a normal plantation inventory program (du Plessis *et al.*, 1997). The plots are generally measured after one year of growth and then re-measured three to four times over the rotation (Gadow and Hui, 2001; Morley, pers. comm³). Permanent sample plots are essential for the development,

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calibration and testing of growth and make provision for the examination of the stability of site index measurements. These data are also of value for model validation purposes (see Chapter 6).

- (ii) Temporary or enumeration plots are measured at mid-rotation and then again just before clear-felling (Kassier, 2005, pers. comm⁴.) and provide age-based information about relative variables required by G&Y models (Gadow and Hui, 2001). Although these enumerated data appertain to mid-rotation stands (four to six years) they are nevertheless very useful for model initialisation purposes. Furthermore it is common practice to collect such data, which means that it is a cost effective method to use such data rather than re-measuring at another age.
- (iii) Interval plots provide the average rate of change in response to a given set of conditions (Gadow and Hui, 2001). Such plots are measured twice within the interval which is long enough to account for short term effects of climatic extremes. Silvicultural practices are not carried out during this time period.

5.4.1 Initial stem biomass (W_{SI})

A method to assign W_{SI} has been devised based on the availability of observed data and a series of questions and actions dependent on what observed data are available (Figure 5.2).

If for example, estimates of SV are available, qDBH can be calculated by rearranging Equation 4.2 given in Section 4.3.1 as

$$qDBH = \left[\frac{SV}{N^{n_{VN}} a_V} \right]^{\frac{1}{n_{VB}}} \quad (5.1)$$

The parameterised values for the multipliers (a_V) and powers (n_{VN} and n_{VB}) as presented in Table 4.7 (see Section 4.3.1) would be used.

⁴ Dr H. Kassier, Forestry Consultant, Pietermaritzburg, 3201

If no SV data are available, but mean dominant height (dHT) of the stand is, BA and qDBH can be determined (Kassier, pers comm⁵). Basal area (BA) is estimated using the empirical model of Pienaar and Kotze (2001) (Equation 5.2)

$$BA = \exp \left[\beta_0 + \frac{\beta_1}{age} + \beta_2 * \ln(SPH) + \beta_3 * \ln(dHt) + \beta_4 * \frac{\ln(SPH)}{age} + \beta_5 * \frac{\ln(dHt)}{age} \right] \quad (5.2)$$

using the age at which the BA is required, SPH for that age, dHT for the above age and a set of coefficients ($\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5$). Sets of coefficients are available for a selection of species and different regional groupings. However, for the purpose of this study the generic model for *E. grandis* is used. All coefficients are available from the Mensuration Modelling Research Consortium (MMRC, unpublished report). Using the estimated BA, qDBH is calculated using

$$qDBH = \text{sqrt} \left[\frac{BA}{N} * \frac{40000}{3.14159} \right] \quad (5.3)$$

where qDBH is in cm.

Where no observed data are available, the SI is estimated using the MAP and MAT of the site (*i.e.* from the FSC. The dHT is estimated as a function of the age at which dHT is required (age_1), site index reference age (age_x) and coefficients β_1 and β_2 (MMRC, unpublished report) using

$$dHt = SI_x * \left[\frac{1 - \exp(\beta_1 * age_1)}{1 - \exp(\beta_1 * age_x)} \right]^{\beta_2} \quad (5.4)$$

The BA is calculated using Equation 5.2, followed by the calculation of qDBH using Equation 5.3. Individual tree stem-mass is then determined using the allometric equation describing the single-mean tree stem mass in terms of qDBH (see Section 4.3.1, Equation 4.1). Initial stem biomass (W_{Si}) is determined as the product of w_s and

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SPH. Essentially this initialisation approach estimates the W_{Si} , which reproduces the first observed value, in a manner similar to the method Sands and Landsberg (2002) describe for assigning foliage biomass.

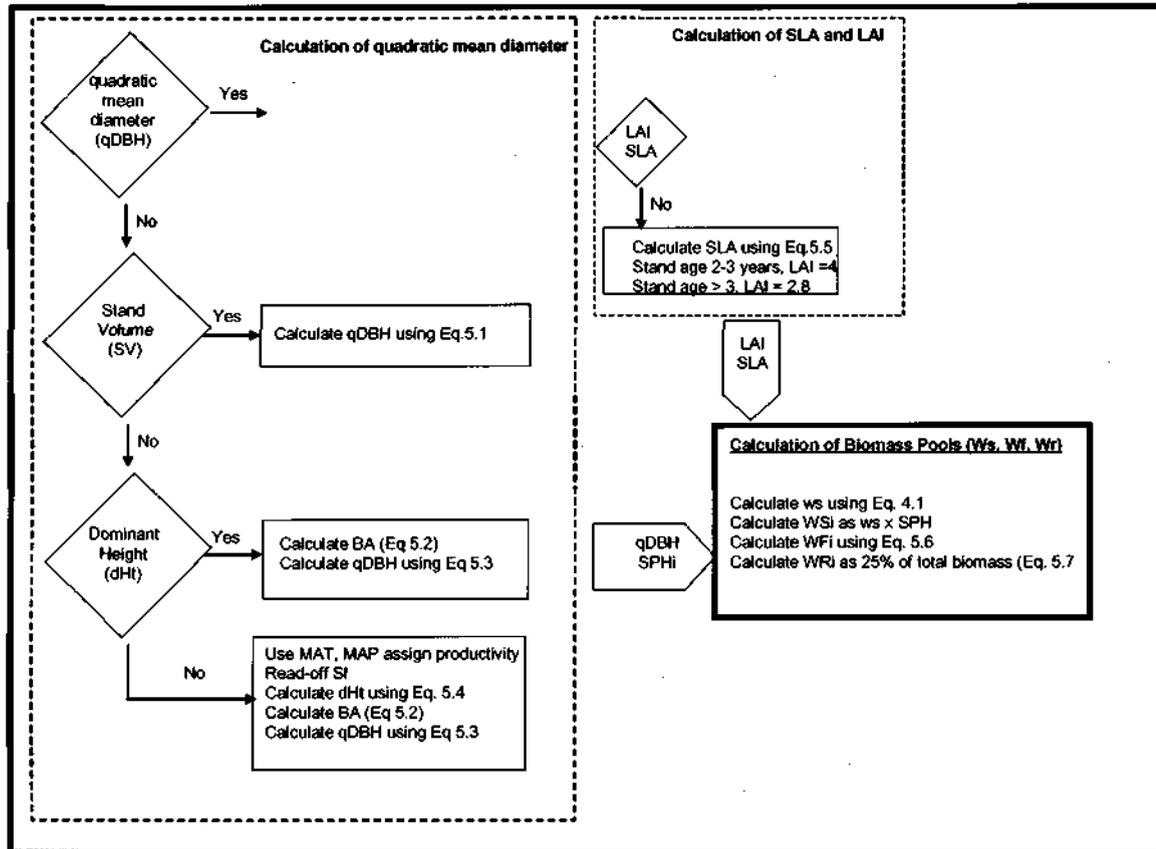


Figure 5.2. Decision flow diagram showing steps to be followed to estimate values for initial biomass pools. Abbreviations are as follows: qDBH – quadratic mean diameter; dHT – dominant height; BA – basal area; SV – stand volume; SLA – specific leaf area; LAI – leaf area index; wS – single-mean tree biomass; SPHi – initial stems per hectare; W_{Fi} , W_{Ri} , W_{Si} – initial foliage, root and stem biomass.

The methods used to determine qDBH as a function of data availability were tested using data from 48 *E. grandis* PSP trials (see Table 7.6 in Section 7.4). Observed data from these trials comprise time-series growth data of SV, SPH, dHT and qDBH. Using observations corresponding to the first measurement (*i.e.* column 4 in Table 7.6) across all sites (*i.e.* SV, dHT and SI₅) corresponding values for qDBH were calculated using the methodology outlined in Figure 5.2. These calculated values of qDBH were

compared to observed data (Figures 5.3a to c). Statistics of these comparisons show that the proportion of the variance in the observed values accounted for by the simulated values (r^2) are all greater than 0.8. Mean biases (predicted qDBH - observed qDBH) expressed as a percentage of observed qDBH were small (-6.4%, -2.6% and 1.09% respectively), indicating that deviations are relatively normally distributed.

Table 5.2. Basic statistics for the observed and predicted qDBH across 48 sites.

Statistics	Observed qDBH (cm)	Predicted qDBH (from volume)	Predicted qDBH (from height)	Predicted qDBH (from SI)
n	48	48	48	48
Mean	12.4	11.7	12.0	12.1
Standard error	0.29	0.31	0.23	0.37
Standard deviation	1.98	2.12	1.61	1.88
r^2		0.96	0.81	0.83
Bias (%)		-0.64	-2.60	1.09
LSD = 0.8				

Additional analyses on these results were performed using GENSTAT® Version 4.2 (Lane and Payne, 1996). A general one-way analysis of variance (ANOVA) was performed to statistically analyse differences between the means of observed qDBH and predicted qDBH. Results showed no significant differences ($P < 0.001$) between the three sets of predicted qDBH and observed qDBH values. This result suggests all methods can be used to adequately predict qDBH.

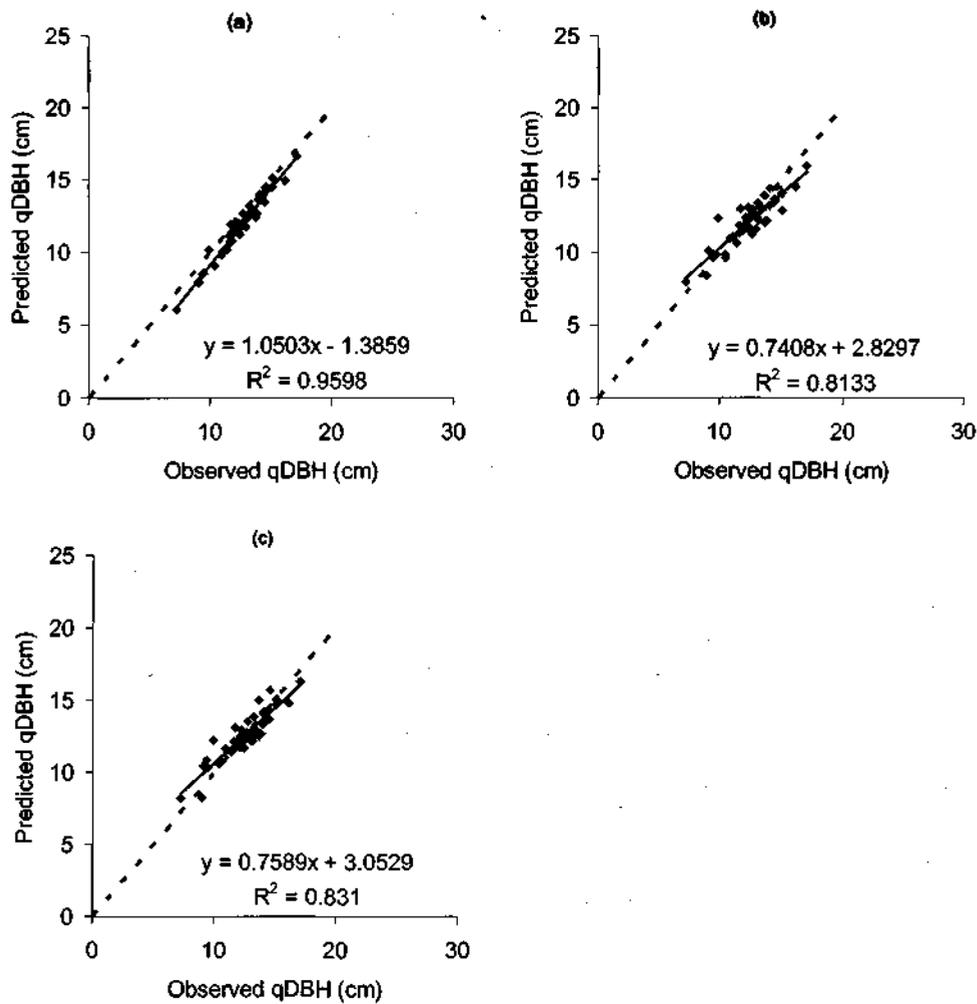


Figure 5.3. Comparison of predicted and observed qDBH for 46 sites. Predicted qDBH was derived from observed a) stand volume, b) dominant height (dHT) and, c) site index at an age of five years. One-to-one lines are shown as (- - -) and (—) is the regression line. Accompanying basic statistics are presented in Table 5.3.

5.4.2 Initial foliage and root biomass (W_{Fi} and W_{Ri})

Foliage biomass is predicted by 3-PG and is used to infer LAI as a function of SLA and W_F (Sands and Landsberg, 2002). Specific leaf area is represented in 3-PG as an age-dependent function (Section 4.3.1, Figure 4.2a and Table 4.8). Consequently, if the LAI and SLA of the stand are known, W_F can be determined.

If SLA is not known it can be estimated using the age-dependent Gaussian function with a non-zero asymptote used in 3-PG to describe the age-dependent decline in SLA (Sands and Landsberg, 2002).

$$SLA = \sigma_1 + (\sigma_0 - \sigma_1)e^{-(\ln 2)(t / SLA)^2} \quad (5.5)$$

where the parameter values are given in Table 4.8.

The LAI that can be sustained by the stand is determined by the availability of water and nutrients, which can be manipulated through the affects of management impacts on the LAI and site productivity (Beadle, 1997). Several studies have shown that in temperate climates, early intensive silviculture results in rapid early growth and canopy closure in several eucalypt species (Cromer *et al.*, 1993; Stape, 2002; Almeida *et al.*, 2004a; Goncalves *et al.*, 2004; du Toit and Dovey, 2005;). Data combined from these studies show peak LAI to vary between 3.5 and 4.8 at two and three years of age (Section 6.4.3, Figure 6.6). Thereafter, as resource competition sets in, LAI tends to decline to an average value of 2.8 (2.5 to 3.2). Sands and Landsberg (2002) and Section 3.3.1 show that irrespective of initial biomass values in 3-PG, after 10 to 15 years of stand growth LAI converges to common values. Under South African conditions, and in short rotation stands, this convergence generally occurs after seven to nine years (data not shown). This suggests that final volume production is fairly insensitive to early LAI values, implying that the aforementioned approach to estimate initial LAI is reasonable. These studies have focused on fast growing eucalypts under high initial stocking and intensive early silviculture; therefore the above argument is applicable to South African *E. grandis*.

Consequently, if the age at which 3-PG is to be initialised varies between two and three years, an average LAI value of 4 is used. For stands older than 3 years, an LAI of 2.8 can be used. Using these values for initial LAI and calculated SLA, initial W_F is calculated using Equation 5.6.

$$W_F = \left[\frac{LAI}{SLA \cdot 0.1} \right] \quad (5.6)$$

Besides the lack of good W_R data, there are no internal feedback loops involving root biomass in 3-PG (Sands and Landsberg, 2002) and hence initial W_R is not very

important. A value for W_R is, however, required and has been assumed to be 25% of the total tree biomass (Shephard, 1985). It follows that

$$W_R = (W_S + W_F)/3 \quad (5.7)$$

Due to the lack of foliage and root biomass data it was not possible to test methods to assign these initial biomass pools. However, because of the way predicted time-series of LAI converges to common values and since no internal feedback loops involving initial root biomass occur in 3-PG (Sands and Landsberg, 2002), it was felt the consequences of errors would not be significant.

5.3.3 Initial stocking and soil water (SPH_i and θ_{Si})

Stocking information is normally obtained from an inventory or enumeration. It can be otherwise determined using an estimate of the mortality, which can be inferred from the initial stocking at planting. Initial soil water on the other hand has very strong feedbacks that pull it into line very quickly and as such it is acceptable to use any value and for the purposes of this study it was assumed to be 50% of the θ_{Sx} .

5.4 DISCUSSION AND CONCLUSIONS

The accuracy of model predictions is affected by the model structure as the well as accuracy of the input data. Although a generic model, the performance of 3-PG is improved when detailed knowledge of a tree species is available from the environment in which it is growing (Waring, 2000). Errors in input data are often the cause of poor model performance in validation studies. Furthermore, the model may give reasonable answers but for the wrong reasons, which could lead to significant errors and costly decisions (Schulze, 1997b). The importance of using accurate model input values is under-rated and is not frequently mentioned in the ecological modelling literature. Rykeil (1996) points out that models cannot provide results that are more accurate and precise than the data that are used as inputs. Consequently it is critical to use the best available data and to check that these data are error free.

To understand the need of using good quality input data, or the implications of poor input data, it is necessary to reflect on some important aspects of 3-PG. Central to the model is the calculation of gross primary production (GPP) depicted as a function of the radiation intercepted by the canopy and the efficiency with which this radiation is converted to carbon (C) in response to prevailing environmental conditions. This intercepted solar radiation (SR) is a function of canopy leaf area index (LAI) and canopy cover, and is calculated from Beers law. The canopy cover is of little consequence because 3-PG is generally initialised during the post canopy closure stage. The radiation use efficiency (GE) on the other hand, is calculated as the product of the maximum canopy quantum efficiency (α_{Cx}) and the vapour pressure deficit (VPD)- soil water- nutrient-and temperature- (f_D , f_θ , f_N and f_T) dependent modifiers, each of which vary between 0 and unity, the molecular weight of dry matter and a factor which converts SR to photosynthetically active radiation (PAR). As VPD increases stomatal conductance is assumed to decrease exponentially. The soil water constraint on stomatal conductance is a non-linear function of available soil water (θ_S), and dependent on the water retention characteristics associated with different soil textures (Waring and McDowell, 2002). With respect to the VPD-and soil water-dependent modifiers, the law of the minimum applies (*i.e.* the physiological modifier (ϕ) = $\min(f_D, f_\theta)$). The temperature-dependent modifier accounts for the variations in mean temperature with respect to the pre-determined parameter values for cardinal temperatures (*i.e.* T_{min} , T_{opt} and T_{max}) for photosynthesis. Growth is therefore constrained as ambient temperatures depart from the optimum temperature required for growth. Based on published information, the canopy quantum efficiency is a linear function of FR (Landsberg *et al.*, 2003). However, since it was assumed in this study that the fertility rating (FR) has no direct effect on quantum efficiency (*i.e.* $f_{N0} = 1$, see Sections 2.3.2 and 3.2.3 and Table 4.6), GPP and total stand biomass are not directly affected by FR.

In Sections 3.3.1 and 3.4.4 it was shown that stand volume (SV) has a high sensitivity to inputs of monthly rainfall (R), maximum and minimum temperature (T_X and T_N) and FR. Accurate inputs of weather (SR, R, T_{AV} and VPD) and physical factors (soil texture, maximum available soil water (θ_{Sx}) and FR) of the sites being modelled is therefore emphasised, particularly if 3-PG is to be used to predict response to climatic

fluctuations (e.g. years with an above average rainfall or during periods of drought). Almeida *et al.*, (2004a) stresses the importance of using actual rather than average weather data to help evaluate the impact of climatic fluctuations on stand productivity. Furthermore the sensitivity analysis of climatic factors showed marked responses to changes in both R and temperature (see Section 3.3.1 and Table 3.3). However, average climatic data can be useful for the estimation of potential production, limits imposed by site fertility (Almeida *et al.*, 2004a), different management options, production in unafforested areas, and to consider “*what if*” scenarios.

Observed daily rainfall data are available for most parts of southern Africa. Long term records of monthly mean temperature are also available but not as often as are R data, and there are no observed records of SR or VPD. Long-term monthly SR is therefore calculated using the Clemence (1992) equation (see Section 5.2) which has been shown to perform particularly well in the winter rainfall region and explains 73% of the variances of observed SR (Schulze, 1997a). This implies that predictions of SR in the summer rainfall region are not as accurate, and, according to Schulze (pers. comm⁶), plots of predicted and observed solar radiation show a great deal of scatter around the one-to-one line. Vapour pressure deficit on the other hand can be computed internally by 3-PG as a function of T_X and T_N . Almeida and Landsberg (2003) present an excellent piece of work evaluating methods to estimate SR and VPD. Results indicate that VPD determined as a function of T_X and T_N , is under-estimated by between 13 to 50% (in Brazil). Under-estimation of temperature could result in an over-estimation of calculated VPD and hence an under-prediction of the growth constraints especially when there are no soil water constraints on growth. In such instances tree growth will be over-predicted.

Where long term averaged temperature data are used as a surrogate for observed monthly temperature, model predictions are affected. Temperature inputs are used to determine the effect temperature has on constraining growth as a function of the cardinal temperatures. The f_T approaches zero as the monthly temperature approaches

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the minimum/maximum temperature values. At such time growth via the α_c is constrained by temperature. Intuitively, during periods of drought the daily or monthly average daytime temperatures will be greater than the long-term monthly temperature. In such cases model predictions will be higher during times of drought than they ought to have been since long-term monthly estimates do not reflect these temperature extremes.

With regard to site information required by 3-PG, soil texture and maximum available soil water capacity (θ_{sx}) are also important since they are both used directly in determining the f_θ . If soil survey information is not readily available these factors can be inferred from existing geological (via the forestry site classification (FSC)) and soils maps. Fertility rating on the other hand is a more complicated problem (see Section 5.3.2) but because of the way the model has been parameterised (*i.e.* $f_{N0} = 1$) the value of FR does not affect the efficiency of resource use (*i.e.* the fertility modifier defaults to a value of 1). Consequently values for FR are pragmatically assigned and based on whether a trial has or has not received fertilisation and values of 0.4 and 0.6 respectively will be used (see Section 2.3.4).

Initial biomass pools can be thought of as “*the launch pad*” from which a “*rocket*” must be launched; if the launch pad is in the wrong area the rocket will miss the target. For instance if the initial biomass pools in 3-PG are too large or too small production can be over- or under-predicted respectively (see Figure 8 in Sands and Landsberg, 2002). These biomass pools (W_{Fi} , W_{Ri} , W_{Si}) should be assigned using observed data. In the absence of such data other methods are available (see Section 5.4). These include assigning values for W_S using qDBH, determined empirically as a function of basic stand variables (*i.e.* SV or dHT) or using the site index (SI) of the site. Foliage biomass is inferred using an age-dependent relationship for the specific leaf area (SLA) and typical values for LAI, and root biomass as a fraction of the above biomass.

The work presented here satisfies the second project objective (see Section 2.1), which is to develop standard techniques to parameterise (Chapter 4) and initialise the 3-PG model. Using the parameter set developed for *E. grandis* (Chapter 4) and methods to

initialise the model, validation studies are performed next. Testing the model performance is imperative to build user confidence in the accuracy of model. This study will give further insights into the strengths and weaknesses of both the empirical and process-based modelling approaches.

CHAPTER 6

EVALUATING THE PERFORMANCE OF 3-PG

6.1 INTRODUCTION

An assessment of the predictive ability of 3-PG was carried out using a series of simple tests. Figure 6.1 shows a general approach used to evaluate models. Particular attention is drawn to:

- Conceptual validation justifies that the assumptions underlying the model, and that the representation of the system, its structure, logic, mathematical and causal relationships are reasonable and consistent with the intended use of the model (Rykeil, 1996);
- Operational or whole-model validation is concerned with the quality of the model predictions compared with reality, and the extent to which model output meets the performance standards required for the intended use;
- Data validation is necessary to check that quality of model inputs are adequate (see Chapter 5).

Testing any model in such a fashion has a number of outcomes. The credibility of the model is established (Huang *et al.*, 2003), the user gains confidence that the model is working properly and that its predictions reflect the most likely outcome in reality (Amaro *et al.*, 2003), and limitations of the parameter set are identified. There have been several key publications concerning the first two approaches outlined above, *e.g.* Chapter 3 of this thesis, Almeida *et al.* (2004b), Landsberg and Waring (1997), Waring (2000), Sands and Landsberg (2002) and Landsberg *et al.*, 2003). Many other evaluations have also been performed using 3-PG. The objectives of this Chapter are to highlight some of these past studies and to test the operational validity of 3-PG.

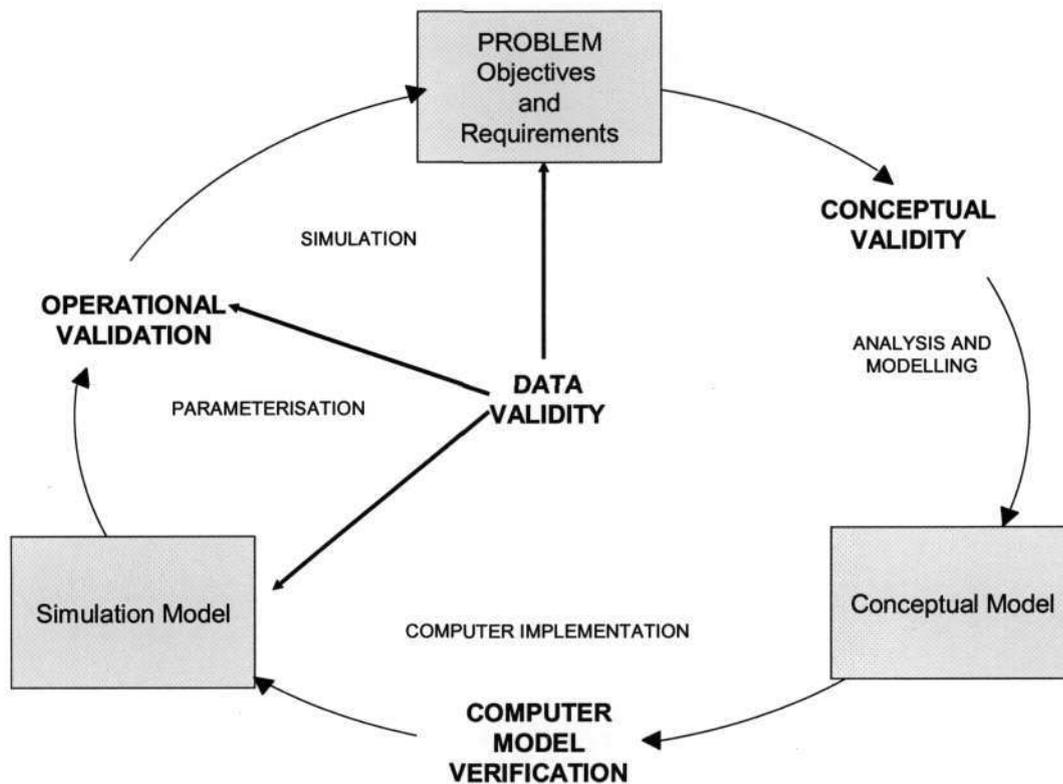


Figure 6.1 Representation of the modelling cycle and the position of operational, conceptual and data validation processes (after Rykeil, 1996 and originally cited from Sargent, 1984).

An overview of some common modelling terminology and semantics is presented next including definitions and explanations of terms such as validation/verification, and parameterisation/calibration. Many authors use these pairs of terms interchangeably, which has led to much confusion. A distinction between model validation and model verification, and parameterisation and calibration is therefore necessary.

6.1.1 Validation or verification?

The terms model testing, model validation and model verification are not used consistently or uniformly in the literature. What is one modeller's verification may be another modeller's validation (Shepherd and Geter, 1995 cited by Schulze 1997b). The Oxford English Dictionary defines "validate" as "make valid, ratify, confirm, well founded and applicable". Verify on the other hand is to "establish the truth or correctness of by examination or demonstration". According to Schulze (1997b),

verification is a measure of the performance of the model, which is what I was taught as an undergraduate in Hydrology. However, Rykeil (1996) defines verification as the confirmation that the computer coding accurately reflects the model, and validation as the process of confirming that a model reflects reality. Landsberg *et al.* (1991) confirms these definitions by defining model validation as an evaluation of the performance of the model either in relation to a set of measurements, or to alternative calculations. However, Landsberg *et al.* (1991) are not convinced that the semantics are sufficiently important to assert differences between these words, which lead to “grey areas” and confusion. The inconsistencies in these terms are important to identify, and possibly stem from the frequent adoption by ecologists of techniques and technologies from other disciplines (Gardner and Urban, 2003). Prisley and Mortimer (2004) highlight differences between these concepts and accept that model evaluation encompasses various aspects of confirming the reliability and the usefulness of a model. In order to be consistent with the ecological literature, the term model validation is used in this Chapter to mean the performance of the model with respect to a set of observations.

6.1.2 Calibration or parameterisation?

Model calibration and parameterisation are often used interchangeably, especially in the literature pertaining to the 3-PG model (*e.g.* Almeida *et al.* (2004b); Landsberg *et al.* (2003)). Calibration is the adjustment of model parameters so as to improve the agreement between predictions and observations (Rykeil, 1996). In particular calibration can be used to estimate parameter values that are unknown or difficult to measure (Rykeil, 1996). With respect to 3-PG, Landsberg *et al.* (2003) talk about the calibration of the model as the fitting of model outputs to individual sets of observational data. For instance the model is run and outputs are compared to predictions. Parameter values are then adjusted to improve the fit and the model is re-run. Successive adjustments lead to better fits between predicted and observed data, especially if there are many observed and predicted pairs of data sets (Landsberg *et al.*, 2003). This description of calibration is identical to the description of model parameterisation used here (Section 4.1) as the assignment or estimation of parameter values performed manually or iteratively using optimisation techniques.

Several authors use the terms model tuning and model calibration interchangeably. Model tuning is a procedure which appears to be similar to calibration, but according to Landsberg *et al.* (2003) is used when appropriate observed data are not available (e.g. root data necessary to assign values to η_{Rx} and η_{Rn}) or as a final step to improve the agreement between predictions and observations. For example Landsberg *et al.* (2003) identify FR and θ_{St} as tuneable parameters because they can take on a range of values. Similarly, Stape *et al.* (2004) tuned the coefficient of stomatal response to VPD even after the model was calibrated. Because of the uncertainties involved with “tuning” a model in such a fashion no model tuning has been used in this study.

6.1.3 Evaluation of model performance

Most of the several dozen papers written on techniques to evaluate model performance suggest dissimilar methods. The interested reader is referred to Amaro *et al.* (2003) and Huang *et al.* (2003) who provide an excellent overview of procedures and methods for model validation. See also Rykeil (1996), Loehle (1997), and Prisley and Mortimer (2004) who present overviews of model evaluation terminology (Section 6.1).

There should at least be an ideal validation procedure that could serve as a standard or consistent method. Huang *et al.* (2003) states that there are no standard statistical techniques used in model validation studies, thereby making validation one of the most “*convoluted and paradoxical topics*” associated with model building. There are many statistical methods that can be used to assess the goodness of fit between model predictions and observations. Some common methods include regression analysis of predicted *versus* observed values, ANOVA, paired t-test, regular and non-central chi tests and various F-tests. Using a set of criteria, Huang *et al.* (2003) examined the usefulness of these various methods, and showed that each statistical method met one or more of the pre-defined criteria, but none of the methods achieved all criteria. This result implies that selection of a statistical test can give an answer you want. This of course has no scientific founding and borders on pseudoscience. Kleppner (1992) cited by Schulze (1997b) states that “*care should be taken not to apply sophisticated statistical tests to reassure ourselves that the... output, ... is of high quality/consistent – if we do not understand the meaning of the statistics we merely fool ourselves in a*

highly sophisticated manner". This is corroborated by Huang *et al.* (2003) who confirm the need for a general strategy for model validation which should look at how well a model fits new data, rather than using statistical tests to decide whether the model is good enough. These statements support my view to keep things simple and perform tests only where necessary.

Amaro *et al.* (2003) recommend that model validation studies should encompass some of the following elements: independent validation sets; dynamic and structural validity; performance of individual components; model generality; model simplicity and operability; biological realism; visualisation and validation statistics. For instance model validation must be based on data sets independent from those used in the model parameterisation; dynamic and structural validity is concerned with how the model will be maintained and improved upon so that it will represent the real dynamic system being modelled; performance of individual components as well as an overall model performance and the assessment of the model generality which could, for instance, give useful insights on regions where the model works best, or does not work well, indicating our lack of understanding of the basic processes. While it would be useful to include such elements in validation studies there is a data availability problem. This problem is more prevalent with respect to the observed biomass data, required for testing the biomass production and allocation components of the model.

A conundrum that has been faced throughout this project has been the lack of suitable data. This is not a unique phenomenon, and Sands (2003) reports that in the early 1980s, Landsberg would often remark that forestry research organisations have cabinets "*stuffed with data that had not been properly looked at and analysed*". However, this largely empirical data (*i.e.* data from spacing and fertiliser trials, *etc*) which is of limited use for application in PBMs. Nothing has changed since then: the ICFR has large amounts of mensuration data, very few biomass data and even less physiological data. Consequently, a detailed model validation such as Amaro *et al.* (2003) suggests is not possible.

However, many independent validation studies have been performed (e.g. Sands and Landsberg, 2002; Landsberg et. al., 2003; Almeida et. al., 2004b; Dye et. al., 2004). In a local study, Dye et al. (2004) used observed data from 12 stands of *E. grandis* x *camaldulensis* (GC) hybrid clones to parameterise 3-PG. 3-PG was then calibrated (or tuned) by iteratively varying the θ_{sx} and FR until a reasonable match between predicted versus observed data was were obtained. Results showed that reasonable estimates of tree growth can be made over a wide range of rotation ages and growing conditions. Results from the other studies have shown 3-PG to be robust and reliable, predicting within an acceptable degree of confidence. Keeping these results in mind, and the premise that 3-PG is generic, it is reasonable to conclude that 3-PG should perform adequately under South African conditions.

Despite these data availability problems, the best use of in-house ICFR data (DBH, HT and therefore SV) has been made and 3-PG was evaluated using four simple tests: predicted versus observed SV using (1) the parameter set developed by Gush (1999) compared to the newer *E. grandis* parameter set (see Chapter 2; Section 6.2); (2) the new parameter set and data sets independent to those used in the model parameterisation (see Section 6.3); (3) observed time-series data (see Section 6.4); and (4) data from a fertilised and irrigated experiment (see Section 6.5).

6.2 NEW VERSUS OLD PARAMETER SETS

The purpose of this test is to determine whether the parameter set developed in Chapter 4 produces more accurate and realistic predictions than those of Gush (1999) described in Section 2.3.4. Using both parameter sets, two sets of model predictions were made and compared to observed SV data from the six trial sites used in the parameter estimation process in Section 4.3.2. These sites were used because observed LAI data were available. Initial biomass pools used in this analysis were derived using the pragmatic approach as described in Section 3.2.1. At the time of this analysis the improved method to assign initial biomass pools (see Section 5.4) had not yet been developed. All other model inputs were those used in Sections 3.2.1 and 4.3.2.

Observed and predicted W_s , qDBH and canopy LAI are compared in Figure 6.2. Each data point is the final observation from each of the six sites, differing in age between 6 and 9 years. These show reasonable and improved fits between observed and predicted data when using the parameters developed in this study as compared to those based on Gush (1999). It is significant that reasonable predictions of LAI are obtained with the new parameters whereas LAI values based on Gush (1999) were frequently over-estimated (see Sections 2.3.4 and 2.4). The emphasis placed on the final observations across each site tends to bias the regression lines because of the slowing in observed growth late in the rotation at several sites that is not being predicted by 3-PG. The reasons for this are not known, but probably are in response to some change in site conditions late in the rotation that have not been captured in the available site data. Another reason that 3-PG does not reflect this downturn in site production could be due to the age-dependent modifier which describes the physiological decline in growth in response to a possible decline in hydraulic properties (Ryan *et al.*, 1997). Details concerning this age modifier are discussed in more detail in Section 6.4.2.

Although stand LAI is much better predicted with the new parameter set (Figure 6.2c), there is a tendency for LAI to be under-predicted. This may be due to an observational error, or due to a deficiency in the parameter set (see Section 6.4.3). Experimentation with parameters that had been left at their default values (Table 4.6) showed that changes in some of these, *e.g.* L_{Cx} , g_{Cx} , η_{Rx} and η_{Rn} can affect both the values estimated for p_2 , p_{20} and a_{Cx} , and the quality of the predictions of LAI. However, they also affect other variables, *e.g.* soil water usage and root biomass, for which no observed data are available.

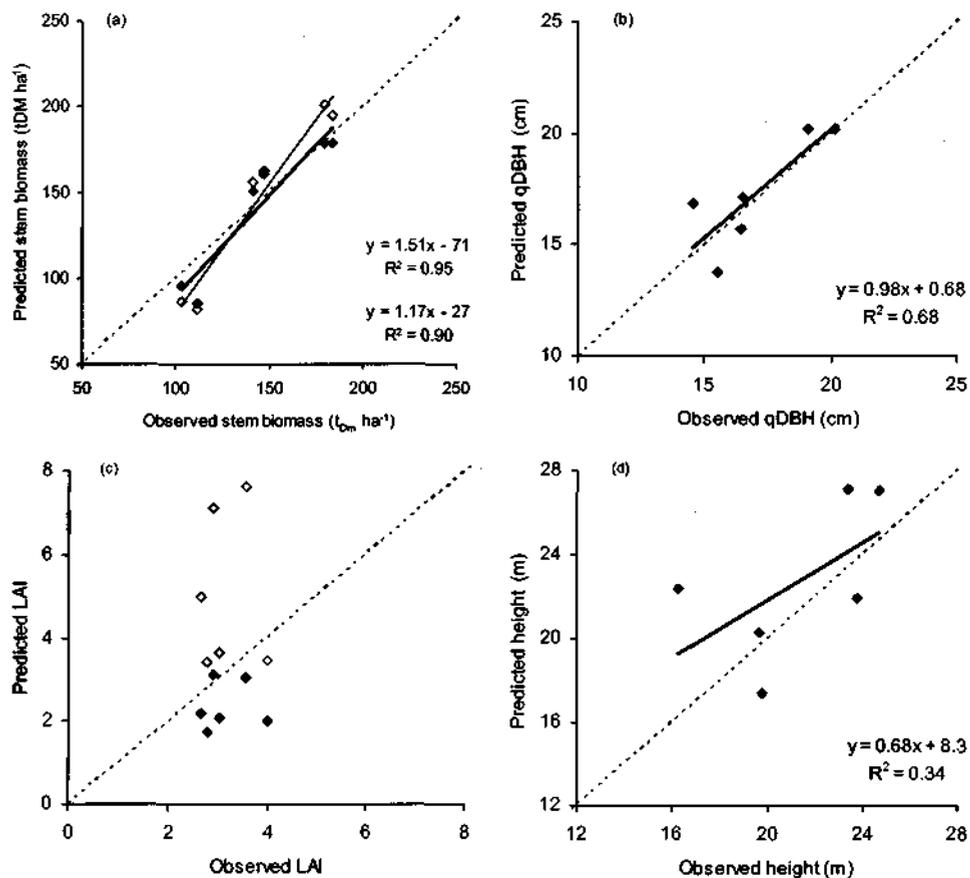


Figure 6.2. Comparison of observed and predicted (a) stem biomass, (b) quadratic mean stem diameter, (c) stand LAI, and (d) stem height at the oldest stand age at the six sites used in the parameter estimation. Predictions used the parameter set developed by Gush (1999) (◇) and the new parameter set (◆). One-to-one lines are shown as (- - -), and (—) and (—) are regression lines for predictions using parameter values from Gush (1999) and from this study. Stem height and quadratic mean stem diameter are not available with the Gush (1999) parameter set. The corresponding regression equations are shown in normal and bold type.

Results indicate the predictions using the new parameter set are realistic, and an improvement on predictions made with the parameter set of Gush (1999). This is especially the case for LAI (Figure 6.2c), which was shown to be over-predicted (see Section 2.2.4) using Gush (1999). The improved prediction of LAI suggests the model's predictions are internally self-consistent and there is thus a greater chance that the right answers are attained for the right reasons!

Figure 6.3 shows predicted W_S and HT using the new parameter set across all sites and all observations. Overall, there is little bias. A more detailed analysis of the predicted time-course of stem biomass, stand LAI, and stem volume, diameter and height shows

overall good agreement with observations at 5 of the 6 sites, except for the later-age observations at sites where there has been a significant cessation of growth. These data and trends are not shown here as they are considered in more detail in Section 6.4.3. At one site, the prediction of LAI is a gross under-estimate, despite good prediction of stem growth (see Sections 6.4.3 and 6.6). Height is an important model output that was not available with the Gush (1999) parameter set. Figure 6.2d and Figure 6.3b show this is relatively well predicted for 5 of the 6 sites.

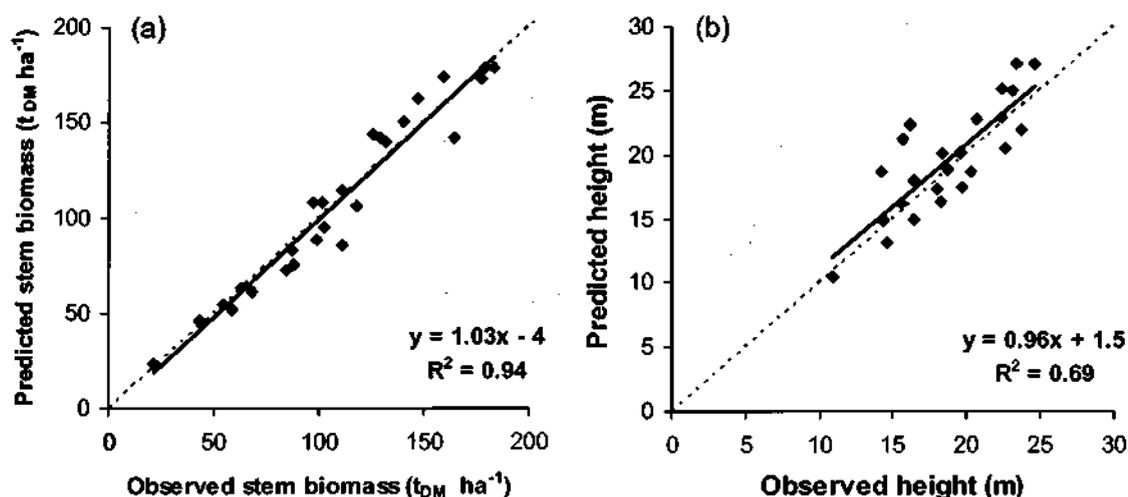


Figure 6.3 Comparison of observed and predicted (a) stem biomass, (b) stem height at all ages at the six sites used in the parameter estimation. Predictions (♦) used the new parameter set, one-to-one lines are shown as (- - -), and (—) are regression lines. The corresponding regression equations are shown in bold type.

6.3 TESTS USING INDEPENDENT DATA SETS

The performance of 3-PG was tested over a wider range of sites than used in Section 6.2, using data from 18 trials of age 5 to 11 years and site productivities (MAI) between 14-51 m³ ha⁻¹ y⁻¹. These sites are representative of South African conditions, and show a highly variable climate with MAP ranging from 780 to 1400 mm, T_X from 22 to 27 °C and T_N from 9 to 17 °C. These sites are a subset of those used in the initial model validation (see Section 2.3.4) and sensitivity analysis (see Section 3.1) and are

independent of those used for the parameterisation (see Section 4.1.1). The observed data consist of SV, either part of the way through the rotation or as final SV at clear felling.

The site data were identical to those used in the sensitivity analysis (see Section 3.2.1). 3-PG was initialised at two years of age using the methods outlined in Sections 5.2, 5.3 and 5.4. Values for W_{Si} were assigned using site indices attained from the FSC (Section 5.4.1). Simulations were performed from age two years and terminated at those ages for which observed data were available (see Tables 2.4 and 3.1).

Regression of predicted *versus* observed SV for these 18 validation sites has an r^2 of 0.77 (Figure 6.4) compared to 0.94 achieved using 6 research plots (Figure 6.3a). Apart from six markedly different sites, predicted SV are within 25% of observed volumes. Although the mean bias is -7.9%, relatively large individual biases are indicative of deviations that are not normally distributed. Similar results were reported in Landsberg *et al.* (2003). The results presented here show the agreement between predicted and observed volume diminish as the duration of the model simulation increases from 1.8 to 9 years. The optimal prediction length is 4 years (slope and r^2 of the regression 0.91 and 0.84 respectively). After 7.5 years the slope and r^2 values decrease to 0.6 and 0.63 respectively indicating that a low proportion of the variance in the observed volumes is accounted for by the predicted values.

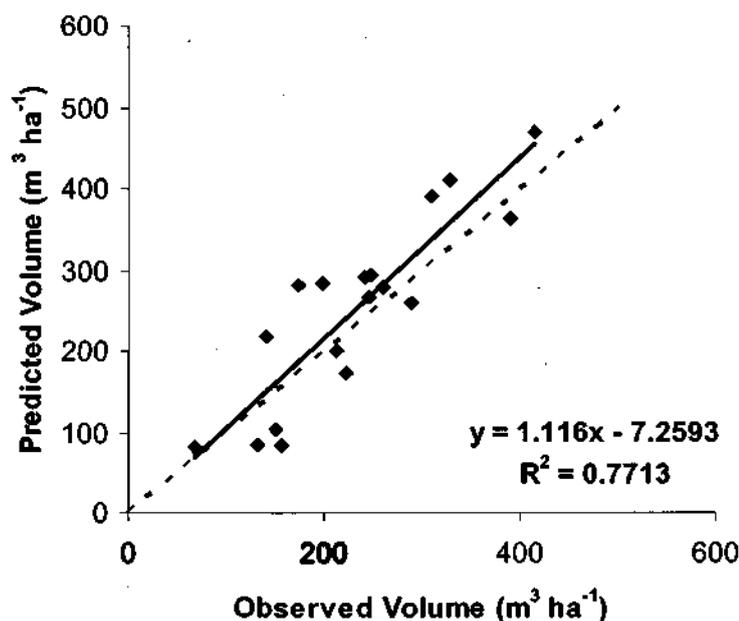


Figure 6.4 Comparison of observed and predicted volume at the 18 sites used in the model validation study. Predictions (♦) using the new parameter set; one-to-one line are shown as (- - -), and (—) is the regression lines. The corresponding regression equation is shown in bold type.

Results from the initial model validation (see Section 2.3.4) showed high and low productivity sites to be under- and over-predicted respectively. Results presented here show a similar, yet less marked trend (*i.e.* over- and under-predictions are not as extreme) and individual biases are less than those from predictions made using the parameter set of Gush (1999). To understand these results, detailed investigations on a per site basis are warranted.

6.4 TESTS USING TIME-SERIES DATA

Testing the model output against time-series data provides an opportunity to evaluate the biological reasonableness of 3-PG and ensures that model predictions “*make sense*”. For example biologically reasonable models would differentiate between sites of varying growth potential or between sites exhibiting environmental constraints compared to those that do not.

3-PG was tested against data from five mensurational trials. These trials, called the M-series, were established by the ICFR during the 1980s. The objective of this suite of trials was to evaluate the effects of initial stand density on the G&Y of short rotation, fast-growing species. Each trial has six stocking treatments ranging from 830 SPH to 2222 SPH, and each received full weed, pest and insect control, and fertilisation where necessary. Blanking (replanting of dead plants) was carried out in the first few months to achieve full stocking for each treatment. Each trial was consistently measured on an annual basis and therefore detailed observed time-series data are available. The trials cover a wide range of growing conditions and potential productivity. Site and climatic details are provided in Table 6.1.

Table 6.1: Site information for the five *E. grandis* M-series spacing trials. Abbreviations are: MAP – mean annual precipitation; MAT – mean annual temperature; FSC – forestry site classification.

Trial	Region	Latitude/ Longitude	MAP (mm)	Depth (cm)	MAT (°C)
M2	KwaZulu-Natal Midlands	29 ^o 31' 30 ^o 33'	992	> 120	17.8
M3	Zululand	28 ^o 39' 32 ^o 05'	1154	> 120	21.2
M4	KwaZulu-Natal Midlands	30 ^o 06' 30 ^o 08'	752	60 to 80	17.4
M5	KwaZulu-Natal South coast	30 ^o 17' 30 ^o 26'	962	60 to 110	18.1
M6	KwaZulu-Natal Midlands	29 ^o 45' 30 ^o 21'	735	70 to 100	17.9

Using data from the 1666 SPH (commonly used stocking in South Africa) treatment across all sites, 3-PG was initialised using first observations of SV for each trial, converted to the appropriate biomass pools for that age (see Section 5.4.1). Weather data were extracted as explained in Section 5.2. Observed monthly temperature data were not available for sites M2 and M6 so long-term monthly averages were used. Similarly, long term monthly SR averages was used for each site. Site information was extracted from the trial register for each trial. These input data are summarised in Table 6.2. Model runs were made from the first age at which observed data are available and terminated at the end of the rotation.

Table 6.2. Site factors and initialisation data for sites M2 to M6. Abbreviations are: FR – site fertility rating; Soil texture: CL – clay-loam; S – sand and C – clay; θ_{Sx} – maximum available soil water; W_{Fi} , W_{Ri} and W_{Si} – initial biomass pools; θ_{Si} – initial soil water content of the soil profile.

Site	Site Factors					Initialisation data			
	Date planted	Latitude	FR	Soil Texture	θ_{Sx} (mm)	W_{Fi} (t _{DM} ha ⁻¹)	W_{Ri} (t _{DM} ha ⁻¹)	W_{Si} (t _{DM} ha ⁻¹)	θ_{Si} (mm)
M2	1986/4	-29	0.6	CL	390	3.7	12.1	32.9	195
M3	1986/5	-28	0.6	S	300	3.8	17.7	49.8	150
M4	1986/12	-30	0.6	CL	130	3.8	6.5	15.9	65
M5	1988/3	-30	0.6	CL	195	3.7	9.0	23.7	97
M6	1990/2	-29	0.4	C	130	4.3	7.9	19.7	65

6.4.1 General results

Basic statistics comparing predicted *versus* observed SPH and qDBH are shown in Table 6.3. This method of analysing data was used by Landsberg *et al.* (2003). However, because time-series data are serially correlated it is not consistent with the assumptions of independence of observation upon which regression analysis is based. Correlated data have little or no additional contribution over and above that of the other (McConway *et al.*, 1999). Nonetheless these statistics help describe the agreement between predicted and observed data: the observed variance accounted for by the predicted qDBH is > 0.91 and that of SPH > 0.87 . Although the mean bias between predicted and observed SPH is relatively low, predicted SPH declines more rapidly than the observed SPH (*i.e.* mortality as predicted by 3-PG was greater than observed mortality). This can be explained by the fact that these trials were managed to achieve full stocking by high quality early silviculture. Furthermore, data used in the model parameterisation came from commercial stands, which undergo very little or no management prior to planting which can lead to higher mortality rates. As a matter of interest, predicted stem number using the $-3/2$ self-thinning power law showed the stands would self-thin after 12 years of age, by which time clear-felling would already have taken place. For short rotation stands self-thinning does not apply, and it is necessary to use the newer mortality function (see Section 2.3).

Table 6.3. Comparison of predicted and observed stems per hectare and quadratic mean DBH (qDBH) for the spacing trials M2 to M6. Basic statistics given include the mean bias (predicted – observed)/observed expressed as a percentage, and the r^2 which shows the variance of the observed data accounted for by the predicted outputs.

Sites		Growth Year							r^2	Bias (%)
		3	4	5	6	7	8	9		
M2	SPH (Predicted)	1387	1359	1334	1308	1282	1257	1232	0.93	0.3
	SPH (Observed)	1361	1334	1306	1292	1278	1264	1236		
	qDBH (Predicted)	11.7	13.2	14.3	15.4	16.0	16.9	17.8	0.91	-8.9
	qDBH (Observed)	13.7	15.7	16.8	17.5	17.6	18.0	18.1		
M3	SPH (Predicted)	1556	1528	1495	1465	1436	1408	1380	0.94	-5.3
	SPH (Observed)	1611	1570	1556	1542	1514	1514	1500		
	qDBH (Predicted)	14.0	15.3	16.7	17.9	18.7	19.4	20.0	0.98	5.1
	qDBH (Observed)	13.9	15.5	16.4	17.0	17.2	17.6	18.1		
M4	SPH (Predicted)	1551	1520	1490	1460	1431	1403	1375	0.73	-6.0
	SPH (Observed)	1556	1528	1528	1528	1528	1514	1514		
	qDBH (Predicted)	7.6	9.3	10.9	12.5	13.3	14.6	15.2	0.93	-4.6
	qDBH (Observed)	8.2	10.7	12.7	13.9	14.2	14.6	14.9		
M5	SPH (Predicted)	1646	1614	1582	1550	1519	1489	1460	0.74	-5.9
	SPH (Observed)	1646	1646	1646	1625	1625	1625	1625		
M6	SPH (Predicted)	1639	1607	1575	1544	1513	1483	1454	0.87	7.22
	SPH (Observed)	1639	1528	1473	1389	1389	1389	1389		
	qDBH (Predicted)	7.6	9.1	10.4	11.7	13.0	14.1	15.0	0.99	2.8
	qDBH (Observed)	8.1	9.2	9.8	11.3	12.7	13.6	14.1		

6.4.2 Model predictions in response to fluctuating weather patterns

Visually, the results from these model predictions are promising. Figure 6.5 shows the predicted time-course of SV across all sites in relation to the observed data. The shaded

bars represent annual rainfall totals for each calendar year (not growing season) and show the climatic variability over the simulation period at each site. With respect to these predicted and observed SVs, and the prevailing drought during the 1991/1992 growing season, the following observations can be made:

- The impact of drought differs at each site and is dependent on the age of the stand at which the drought occurs and is less on the older stands.
- Tree growth at similar aged sites, subsequent to 1992, is reduced to approximately half of that before the drought (*i.e.* there is a long-term effect of the drought).
- This reduction in growth rate continues for up to two years after 1992.
- M6, which was two years of age at the time of the drought, never seems to recover as shown by very low average growth rate over the remainder of the trial.

With respect to the growth rates for predicted and observed SV, *i.e.* the slope of the SV curve in Figure 6.5, the following observations and explanations can be made:

- Predicted growth rates at between 2 and 5 years tend to be lower than the observed growth rate. Landsberg (2001, pers. comm⁷) made a similar observation which he attributed to the fact that 3-PG cannot account for the range of growth rates on different soil types if $f_{N0} = 1$ (see Section 2.3.2).
- Generally the observed growth rates diminish towards the end of the rotation leading to over-predictions in the final SV. This lower observed growth rate is probably due to a reduction in GE or a decline in site resources (Gower *et al.*, 1996). If the parameter maximum stand age in the age-related growth modifier is reduced from 30 years to 15 years, the agreement between predicted *versus* observed final volume is vastly improved. For example predicted *versus* observed SV pairs for sites M2 to M5 are 387 and 381 m³ ha⁻¹, 421 and 414 m³ ha⁻¹, 233 and 245 m³ ha⁻¹, 268 and 260 m³ ha⁻¹, and 216 and 173 m³ ha⁻¹. However, since there is no biological reason to change this

⁷ Dr J. Landsberg, Landsberg Consulting, Canberra, Australia.

parameter value it is not acceptable to do so unless of course such an adjustment is seen as model calibration!

- The degree to which these values decline is more apparent in the CAI data which show annual observed increments to drop below $20 \text{ m}^3 \text{ ha}^{-1}$. Since early predicted growth rates are less than observed rates, predicted CAI does not correspond well with observed CAI. However, predicted CAI does follow a similar trend to these data and tracks the observed data reasonably well. With the exception of M6, predicted CAI is less than observed for young trees and higher than observed for older trees.
- It is interesting that observed tree growth across all sites show a lagged response to the 1991/1992 drought with CAI data declining only in the following year. This trend is replicated by 3-PG.
- Observed and predicted CAI accurately reflects growing conditions. Growth increases during favorable conditions and declines as environmental constraints are imposed (*i.e.* temperature, water and/or VPD limitations). More details are presented later in Section 6.4.5.

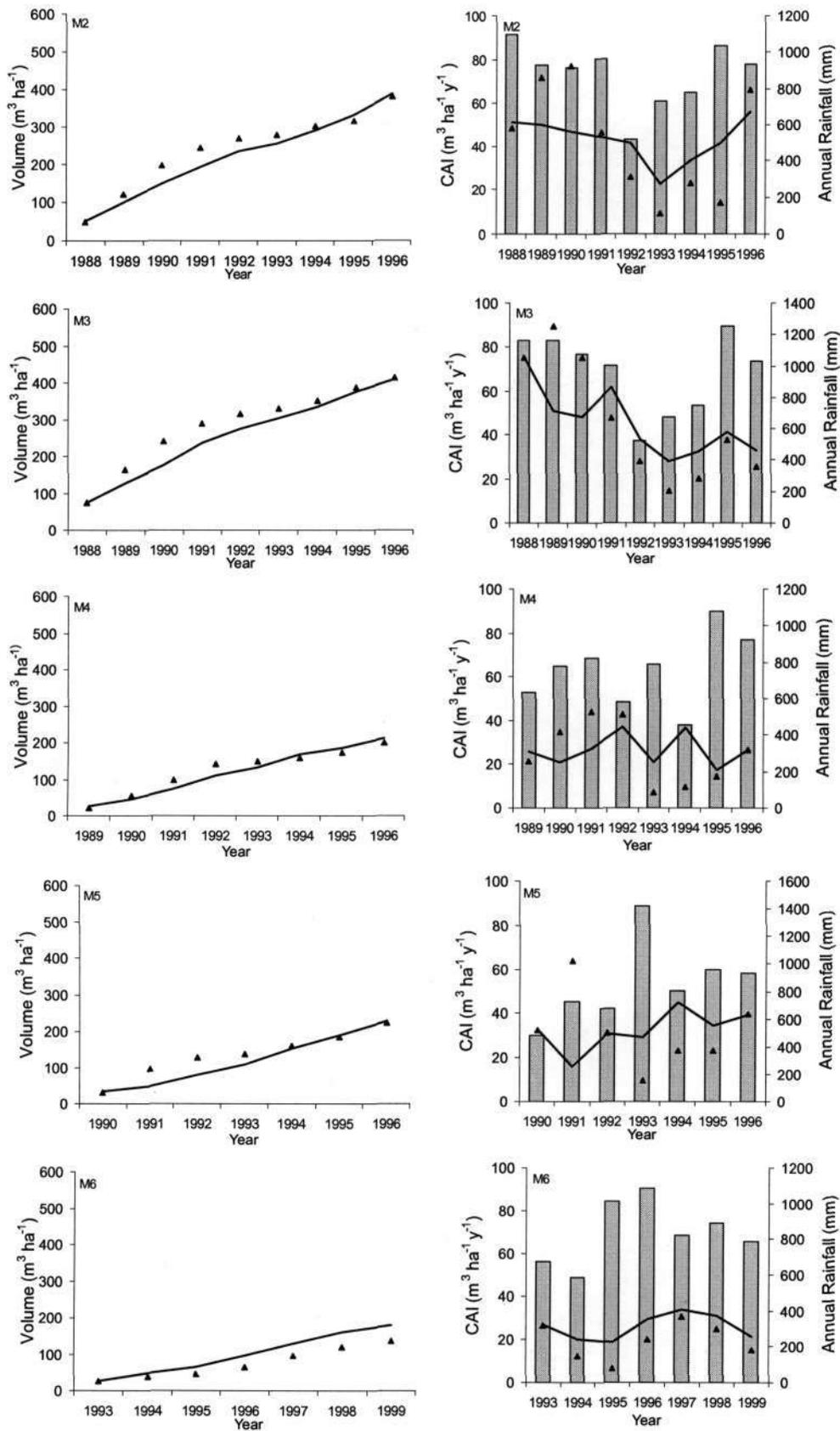


Figure 6.5. Predicted (—) and observed (▲) data pertaining to stand volume and current annual increment (CAI) over the rotation for trials M2, M3, M4, M5 and M6. Annual rainfall is depicted as shaded bar plots.

6.4.3 Biological realism in model predictions

Another important process in model validation is to check that predictions are obtained for the right reasons. This is essentially a check of the biological realism of the model. For example, canopy LAI determines the canopy conductance and the amount of radiation intercepted by the canopy. Therefore biological realism requires that predicted maximum LAI and the general trend thereof throughout the rotation should be realistic and consistent with observed data for *E. grandis*. Since no LAI data were available for these six sites (Table 6.1), LAI values typical of sites in South Africa were used as a check.

Du Toit and Dovey (2005) have shown that LAI reaches a maximum in developing stands followed by a rapid decline after canopy closure. Thereafter, LAI reaches an equilibrium (Beadle, 1997), but may show seasonal variations as a response to fluctuating environmental conditions (Gower *et al.*, 1993). Local data indicate maximum LAI to occur at between 2.5 and 3 years and to vary between 4.0 and 5.3 at canopy closure (du Toit and Dovey, 2005; Campion *et al.*, 2005). Average LAI values of 4.1 and 3.8 at two and three years respectively, have also been shown (Dovey and du Toit (2005). Thereafter, as resource competition sets in, LAI declines to an average of 2.8 (see Section 5.4.2). Other studies by Dye *et al.* (1997) show maximum LAI in the Zululand area (*e.g.* M3) is approximately 3, while at other sites this value does not exceed 1.5. Generally, LAI takes on values between 2 and 3.5 (Dye *et al.*, 2004). Predicted LAI at the study sites are shown in Figure 6.6. Superimposed on these data are peak LAI data from Du Toit and Dovey (2005) and Campion *et al.* (2005). Although the LAI predicted at M3 (dotted line) is greater than at other sites, predicted trends are consistent with the others shown in Figure 6.6. However, using the work done by Dye *et al.* (1997) as a reference, peak LAI at M3 is over-predicted.

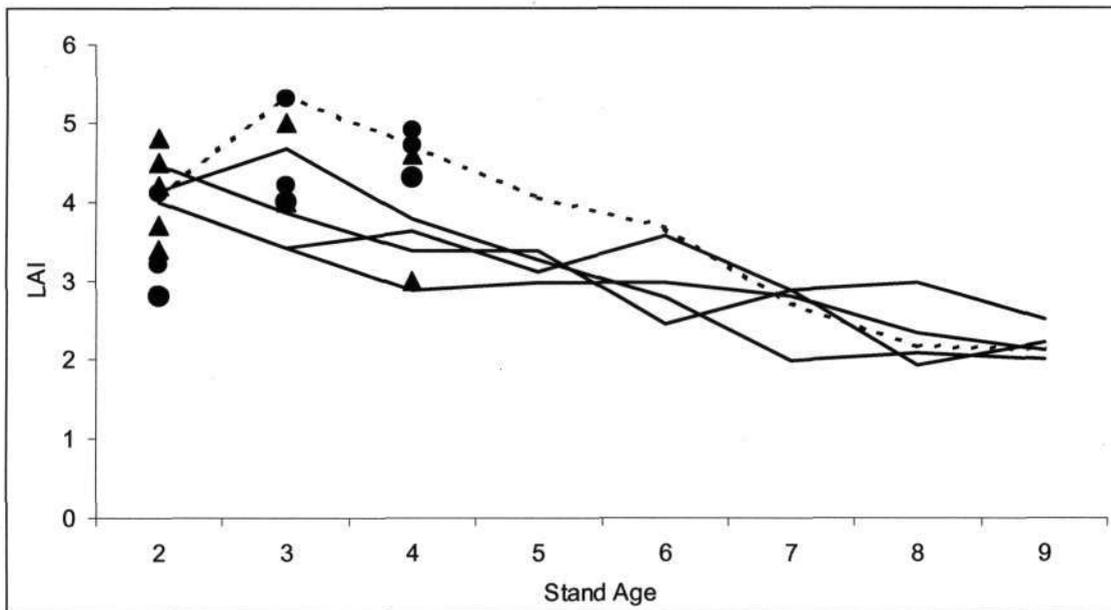


Figure 6.6. Predicted time-course of LAI for all study sites (M2 to M6). Symbols ▲ and ● represent observed LAI at two separate sites of several treatments each in the Kwa-Zulu Natal Midlands (Campion *et al.* 2005); du Toit and Dovey, 2005). The dotted line (- -) represents the M3 site and solid lines (—) representing M2, M4, M5 and M6 sites.

Model outputs tend to reflect reality and show good signs of biological realism. Predicted LAI over the range of sites tested correspond to peak LAI and general trends that have been recorded in other *E. grandis* studies. However, at M3 predicted LAI is not consistent with values for *E. grandis* under local conditions. For example, at M3 the maximum LAI is predicted to be over $5 \text{ m}^2 \text{ m}^{-2}$ rather than $3 \text{ m}^2 \text{ m}^{-2}$ as shown by Dye *et al.* (1997) (see Section 6.4.3). This means that 23% more SR is intercepted (using Beers law, LAI values of 3 and 5.5 equate to light interception values of 0.77 and 0.93 respectively). Despite these unrealistically high values of LAI (and subsequently higher intercepted SR) SV predicted at M3 at this age is less than observed. This is very puzzling and a result that cannot easily be explained. This result could be explained by the work done by Binkley *et al.* (2004), which suggests that more productive sites have a higher efficiency of resource use than less productive sites.

Leaf area index is estimated by 3-PG from W_F and SLA which is calculated as an age-dependent function using parameters pertaining to the SLA of young and mature trees (*i.e.* σ_0 and σ_1). It is therefore possible to change the LAI calculated by changing these parameters. Biomass allocation studies in the vicinity of the M3 trial revealed that for young and mature trees SLA is 7.5 and 4 m² kg⁻¹ respectively (see Figure 4.2, Section 4.3.1). Using these values for σ_0 and σ_1 produces more acceptable LAI values for the M3 site but then LAI values are under-predicted at the remaining sites. Since 3-PG is a generic model which uses one set of parameter values, these values for SLA cannot be changed as suggested. The problem may lie in the efficiency of light resource usage at these Zululand sites and that 3-PG does not account for this.

Absorbed PAR is another very important component of 3-PG and is determined using Beers law and the canopy cover of the stand. The parameter set developed here assumes that canopy closure takes place at 2 years. Following that 3-PG assumes that the canopy is uniform. However, this is not necessarily true for stands with significant mortality. In such instances 3-PG will reflect larger amounts of intercepted radiation which will result in erroneous calculations of dry mass production (Landsberg and Waring, 1997). Implications of this are best described using an example. If a stand is 5 years of age (canopy cover = 1) and the LAI is 3, then of the total incoming radiation, 77% will be intercepted (via Beers law). Since the canopy cover is unity the full 77% of the light intercepted is available for use in carbohydrate production. If, however, the canopy is not uniform and a value for canopy cover was, for example, 0.85 then only 65%, instead of 77% of the SR will actually be used in photosynthesis. This example illustrates the potential for 3-PG to over-predict intercepted incoming SR, which leads to an over-prediction of NPP. Coupled with these errors are reduced growth efficiencies towards the end of the rotation that 3-PG is not able to replicate (Figure 6.5).

6.4.4 Improvement in model predictions

The possibility of further improving these predictions by varying selected parameters and initialisation values was explored. Selected parameters were the maximum NPP allocated to roots (η_{Rx}), the theoretical maximum canopy quantum efficiency (α_{Cx}) and parameters related to the fertility modifier (f_N). Minimum available soil water capacity

was varied to emulate a phreatic surface or GW table. Besides these parameters having moderate to high sensitivity rankings (see Section 3.3.2, Table 3.3), the reasons their values were varied are highlighted as follows:

- Below ground carbohydrate allocation as a proportion of NPP is regulated by soil water deficits and nutrition. As such the process is an important one and if in error will affect the amount of carbohydrate allocated aboveground. Since no observed root data were available it was impossible to determine how root allocation varies between poor and good growing conditions. Default values of 0.6 and 0.25 are therefore used for η_{Rx} and η_{Rn} , respectively (see Section 4.3.1). Incorrect values for these parameters have a considerable effect on monthly production. For example a value of 0.5 for η_{Rx} implies that during times of stress 10% less NPP will be allocated below ground than if a value of 0.6 had been used. Similarly, $\eta_{Rn} = 0.3$ means that under good growing conditions 5% more NPP would be allocated belowground than if 0.25 were used.
- The parameterised value for a_{Cx} is 0.064 (see Section 4.3.2) and is comparable to the value of 0.07 given by Landsberg *et al.* (2003). However, because this parameter has a very high sensitivity ranking very small changes in its value have a large effect on modelled output. For instance if a value of 0.07 is used instead of 0.064, SV at a typical site in the Kwa-Zulu- Natal Midlands could, in the absence of growth constraints, increase by as much as 130 m³ ha⁻¹ over the full rotation.
- Default values were assigned for FR determining how fertility affects production and allocation, because no objective method was available. When $f_{N0} = 1$, the effect of site nutrition on the canopy quantum efficiency is not accounted for. This modifier, f_N (FR), is proportional to FR and is represented in 3-PG as f_N (FR) = $f_{N0} + (1 - f_{N0})$ FR where f_{N0} is the value of f_N when FR=0. Landsberg *et al.* (2003) found that $f_{N0} = 0.5$ was suitable when the model was calibrated against growth data from a range of soil types and hence FR values, while Almeida *et al.* (2004b) set f_{N0} to a value of 0.6.

- During periods of below average rainfall, deep rooted eucalypts are able to maintain transpiration by accessing water from deep in the profile or from a water table (Knight, 1999). Work done by Dye and Poulter (1992) in the Eastern Transvaal showed that water use by *E. grandis* can exceed annual rainfall. This suggests that the rate of tree growth can continue unimpeded by climatic fluctuations where water tables are prevalent. Soil water deficits during the 1991/1992 drought did not cause severe stress in *E. grandis* trees and failure of these trees to respond to drought and soil water deficits can be attributed to the ability of the trees to extract soil water to a depth of at least 8m (Dye, 1996). Such access to deep water is possible because of the dimorphic nature of eucalypt root systems which consist of wide-spreading surface roots, tap roots in young trees and sinker roots in mature trees (Knight, 1999). In a study to investigate the rooting strategies of *E. grandis* on deep sands in Zululand, isotopes were used to trace the source of water and therefore distinguish between soil water and GW. Generally GW was detected between 4 and 8m of depth (Scott, 1993). It is reasonable to assume the possibility of GW access especially when tree growth continues unimpeded during periods of sub-optimal rainfall or drought. To test the likely consequence of such access, 3-PG was set up to account for the presence of a GW store. This was done by setting the $\theta_{Sx} = \theta_{Sn}$. The θ_{Sn} was also varied so that GW access was restricted to periods when current monthly θ_S was approximately 50% of the θ_{Sx} .

The parameter values were altered as follows: (1) η_{Rx} reduced from 0.6 to 0.5; (2) α_{Cx} increased from 0.064 to 0.07; and (3) f_{M0} reduced from 1 to 0.5. For each alteration new sets of SV predictions were made and compared to observed data of trials M2 to M6 (see Section 6.4, Table 6.1). Observed and predicted growth rates over a five year time period are shown in Table 6.4 and Figure 6.7. The nominal predictions were based on the original (*i.e.* unaltered) parameter values (see Section 4.3, Table 4.6). The other predictions refer to the growth rates in response to the changes in parameter values and access to GW by changing the minimum available soil water. With respect to altering

parameter values the changes in growth rate are not consistent between sites. For instance a decrease in η_{Rx} and an increase α_{Cx} have a greater effect on production at M2 and M3 than at M4, M5 and M6. On the contrary, setting $f_{N0} = 0.5$ consistently improves stand production over the entire course of the rotation at M6. This improvement is not consistent with the other sites therefore suggesting that the FR modifier may either be site-specific or M6 exhibits FR limitations that do not occur at the other sites.

Table 6.4. Observed and predicted SV growth rates (GR) over a five year time frame across all sites. Column 3 shows predicted (nominal) growth rates when unaltered parameter values are used (*i.e.* $\eta_{Rx} = 0.6$; $\alpha_{Cx} = 0.064$ and $f_{N0} = 1$). Columns 4 to 8 show growth rates across all sites in response to changing parameter values individually (*i.e.* only one at a time: $\eta_{Rx} = 0.5$; $\alpha_{Cx} = 0.07$ and $f_{N0} = 0.5$) and the minimum available soil water. GW (1) and GW (2) are two scenarios where full GW access is activated and access permitted only during periods of water stress. See also Figure 6.7.

Sites	Average stand volume growth rate (over five years, $\text{m}^3 \text{ha}^{-1} \text{y}^{-1}$)						
	Observed	Nominal	GR in response to changes in parameter values and site information				
			η_{Rx}	α_{Cx}	f_{N0}	GW (1)	GW (2)
M2	48	35	38	40	26	61	47
M3	53	40	43	45	30	56	46
M4	30	21	22	23	16	54	38
M5	26	19	20	20	15	53	37
M6	9	17	19	19	12	46	25

Access to groundwater (GW1) by setting $\theta_{Sx} = \theta_{Sn}$ produces very large predicted volumes especially at sites where soil water is limiting, or over prolonged periods of drought. If, however, groundwater access (GW2) is limited only to periods where θ_S is a fraction of θ_{Sx} ($f_\theta = 0.5$) emulating temporary water constraints to growth, tree growth rates are more realistic with volumes showing a better agreement with observed data across most sites.

The results outlined here demonstrate the possibility of improving model predictions by varying selected parameter values and site factors. However, such changes to parameter values cannot be done on an *ad hoc* basis with no real justification. If additional site information, such as the presence of GW or soil nutrition inferred from soil analyses are

available then it may be possible to vary model parameter and site information. Where such information is not known it is not acceptable to vary such parameters or site factors to improve the model prediction.

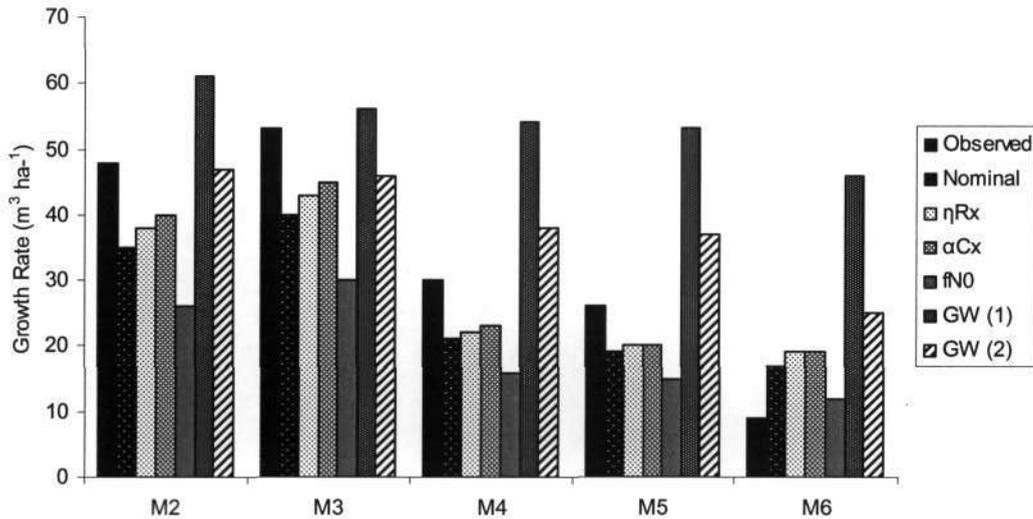


Figure 6.7 Growth rates over a 5 year simulation period for predicted (shades of black and grey) and observed (solid) stand volume for sites M2 to M6. Abbreviations in the legend pertain to the different model simulations performed as described in Table 6.4. Nominal refers to growth rates when unaltered parameter values are used (*i.e.* $\eta_{Rx} = 0.6$; $\alpha_{Cx} = 0.064$ and $f_{N0} = 1$). These three parameters and reference to groundwater (GW) shown in the legend (and columns 4 to 8 in Table 6.4) refer to growth rates across all sites in response to changing parameter values (*i.e.* $\eta_{Rx} = 0.5$; $\alpha_{Cx} = 0.07$ and $f_{N0} = 0.5$) and the minimum available soil water. GW (1) and GW (2) are two scenarios where full GW access is activated and access only during periods of water stress.

6.4.5 Detailed 3-PG monthly outputs

This section considers detailed monthly 3-PG output (as opposed to annual model output) as a means to evaluate and understand growth responses to climatic fluctuations and growth constraints. These model simulations are performed at M2 which was arbitrarily chosen (see Section 6.4, Table 6.1) and use parameter values developed in Chapter 4, but with both (i) actual monthly and (ii) long term average weather data. Results from these simulations are presented for 1993, 1994 and 1995 in Figures 6.8 and 6.9 respectively. Each of these figures comprises three charts which show: (a) the

prediction of monthly R , θ_s , T_{AV} and VPD; (b) soil water, VPD and temperature modifiers (f_θ , f_D and f_T); and (c) the modified canopy quantum efficiency (α_C), root and stem partitioning coefficients (p_R and p_S).

In order to effectively interpret these results the following points must be kept in mind:

- f_T is a function of cardinal temperatures and T_{AV} each month; f_θ is a function of current θ_s , θ_{Sx} and soil texture; f_D is a function of monthly average VPD and the stomatal response to VPD (k_D).
- α_C is calculated monthly and takes into account these environmental modifiers and any constraint imposed by the site fertility (if $f_{N0} < 1$).
- f_θ and f_D are applied as a law of the minimum and applied as the physiological modifier.
- Using this modified value, the molecular weight of dry matter and a conversion factor for SR to PAR (both of which are set as constant values in 3-PG) the GE is calculated.
- Gross primary production produced is the product of intercepted SR and α_C , and is reduced by respiration to produce NPP.
- Net primary production is partitioned to roots and above ground biomass. Root allocation is based on environmental conditions and if limitations to growth exist root allocation increases. The ratio of foliage to stem allocation declines with increasing tree size.

During 1993 annual rainfall was 729 mm, approximately 70% of the amount in 1995. Final SV at age 11 years predicted using actual weather data is 457, compared to 433 $m^3 ha^{-1}$ predicted using long term averaged weather data.

Figures 6.8a and 6.9a show that simulated soil water decreases during winter and months having lower than average R , increasing following very wet events and over summer. It is evident that predicted soil water (Figure 6.8a) is responsive to fluctuating R as shown between 1994 and 1995. Average temperatures and VPD also fluctuate seasonally. VPD shown here is not based on relative humidity and temperature data but

calculated from T_X and T_N , and may be under-estimated (see Sections 5.2 and 5.4). Nevertheless the trends shown here are reasonable and respond in an expected manner.

Figure 6.9a show similar trends to those shown in Figure 6.8a except that each year is characterised by identical weather patterns because these data are long term means. On these grounds the monthly modifiers shown in Figure 6.9b are replicated on an annual basis in accordance with the weather data shown in Figure 6.9a.

Figure 6.8b shows how the environmental modifiers respond to the prevailing weather conditions. For example during 1993 the available soil water decreases in response to decreased R amounts. The soil water modifier follows a similar trend. Figure 6.8b shows that during time of drought $f_\theta < f_D$. Because growth is limited by the minimum of these modifiers, growth is therefore limited by soil water, not VPD, during such periods of water stress. During the winter months temperature does limit growth, but as the weather warms up and R increases in summer the temperature (and soil water) limitations on growth are reduced.

3-PG uses the growth modifiers to reduce the quantum efficiency α_C from its unlimited value of $0.064 \text{ mol mol}^{-1}$ (see Figures 6.8c and 6.9c). It is interesting how monthly values of α_C tracks those of f_θ (6.8b and 6.9b) during the winter months and temperature and VPD during the remainder of the year. These very low values of α_C indicate severe growth constraints which impact negatively on above ground allocation. In these cases more carbohydrate is allocated to roots as shown in Figure 6.8c. However, during favourable months (*e.g.* February to September 1994) allocation to roots is very low. These results demonstrate how predictions can better reflect reality when actual weather input data are used because it is these data that allow for site constraints to growth to be recognised.

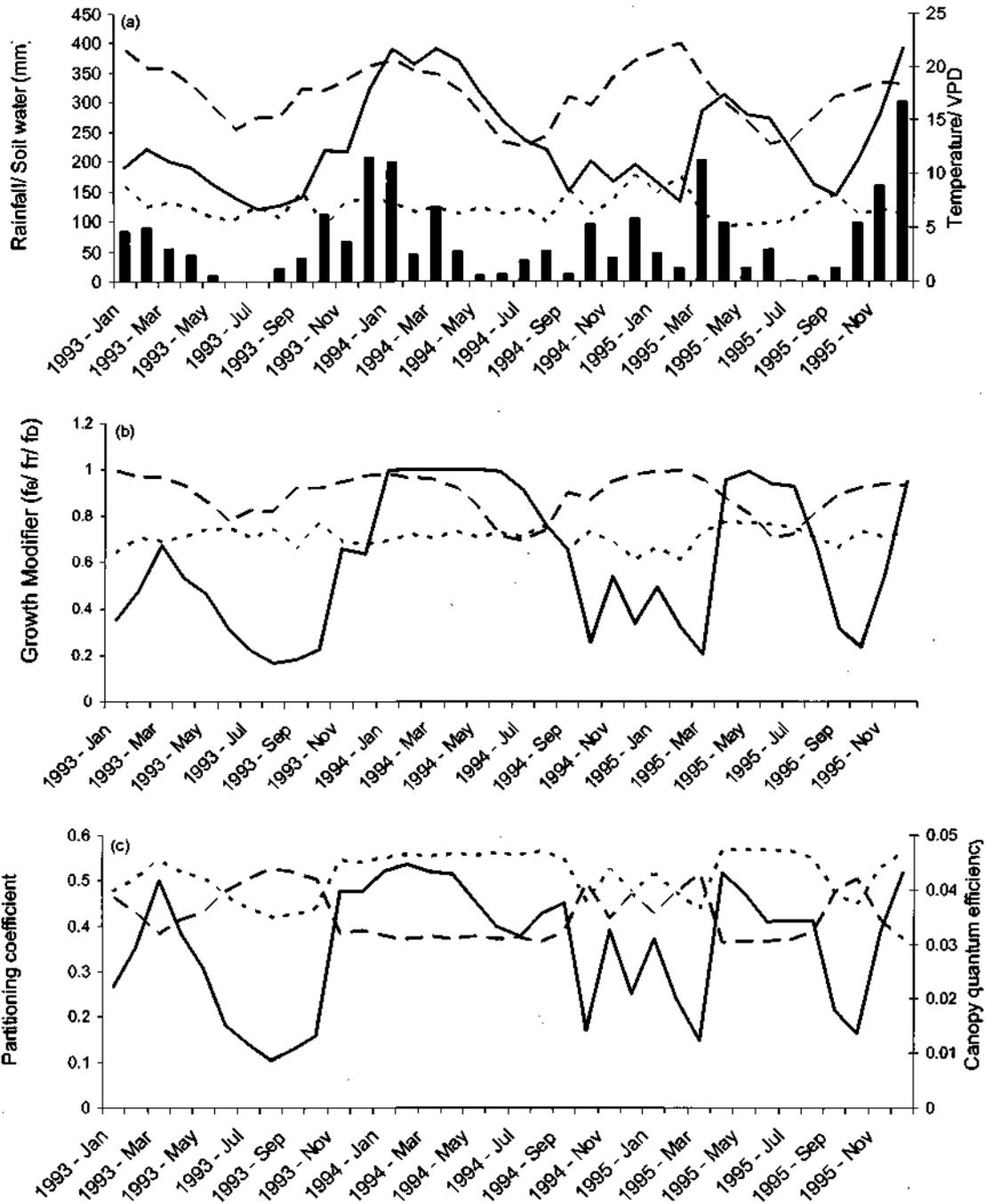


Figure 6.8. Detailed model output from site M2 for 1993, 1994 and 1995 when using actual weather data. (a) shows monthly rainfall totals (mm/ month, solid bars), mean temperature ($^{\circ}\text{C}$, —) and VPD (mbar, ----) as determined by T_X and T_N , and monthly predicted θ_S contents (mm per total soil depth, —); (b) shows the temperature (—), soil water (—) and VPD modifiers (----), and (c) the canopy quantum efficiency (—) taking into account the environmental modifiers, and the root (—) and stem (----) partitioning coefficients (p_R and p_S).

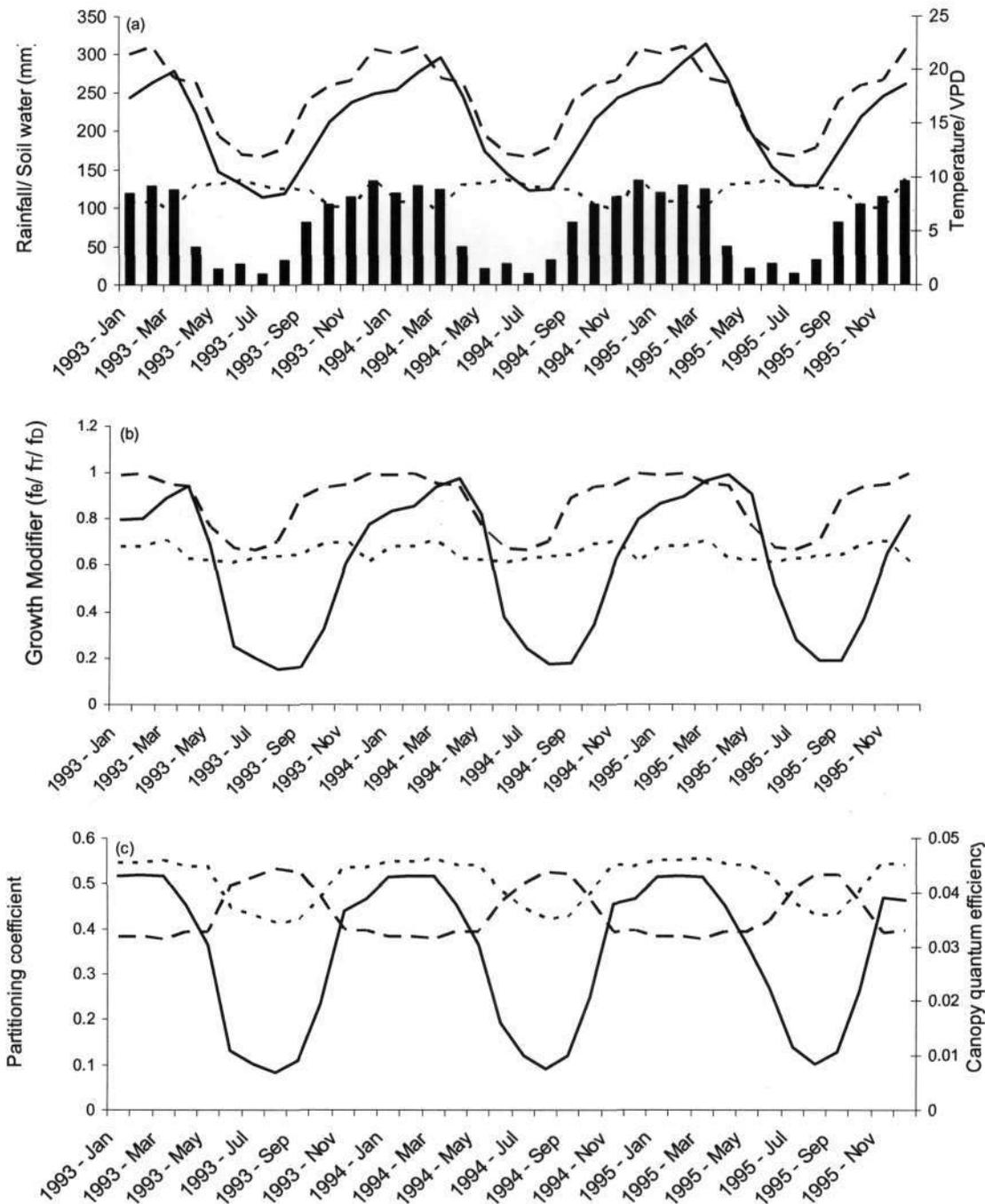


Figure 6.9. Detailed model output from site M2 for 1993, 1994 and 1995 when using average weather data. (a) shows monthly rainfall totals (mm/ month, solid bars), mean temperature ($^{\circ}\text{C}$, —) and VPD (mbar, ----) as determined by T_X and T_N , and monthly predicted θ_s contents (mm per total soil depth, —); (b) shows the temperature (—), soil water (—) and VPD modifiers (----), and (c) the canopy quantum efficiency (—) taking into account the environmental modifiers, and the root (—) and stem (----) partitioning coefficients (p_R and p_S).

6.5 TESTS AGAINST RESULTS FROM A FERTILISATION TRIAL⁸

As part of an independent validation, 3-PG was tested against growth data from an irrigated and fertilised *E. grandis* stand in the KwaZulu-Natal Midlands. This model validation forms part of the work conducted by Campion (2005), and has been published as Campion *et al.* (2005). A brief overview of this work is presented here. The interested reader can refer to Appendix B where the paper by Campion *et al.* (2005) is attached.

The site has a MAP and MAT of 919 mm and 16.6⁰C respectively. The soils have a clay loam texture and range between 0.5 and 1m in depth. The trial has 16 plots consisting of a control, irrigated, fertilised and irrigated-fertilised treatments. Predictions were made using the parameter values developed in Chapter 4, weather data collected from an on-site weather station and detailed site information. The model was initialised with early observations of W_S and W_F . The model was used to predict foliage and stem biomass, and LAI from an age of two until four years of age.

Results showed a good correlation with growth data across all treatments (see Figure 1 in Campion *et al.*, 2005, Appendix B). At 3.9 years, predicted LAI over all treatments ranged from 3.8 to 5.1, similar to the observed range of 4.3 to 4.9. Predicted SV at 3.9 years ranged from 79 to 121 m³ ha⁻¹ across all treatments, compared to observations of 100 to 118 m³ ha⁻¹. After three years 3-PG tends to under-predict SV in the non-irrigated treatments. Campion *et al.* (2005) attribute these discrepancies to (1) potential access to ground water not accounted by 3-PG; (2) errors in soil water and, and hence transpiration because of the simplistic manner that soil water is calculated (*i.e.* simple one layer soil water budget, and (3) under allocation of NPP to stemwood (*i.e.* too much being allocated to root biomass in response to erroneous measures of VPD and soil water constraints).

⁸ More details regarding this validation study is presented in Appendix 5, published as Campion *et al.* (2005).

6.6 CONCLUSIONS

This chapter looked at the performance of 3-PG using four different tests each using different data sets. Results showed: (1) that the use of the new parameter set provides accurate and realistic predictions of stand volume (SV) and leaf area index (LAI); (2) predictions are reasonable over a wide range of growing conditions, but tend to over-predict on low productivity sites and under-predict on high productivity sites; (3) model predictions in response to fluctuating weather patterns show that general growth trends (*e.g.* CAI) reflect reality. Absolute values of current annual increment (CAI) did differ as a result of errors in model input data highlighting the need to have accurate site and weather inputs (see Section 5.4); and (4) 3-PG predictions are able to capture differences between irrigated and fertilised sites (*i.e.* treatment differences).

Under certain conditions model predictions are in error. These include:

- The over-prediction of LAI in Zululand. This can be rectified by either changing the parameters that describe the relationship between specific leaf area (SLA) and stand age or the way in which the canopy cover of the stand is calculated. If the canopy cover is made to either decline over the life of the stand (*i.e.* an age-dependent relationship), or made site-specific, LAI predictions could be improved upon especially in commercial stands where tree mortality is high.
- The over-prediction of SV towards the end of the rotation. Reasons for this are not clear, and could be in response to a change or decline in site resources not captured by the model, or due to an incorrect value used for the parameter describing the physiological decline over the age of the stand (age modifier).
- The over-and under-predictions that generally occur over low and high productivity sites. These trends could be in response to the weather having an intrinsic error attached (see Sections 5.2 and 5.4). For instance, solar radiation (SR) data are long-term means and hence would not reflect conditions experienced during periods of above average monthly rainfall (R) as the cloudy conditions reduce incoming SR. In addition, production will be over-estimated during wetter periods (*i.e.* $f_{\theta} > f_D$) because vapour pressure deficit

(VPD) (see Sections 5.2 and 5.4) is over-estimated by virtue of the method by which it is calculated (via T_X and T_N). The effect of this will be more pronounced when VPD is more limiting than available soil water (θ_S).

Despite these shortcomings results from this rigorous model validation show that 3-PG generally performs well, and predictions made are biologically reasonable and capture seasonal growth constraints. These results suggest that 3-PG works reasonably well for South African conditions and could be a useful tool to understand the implications of drought on tree growth. This study has helped achieve the third objective of this study. With the confidence in model predictions gained here, Chapter 7 considers some possible applications of 3-PG applicable within the South African context. In closing, the following quote from Dirac (1963) cited by Hopkins and Leipold (1996) is appropriate:

“I think there is a moral to this story, namely that it is more important to have beauty in one’s equations than to have them fit experiment If there is not complete agreement between results of one’s work and experiment, one should not allow oneself to be too discouraged, because the discrepancy may well be due to minor features that are not properly taken into account and that will be cleared up with further developments of the theory.”

CHAPTER 7

POTENTIAL APPLICATION OF 3-PG IN SOUTH AFRICA

7.1 INTRODUCTION

Several benchmark publications have recently been written about the implementation and application of PBMs in forest management (for reviews see Battaglia and Sands (1998a); Mäkelä *et al.* (2000); Sands *et al.* (2000); Battaglia *et al.* (2004); Sands (2003)). Potential applications of PBMs, highlighted by McMurtrie *et al.* (1990); Battaglia and Sands (1998a); Landsberg (2003), include: (1) the prediction of G&Y on existing plantations; (2) site-species matching; (3) identification and the understanding of site limitations to productivity; (4) risk assessment; (5) questions for which results from long term experiments are not feasible. Current applications of PBMs have become more diverse than they were in the past when they were used mainly for research, or in the prediction of economic and volume yield. Although PBMs are still extensively used for research purposes and understanding stand growth dynamics, they are now also being used to help in the management of risk, provide insights into sustainability of forest management practices, isolate the consequence of environmental factors on growth, and for understanding potential effects of climate change on tree growth (Battaglia and Sands, 1998a).

The role of 3-PG in South Africa is uncertain due to a lack of understanding of the model and its potential applications, and misgivings surrounding the accuracy and reliability of predictions made using PBMs in general. The validation of 3-PG in Chapter 6 showed promising results, and that the model can give reasonable and realistic predictions of SV over a range of growing conditions. It is therefore believed that 3-PG could potentially play a useful role within South African forestry, both as an operational and a strategic tool. Strategic applications may include the: (1) prediction of potential productivity on a site-by-site basis; (2) broad-scale productivity estimates based on remote sensing and the spatial application of 3-PG; (3) identification of production constraints; and (4) estimation of C fluxes to help address sustainability issues. Operationally, 3-PG could complement EBMs or be used in conjunction with

them as a hybridised product. EBMs are currently used to predict final standing volume for scheduling harvest operations. These predictions are based on inventory data collected several years before clear-felling age. However, if weather conditions during this prediction window differ significantly from the average then model predictions will be in error, because EBMs are based on average conditions (see Section 7.4). 3-PG on the other hand could be initialised using this inventory data and used to make predictions of final SV.

The objective of this chapter is to present three potential applications of how 3-PG could be used in South Africa. These are the determination of potential site productivity, the identification of factors limiting growth, and the use of 3-PG to predict SV at the end of the rotation. These applications are presented within the framework of the forestry site classification (FSC) which categorises sites into cool temperate, warm temperate and sub-tropical zones as shown in Table 7.1 (see Section 5.1).

Table 7.1. Classification of sites, according to site mean annual precipitation (MAP) and mean annual temperature (MAT), showing regions best suited to growing *E. grandis* (Smith *et al.*, 2005).

Climate Zone	Class	MAT (°C)	MAP (mm)	Suitable for <i>E. grandis</i>
Cool Temperate	CT1 – CT3	10 to 14	<700, 700-800, >800	No
	CT4 – CT6	14 to 15	<800, 800-900, >900	No
	CT7 – CT9	15 to 16	<825, 825-925, >925	Yes
Warm Temperate	WT1 – WT3	16 to 17	<850, 850-950, >950	Yes
	WT4 – WT6	17 to 18	<875, 875-975, >975	Yes
	WT7 – WT9	18 to 19	<900, 900-1000, >1000	Yes
Sub-Tropical	ST1 – ST3	19 to 20	<925, 925-1025, >1025	Yes
	ST4 – ST6	20 to 21	<950, 950-1050, >1050	Yes
	ST7 – ST9	21 to 22	<975, 975-1075, >1075	Yes

Smith *et al.* (2005) assessed the productivity of *E. grandis* using stand-level growth and inventory data from approximately 90 PSP *E. grandis* sites. These growth data were grouped according to the MAP and MAT of each site and estimates of site potential made. These estimates showed: site index at five years (SI₅), maximum MAI (MAI_X), and age at MAI_X (MAI_{Xage}) were limited by the quality and type of observed data available. For instance, estimates of SV are in general based on observed HT and DBH. Furthermore, these growth data are representative of only one climatic window in space

and time (*i.e.* that associated with each PSP and its rotation) during which time there may or may not have been a drought or other significant event such as insect attack. Due to these uncertainties in the climatic (and growth) data it is believed that 3-PG can give additional estimates of productivity (*e.g.* LAI or GE) and better estimates of productivity encompassing a range of climatic conditions, significant events and management scenarios.

7.2 PREDICTING POTENTIAL PRODUCTIVITY

The purpose of this section is to use 3-PG to make estimates of potential site productivity, and to compare these estimates to those made by Smith *et al.* (2005) for selected site classes. Growth in response to theoretical scenarios (*e.g.* access to GW, or optimal nutrient conditions) is also explored. Five sites representing the CT9, WT4, WT6, ST1 and ST9 classes (Table 7.1), shown in Table 7.2, were selected. So as to capture a wide range of site productivity, the observed weather data for 1950 to 1999 were used and 3-PG was used to simulate all possible eight-year rotations over this period (*i.e.* as if trees were planted each year and grown till the end of the rotation). Site and soil factors were the same as those used in Sections 2.3.4 and 3.2.1. Initial biomass pools at age two years were determined using SI data from the FSC (see Section 5.4). Summary weather data for sites representative of these FSC areas are provided in Table 7.2.

Table 7.2. Summary weather data for the five sites used to estimate productivity for the climatic zones of the site classification. Total rainfall and solar radiation give the ranges in totals over successive eight year rotations over the full climatic record. Abbreviations comprise: MAP – mean annual precipitation; MAT – mean annual temperature.

Climate Zone	Location	Total rainfall (mm)	Total solar radiation (MJ m ⁻²)	MAP (mm y ⁻¹)	MAT (°C)
CT9	Glendale	6279-9350	2287	868	16.1
WT4	Baynesfield	6534-8340	2368	817	17.4
WT6	Windy Hill	7555-9418	2415	969	17.3
ST1	Bloemendal	7453-9212	2383	905	19.1
ST9	Amangwe	9170-12916	2415	1194	21.8

Total rainfall shown is an indication of the minimum and maximum total rainfall (and therefore the range in total rainfall) over successive eight year rotation periods between 1950 and 1991. Similarly, total SR refers to totals over the entire rotation and is a single value because only mean radiation data were available (see Section 5.2). For example at Glendale the total rainfall between 1962 and 1970 amounted to 6279 mm compared to 9350 mm occurring between 1983 and 1991. During these same periods an average of 2287 MJ m⁻² of SR was recorded.

3-PG was initialised at an age of 2 years and run for successive eight-year periods (*i.e.* until a stand age of 10 years). Since, 3-PG was initialised at two years of age only 8 years worth of climatic record were used for each model run (*e.g.* 1950-1958, 1951-1959 *etc.*). By performing model simulations in such a fashion, the full range of response to the 50 year climatic record is utilised and upper and lower ceilings to productivity were established. The estimates of site productivity were SI₅; MAI_X; MAI_{Xage}, SV, NPP and the GE, all of which are shown in Table 7.3.

It is important to remember that the estimates presented here were developed using only one site per climatic class. The range in values presented is a consequence of modelling for several rotations at a single site. To provide more accurate estimates several sites representative of soils, fertility and weather extremes will need to be used.

Estimates of SI₅ reported in Table 7.3 are the average tree height at five years and serve as a rough estimate of the true site index (*i.e.* the dHT of the top 20% of trees at age five). The results shown are comparable to the estimates of SI₅ presented within the FSC. The predicted range of MAI_X and the MAI_{Xage} are realistic for each of the sites and comparable with observed data. The range of MAI_X at WT6 and ST9 are not as extreme as those observed and may be due to 3-PG estimates being based on one site only.

Table 7.3. Estimates of potential productivity for six sites covering the full range of climatic zones. Values in parenthesis are estimates made using observed data depicted in the forest site classification. Abbreviations are as follows: SI_5 – site index at a reference age of five years; MAI_X and MAI_{Xage} – peak and age at peak mean annual increment; SV – final stand volume; NPP – net primary production; GE – radiation use efficiency.

Estimate of productivity	CT9	WT4	WT6	ST1	ST9
SI_5 (m)	14-17 (15)	15-17 (14)	17-20 (18)	15.5-17.7 (14)	20-24 (22)
MAI_X ($m^3 ha^{-1} y^{-1}$)	19-27 (20-40)	19-25 (16-35)	32-44 (24-49)	21-28 (-)	47-68 (33-85)
MAI_{Xage} (y)	6-9 (10)	6-9 (11)	5-9 (9)	6-9 (10)	4-9 (6)
SV ($m^3 ha^{-1}$)	156-235	184-237	313-411	207-257	455-595
NPP ($t_{DM} ha^{-1}$)	194-250	210-256	306-387	213-259	416-528
Growth efficiency ($g_{DM} MJ^{-1}$)	0.70-1.73	0.7-1.6	0.7-2.3	0.89-1.06	1.09-2.6

Net primary production provides a measure of the ability of the trees on the site to fix C because it constitutes the total C assimilated. Stand volume, on the other hand, is a measure of how much NPP is partitioned to the utilisable timber which is affected by environmental stress. The SV therefore varies in response to climatic and environmental growth constraints. This helps explain the large range shown in the values of SV. For instance, during periods of high soil water deficits, allocation to below ground increases, which results in less carbohydrate being available for stem growth. The GE is a very useful value to consider and is calculated as the product of the molecular weight of dry matter, conversion of SR to PAR and the α_C . Since the former two variables are fixed parameter values (see Section 4.3, Table 4.6) the GE is directly proportional to site growth limitations (e.g. growth modifiers) reflected in α_C . Larger GE values imply that available site resources are better used and environmental stress is low.

The usefulness of 3-PG for exploring the effects of growth in response to theoretical scenarios was explored. Two contrasting sites, CT9 and ST9, were used and (i) “allowed” to access GW during dry winter months and times of drought and (ii) given optimal nutritional conditions. 3-PG was set up to access GW during periods of soil water deficits by setting the $\theta_{Sn} = \theta_{Sx}$ so that these sites are never constrained by water

deficits. When $\theta_{Sx} = \theta_{Sx}$ additional water is added to the system such that $\theta_S > \theta_{Sx}$. Optimal nutritional conditions were emulated by setting FR to 1 which together with parameter values shown in Table 4.6 (*i.e.* f_{N0}) only affects below ground allocation. Results from these scenarios are presented in Table 7.4.

Table 7.4 Productivity estimates in response to groundwater (GW) access and optimal site nutrition for contrasting sites CT9 and ST9. Baseline estimates refer to normal site conditions (Table 7.3). Abbreviations are as follows: SI_5 – site index at a reference age of five years; MAI_X and MAI_{Xage} – peak and age at peak mean annual increment; SV – final stand volume.

Productivity	CT9			ST9		
	Baseline	GW access	FR=1	Baseline	GW access	FR=1
SI_5 (m)	13-17	20-21	15-19	20-24	24-25	21-25
MAI_X ($m^3 ha^{-1} y^{-1}$)	15-25	41-45	24-34	47-68	64-65	55-77
SV ($m^3 ha^{-1}$)	156-235	368-397	236-314	455-595	636-654	516-675
NPP ($t_{DM} ha^{-1}$)	185-268	386-416	192-274	416-528	564-578	429-539
GE ($g_{DM} MJ^{-1}$)	0.42-1.95	0.94-2.17	0.42-1.80	1.09-2.6	1.25-2.6	0.99-2.62

At CT9 final SV and NPP increase substantially in response to access to GW. The increase in the lower threshold value of the GE (0.42 to 0.94) does indicate that in drier years GW access helps alleviate soil water deficit conditions. With respect to ST9 a similar result is apparent.

On the other hand optimal site nutrition has a relatively small effect on overall production. This is important because only below ground allocation is affected by FR with the current parameter set ($f_{N0} = 1$). However, if f_{N0} is set to 0.5, then under baseline conditions, SV at CT9 and ST9 would have been 104-154 $m^3 ha^{-1}$ and 345-455 $m^3 ha^{-1}$ respectively. In this case, full fertility would have had a large effect on production.

7.3 IDENTIFICATION OF FACTORS LIMITING GROWTH

Questions are continuously asked in the South African forest industry concerning the “true” production potential of forest plantations. These include whether or not site

potential is limited by genetics, silviculture, nutrition, water or a combination of these. It is commonly assumed, mainly by personal observation and empirical studies, that plantation productivity is constrained mainly by water. The value of PBMs is that they can determine constraints on growth, leading to important insights into factors limiting productivity. Such information is key to forest planning in that it enables the identification of areas where effort should be expended to maximise growth.

The usefulness of 3-PG to predict measures of site productivity and the effects of possible scenarios on growth was explored in Section 7.2. Results from this study are intuitive to a certain extent, but to fully understand the growth dynamics it is necessary to consider constraints on growth. Constraints on growth in 3-PG are calculated using environmental modifiers, which describe how environmental stress limits production. These modifiers describe how θ_s and VPD affect g_C (and therefore ET), below ground allocation to roots, and α_C ; how T_{AV} affects photosynthesis through modification of α_C ; and how FR affects α_{Cx} and below ground allocation. The physiological modifier (ϕ) is defined as the product between the age modifier (f_{age}) and the minimum of f_θ and f_D , and affects both canopy conductance and α_C .

The relative importance of these modifiers in limiting NPP was examined using 3-PG. Battaglia and Sands (1997) performed a similar study where they compared actual production against the theoretical maximum production (in terms of NPP) obtained assuming no factors were limiting growth. Those authors showed the relative importance of each potentially limiting factor (see Figure 9 in Battaglia and Sands, 1997).

Using the same five sites used in Section 7.2 (Table 7.2), a similar analysis to that of Battaglia and Sands (1997) was performed. By setting the FR = 1, $\phi = 1$ and $\alpha_C = \alpha_{Cx}$, the theoretical maximum NPP and volume growth were determined using the full climatic record across all sites. The average theoretical maximum NPP (on a per site basis) was calculated as the average of total NPP produced over all possible rotations over the full climatic record.

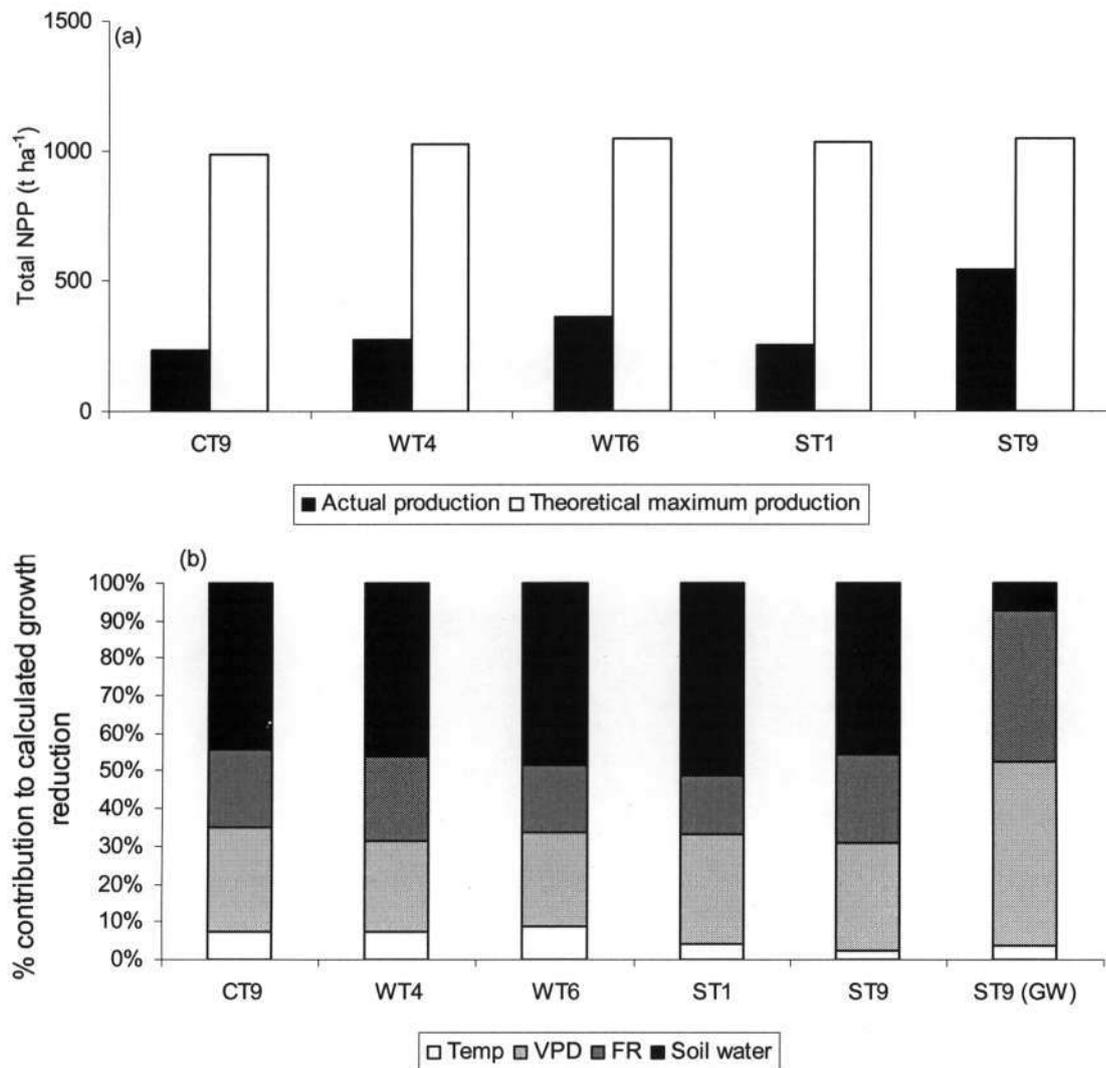


Figure 7.1 Effects of factors that potentially limit production across 5 site types. (a) Comparison of actual and theoretical maximum production at each site. (b) Relative importance of temperature, VPD, FR and soil water supply which potentially limit production. ST9 (GW) refers to a scenario where groundwater access is available.

Actual production determined as the growth in response to all environmental limitations inherent in the 49 yr climatic record was also determined at each site. Figure 7.1a compares actual production and theoretical maximum production, which is seen to be approximately a third of the maximum. This is a big difference, and is largely because under South African conditions several factors combine to limit growth, especially soil water availability (see below).

A more realistic and meaningful approach to illustrating growth constraints on production looked at the relative effect of each environmental factor on stand production. Due to the computational complexity of getting these results, results are given for only one eight-year rotation for each of the five sites. These results therefore are in response to the prevailing climatic conditions of this single rotation and by no means reflect all possible permutations. The affect of each constraint on production was determined by altering the 3-PG computer code as shown in Table 7.5.

Table 7.5. 3-PG coding changes made so that the relative contribution of each factor on total production could be calculated. Abbreviations are as follows: ϕ – physiological modifier; $f_D, f_\theta, f_{age}, f_T$ and f_N – modifiers expressing effects of vapour pressure deficit, soil water, stand age, temperature and site nutrition; FR – site fertility rating; a_{C_x} and a_C - theoretical maximum and modified canopy quantum efficiency.

Limitation	3-PG coding changes to emulate effect of site limitations
All limitations	FR = site fertility; $\phi = \min(f_D, f_\theta) f_{age}; a_C = a_{C_x} f_T f_N \phi$
Theoretical maximum	FR = 1; $\phi = 1; a_C = a_{C_x}$
Soil water	FR = 1; $\phi = f_\theta; a_C = a_{C_x} \phi$
VPD	FR = 1; $\phi = f_D; a_C = a_{C_x} \phi$
Temperature	FR = 1; $\phi = 1; a_C = a_{C_x} f_T$
Site fertility	FR = site fertility; $\phi = 1; a_C = a_{C_x} f_N$

The effects of θ_s , VPD, T_{AV} and FR on actual production are presented in Figure 7.1b; the area occupied by each factor illustrates the relative importance of that factor in limiting growth for a particular site (*i.e.* the larger the proportion of the shaded area the greater that particular constraint). For example: at CT9, of the reduction in growth below the theoretical maximum, 7, 44, 27 and 21% of the reduction is due to limitations imposed by temperature, water, VPD and FR respectively. Soil water and VPD are the factors that have the greatest effect on growth across all sites. However, if access to groundwater is permitted at the Zululand site (shown as ST9 (GW)) the limitation to growth imposed by temperature, water, VPD and FR change from 2, 45, 29 and 23% to 4, 7, 49 and 40% respectively, noting that the absolute reduction is different in both cases. This scenario demonstrates that in the presence of GW, soil water would not limit growth at this site. Temperature constraints on growth have the greatest effect on CT9 and WT6. The results shown here are limited as they present a summary of growth constraints over only a single rotation.

Constraints on growth and their effects are seasonal and therefore change throughout the year. For instance, factors limiting production will differ between summer and winter months. In a similar fashion to what has just been described, the relative importance of each factor on overall production is plotted in Figure 7.2 as a function of stand age 2 to 10 years for WT4, WT6, ST1 and ST9. These results show how each factor constrains growth and how these limitations are strongly seasonal. For example Figure 7.1 shows how θ_s at all the sites has a large effect on production. At ST9 θ_s deficits have a large impact on growth between month 58 and 94 (approximately 60% reduction in growth) and coincides with the drought during 1991/1992. It is important to understand that because $\phi = \min(f_D, f_\theta)$, at some times water is the limiting factor, and at others it is VPD. For the same site the effects of T_{AV} show a very slight limitation to overall production. These results are not expanded upon.

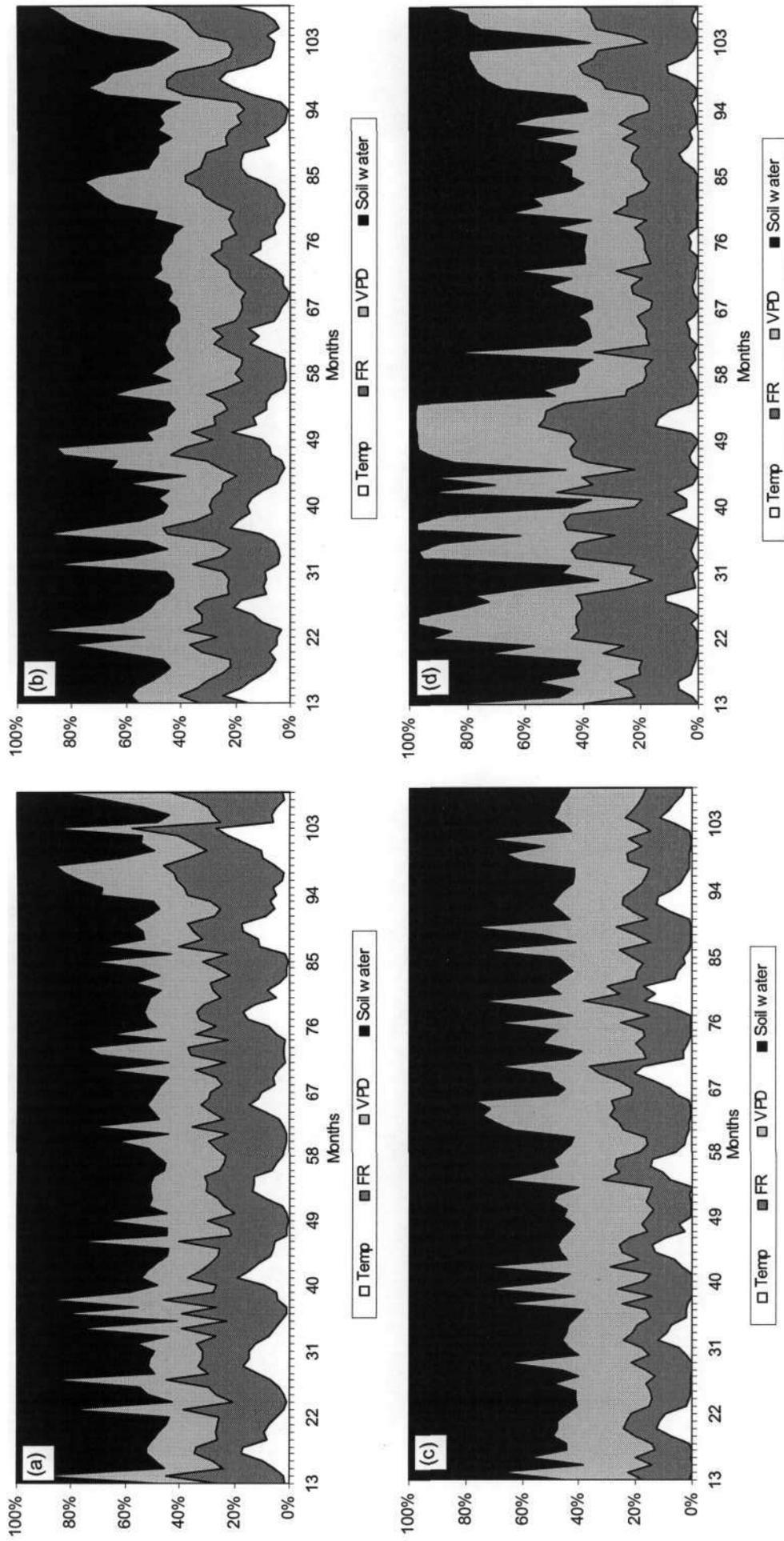


Figure 7.2. The relative importance of temperature, site fertility, VPD and soil water in limiting production (*i.e.* the percentage contribution to calculated growth reduction) over a single rotation at (a) WT4, (b) WT6, (c) ST1 and (d) ST9.

7.4 GROWTH PROJECTION

In South Africa stand-level EBMs are generally applied to make predictions required for management planning and harvest scheduling purposes. These models make use of stand attributes (*e.g.* age and SI_5) and comprise components to calculate dHT, BA and SPH. These components, linked together in a multi-component model framework, are implemented as G&Y simulators. Using inventory data, collected at ages between four and six years for *E. grandis* plantations, these models are initialised and used to predict final SV at stands earmarked for clear-felling. Such predictions can be fairly accurate and, provided they are applied on sites or under conditions similar to those used to develop the models, they provide more precise predictions of forest behaviour than do PBMs (Korzukhin *et al.*, 1996). However, since EBMs are purely statistical and therefore descriptive they cannot account for climatic fluctuations and changes in site and silviculture from rotation to rotation (Johnsen *et al.*, 2001; Korzukhin *et al.*, 1996; Battaglia and Sands, 1998a). Inherent in them is also a degree of circular logic: the productivity of the site cannot be quantified until trees have been grown and been measured, at which point it is known how well they have grown (Landsberg and Gower, 1997).

Used in isolation EBMs are of limited use and therefore require additional data to provide useful information. Such information can be compiled from three sources: area estimates of the plantation, stand level inventory of the plantation, and growth and harvesting models based on dynamic inventory data (Vanclay, 1994). It is worth mentioning that PBMs can complement EBMs within a hybridised framework. Hybrid modelling combines the strengths or “*best features*” of both PBMs and EBMs: the output from the PBM is used as an input into the empirical model. For instance, the power of a PBM is that it incorporates a mechanistic description of the stand interaction with the environment, while the power of EBMs is in using historical yield data to introduce site-specific determinants of yield that are difficult to interpret using PBMs (Battaglia and Sands, 1998a). Model hybridisation, which is still a relatively new concept, has yet to be accepted in South Africa, and as such it is not expanded upon here.

However, the first challenge is to demonstrate that PBMs are useful and can make better predictions (especially under a varying and fluctuating climate) than do EBMs. Accordingly, the hypothesis that 3-PG can make predictions that are comparable to, if not better than, traditional techniques was explored.

Data used in this study were selected from the *E. grandis* PSP database. A total of 52 representative sites from four physiographic regions (e.g. Lowveld, Zululand coastal and interior, and Natal midlands) and all zones covered by the FSC were chosen. These sites account for MAP (780-1400 mm) and MAT (15-22 °C) ranges that occur in South Africa and represent a range of site productivities (SI₅ between 11 and 30 m). Details of these sites are presented in Table 7.6.

Table 7.6. Information regarding the 52 PSP sites used for the comparison between empirical and 3-PG models. Shown are the physiographic region (1= Zululand coastal, 2= Zululand interior, 3= Midlands and 4= Lowveld), planting dates, measurement ages (first and final), mean annual precipitation (MAP), mean annual temperature (MAT) and forest site classification (FSC) zones (see Table 7.1).

Site	Region	Planting Date	First age (y)	Last age (y)	MAP (mm)	MAT (°C)	FSC Zone
1	1	Dec-93	1.63	4.56	1040	21.5	ST8
2	1	Feb-87	4.12	6.37	1040	21.5	ST8
3	1	Dec-93	2.82	4.56	1040	21.5	ST8
4	1	Oct-87	3.46	5.71	1061	21.5	ST8
5	1	Oct-87	3.46	5.71	1157	21.3	ST9
6	1	Sep-93	1.88	3.88	1157	21.3	ST9
7	1	Apr-89	3.21	8.03	963	21.8	ST2
8	1	Apr-89	3.21	8.14	1210	21.1	ST9
9	1	Jun-89	3.04	7.99	1195	21.0	ST9
10	1	May-89	3.13	7.31	1215	21.1	ST9
11	1	Apr-89	3.21	7.39	1248	21.2	ST9
12	1	Apr-89	3.21	7.39	1215	21.1	ST9
13	1	Jun-89	3.04	7.23	1215	21.1	ST9
14	1	Jun-89	3.04	7.74	1248	21.2	ST9
15	1	Jun-93	2.13	5.11	1198	21.5	ST9
16	1	Jul-93	2.05	4.98	1093	21.6	ST9
17	1	Jul-93	2.05	4.98	1122	21.7	ST9
18	1	May-93	2.21	5.19	1294	21.0	ST9
19	1	Jul-93	2.05	5.02	1052	19.4	ST3
20	1	Apr-93	2.29	5.23	1110	21.6	ST9
21	1	Nov-93	2.90	4.64	1163	21.6	ST9

Site	Region	Planting Date	First age (y)	Last age (y)	MAP (mm)	MAT ($^{\circ}$ C)	FSC Zone
22	2	Jun-88	5.38	8.13	1170	18.8	WT9
23	2	Jul-87	6.13	8.81	1024	17.7	WT6
24	2	Oct-87	5.22	7.63	1010	17.0	WT6
25	2	Sep-88	4.96	6.71	1036	16.6	WT3
26	2	Apr-93	3.61	5.33	876	18.2	WT7
27	2	Nov-93	3.02	4.72	810	17.7	WT4
28	2	Oct-93	3.11	4.79	791	18.3	WT7
29	2	Jan-91	4.71	7.56	787	14.9	CT4
30	2	Feb-89	7.74	9.47	786	15.4	CT7
31	2	Jan-89	7.83	9.56	784	15.1	CT7
32	3	Mar-89	5.55	9.45	1024	16.8	WT3
33	3	Sep-87	8.17	10.84	1285	17.0	WT6
34	3	Nov-93	2.00	6.70	842	17.6	WT4
35	3	Mar-91	4.67	9.38	921	18.0	WT5
36	3	Mar-91	4.67	9.38	902	17.8	WT5
37	3	Feb-93	2.50	7.40	919	17.1	WT5
38	3	Jan-90	5.58	10.52	919	17.1	WT5
39	3	Jan-90	5.58	10.48	814	17.9	WT4
40	3	Jan-90	5.58	10.48	915	17.5	WT5
41	3	Sep-89	5.92	10.81	840	17.9	WT4
42	4	Oct-95	1.83	4.81	1314	18.6	WT9
43	4	Jul-95	2.08	5.02	1280	18.8	WT9
44	4	Jan-80	5.67	12.34	1227	19.5	ST3
45	4	Jun-93	4.14	7.10	1357	18.5	WT9
46	1	May-93	1.67	6.97	832	21.7	ST7
47	1	May-91	5.04	8.99	1178	21.6	ST9
48	1	Feb-90	3.00	10.21	1084	21.8	ST9
49	1	Jan-91	4.09	9.29	1084	21.8	ST9
50	1	Aug-95	2.70	4.76	1084	21.8	ST9
51	1	Jan-96	2.29	4.34	962	21.9	ST7
52	1	Feb-91	5.27	9.21	865	21.8	ST7

Predictions of final SV using Emp_{SA} , a locally developed empirical model, were made for each site. As input, Emp_{SA} uses components which determine the dHT, survival and BA for a particular stand. Components for these quantities are based on the Chapman-Richards 3-parameter function (Brickell, 1969), Clutter and Jones difference form (Clutter and Jones, 1980), and a multiple regression model reported by Pienaar and Harrison (1989), respectively. Coefficients required for each of these functions are reported in Kotze (2000) and were developed using data sets from 335 PSPs over all physiographic regions. In order to make projections, these functional forms were converted to difference equations so that knowledge of tree height for a specific age can be used to project height to any given age. Final SV was calculated using predicted

dHT, survival and BA using a Max-Burkhardt segmented polynomial function (Max and Burkhardt, 1976).

Two sets of Emp_{SA} predictions are made, distinguished by the age of the observed data used to initialise the model: (1) using the first observed data (2-8 years), *i.e.* column 4 in Table 7.6 ($Emp_{SAfirst}$), and (2) initialised using enumeration data at an age of 5 years (Emp_{SAenum}). The reason for making this distinction is because empirical models are operationally initialised using enumeration data.

Predictions of final SV across all sites were also made using 3-PG. The required weather data and site factors were collected in a fashion similar to that described in Sections 5.2 and 5.3. Since detailed information regarding soils and fertiliser application was not available, the FR was set at a constant value of 0.4. The initial biomass pools were derived using first observed estimates of SV as described in Section 5.4. Model runs were made for all sites until the last observation, and prediction duration varied between just under 2 years to 7 years in duration.

3-PG accounted for 46% of the variation in observed SV across all 52 sites. Regression analysis across all these sites revealed two aberrant sites (Sites 44 and 46) where the predicted volume was double the corresponding observed data. These large SVs can be explained by the extraordinarily high observed mortality rates (50% of initial SPH). It is suspected that this low survival may be the result of drought. If these sites are omitted the agreement improves. Figure 7.3 shows predictions of SV for each site compared with corresponding observations. The agreement between 3-PG predictions and observed data (Figure 7.3a) is far better than predictions made with $Emp_{SAfirst}$ (Figure 7.3b) with the latter exhibiting consistent model under-predictions.

Wilmot (1982) suggests that the performance of models (and accuracy of predictions) can be evaluated and compared by calculating the root mean square error (RMSE). The RMSE can be statistically separated into the systematic ($RMSE_S$) and unsystematic ($RMSE_U$) components. The $RMSE_S$ quantifies the bias of the predicted volumes from the 1:1 relationship and the $RMSE_U$ describes the random variation of the observed data

from the predicted mean. A “good” model according to Wilmot (1982) will have a $RMSE_S$ that approaches zero and a $RMSE_U$ that should approximate the $RMSE$ which itself should be low.

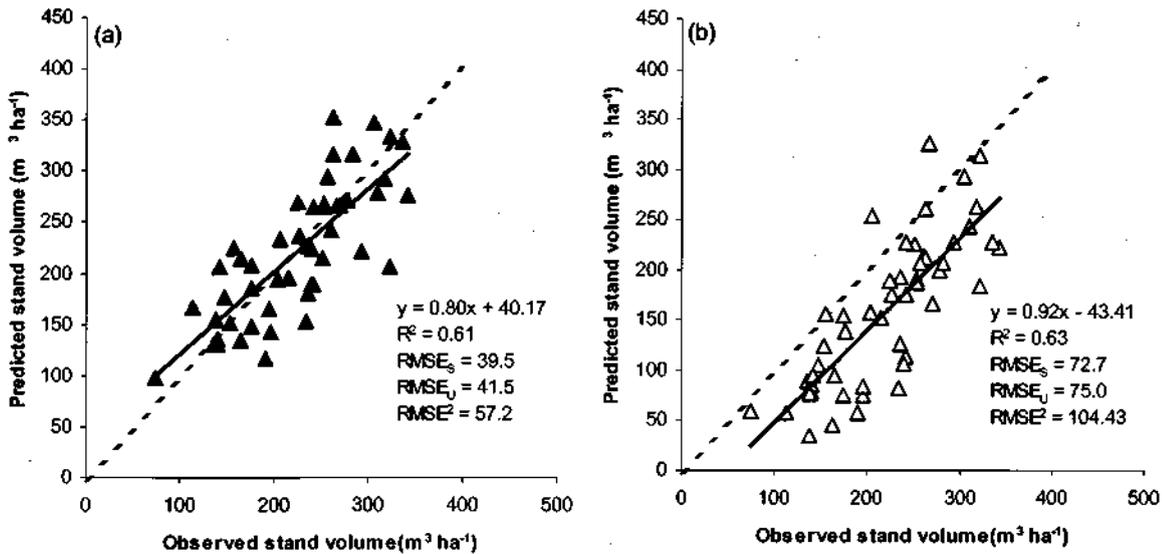


Figure 7.3. Comparison of predicted and observed final stand volume for predictions made using (a) 3-PG (▲) and (b) empirical methods (Δ) across 50 PSP sites. One-to-one lines are shown as (---) and (—) are regression lines. Corresponding regression equations and $RMSE_S$, $RMSE_U$ and $RMSE$ are also shown.

The $RMSE_S$ and $RMSE_U$ (Figure 7.3b) corresponding to the relationship between $Emp_{SAfirst}$ predictions and observed volume indicate a large degree of bias and error. Although a useful result (Figure 7.3b), the fashion in which Emp_{SA} was applied is not how empirically models are generally applied in practice. Operationally, enumeration data would have been used to initialise Emp_{SA} and predictions made over a shorter time period, which intuitively would be more accurate than predictions made, over an eight year period as done in the above example.

Emp_{SA} was initialised using enumeration data from 10 sites (Table 7.6, sites 7, 8, 9, 11, 34, 35, 36, 40, 41 and 48), and predictions of final SV made. Figure 7.4 shows (a) predictions made when using first observations ($Emp_{SAfirst}$ as shown in Figure 7.3b), and (b) predictions made when using enumeration observations (Emp_{SAenum}) for these 10 sites. Despite the relatively large $RMSE$ associated with both figures it is apparent that

the predictions made by $\text{Emp}_{\text{SAenum}}$ are more realistic and have less of an unsystematic error than does $\text{Emp}_{\text{SAfirst}}$. The relatively larger RMSE_S in Figure 7.4b can be explained by the climatic fluctuations experienced at several of the sites (see next) which $\text{Emp}_{\text{SAenum}}$ is unable to account for.

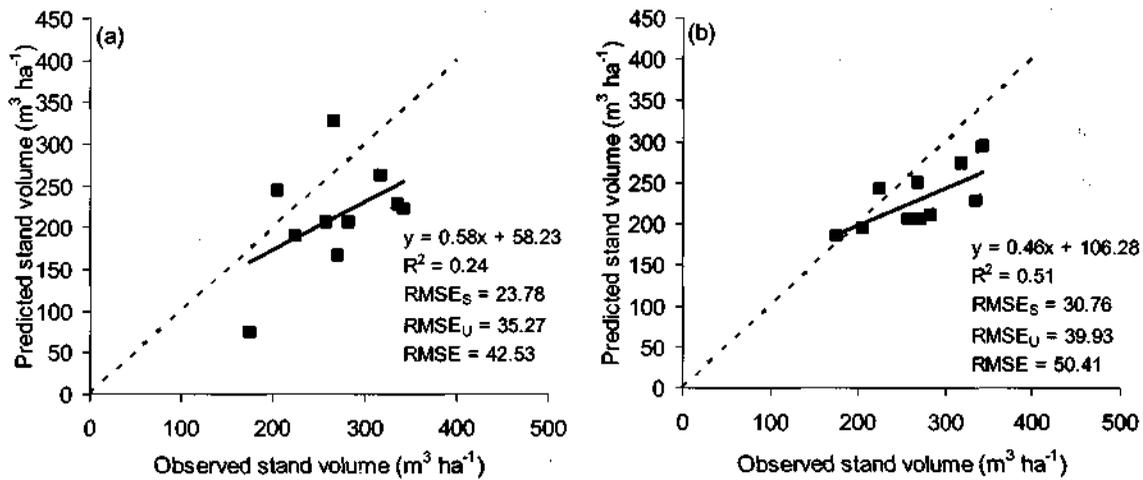


Figure 7.4. Predicted and observed stand volume for (a) predictions made when the empirical model ($\text{Emp}_{\text{SAfirst}}$) is initialised using first observations, and (b) initialised using observations between 4 and 6 years of age ($\text{Emp}_{\text{SAenum}}$). One-to-one lines are shown as (- -) and (—) are the regression lines. Corresponding regression equations and RMSE_S , RMSE_U and RMSE are also shown.

For six sites of the 10 sites (*i.e.* sites 7, 8, 9, 35, 36 and 4) these same results are presented in Figure 7.5 as time-series showing successive model predictions as a function of stand age. These show annual predictions of SV made with 3-PG, $\text{Emp}_{\text{SAfirst}}$ and $\text{Emp}_{\text{SAenum}}$, and observed SVs where available. Figures 7.5c-f shows that $\text{Emp}_{\text{SAfirst}}$ consistently under-predicts SV.

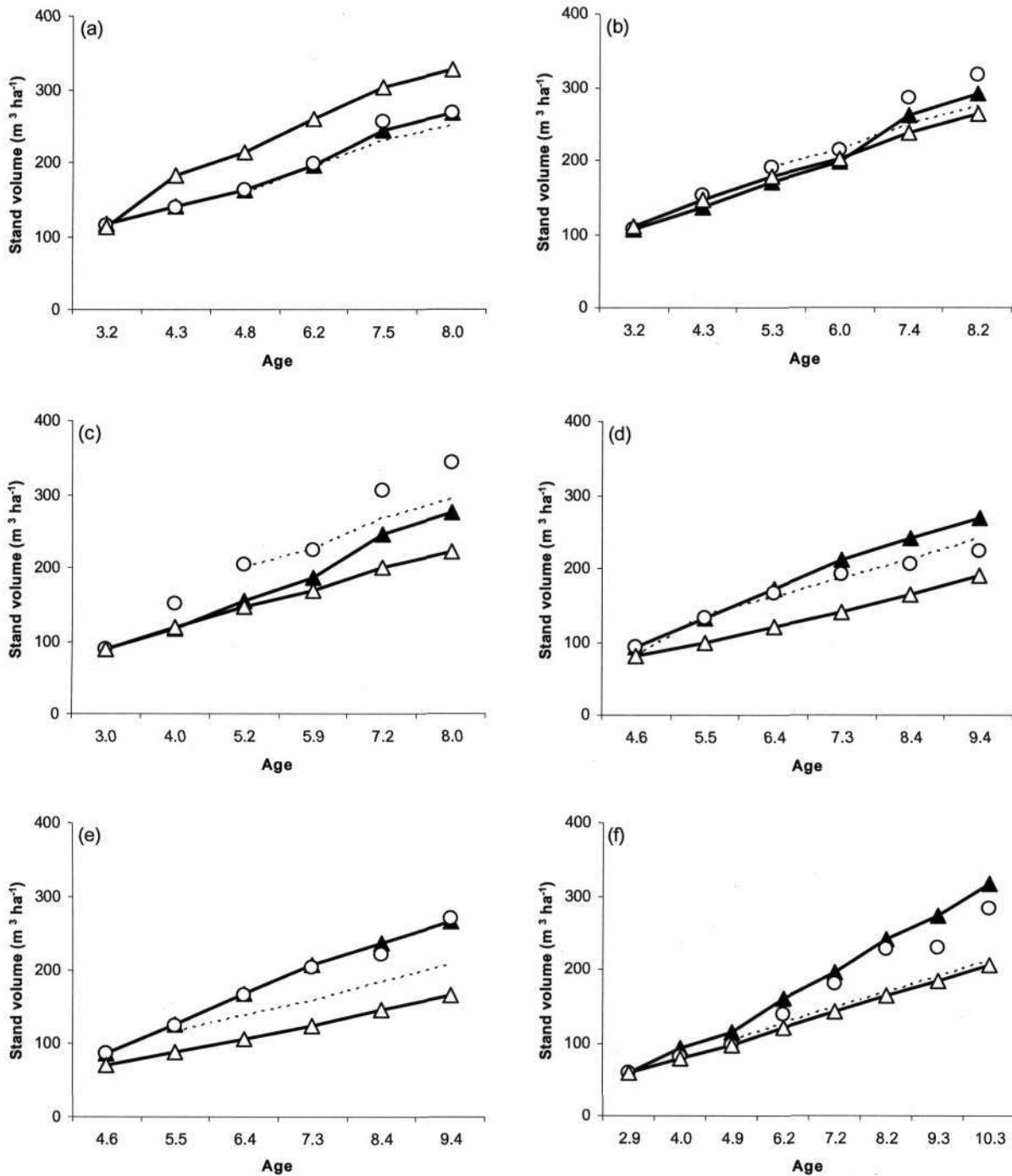


Figure 7.5. Time-series data showing observed volume data and predictions made using 3-PG and empirical models for six sites of differing ages. Results shown are denoted as follows: (o) – observed data; (-▲-) – 3-PG predictions; (-△-) - Emp_{SAfirst} predictions and (- - -) predictions made using Emp_{SAenum} when initialised using data of between 4 and 6 years of age.

In the examples shown, predictions by 3-PG are generally very similar to the observed data except for the site shown in Figure 7.5c. At this site the weather input data may not have been representative of the site conditions. The broken lines within each figure are those predictions made using Emp_{SAenum} , and in certain cases (e.g. Figure 7.5a and d), these predictions track observed data in a far more realistic fashion than do those made with $Emp_{SAfirst}$. The observed growth rate shown in Figure 7.5d is relatively constant. This indicates growing conditions were non-stressful, and explains the accurate empirical predictions.

It is important to note that even though 3-PG is initialised at the date of the first observations, its predictions are closer to the observed volumes than are volumes predicted using the empirical model initialised using enumeration data. Where drought conditions are prevalent (e.g. Figure 7.5e and f) or wetter than normal periods occur (e.g. Figures 7.5b and c) empirical predictions are not accurate as they cannot account for fluctuating weather patterns and hence the variability of on site resources.

7.5 CONCLUSIONS

The objective of this chapter was to explore the practicality of using 3-PG as a strategic and operational tool. Results have shown that:

- Estimates of potential site productivity are consistent with empirically based estimates. Furthermore, 3-PG was able to make additional estimates of productivity (*i.e.* net primary production (NPP) and radiation use efficiency (GE)) that empirical models cannot make.
- 3-PG can simulate growth responses to different scenarios (or “*what if*” questions), such as access to groundwater (GW) or conditions for nutrients are non-limiting.
- 3-PG is able to explore site constraints which limit growth, and how these limitations change on a seasonal basis.

- 3-PG makes more realistic predictions of tree growth than empirical models do, especially under fluctuating weather conditions (see Sections 7.3 and 6.4.2).
- These outcomes demonstrate that 3-PG could be a useful tool for operational and strategic applications. It is suspected that this model will be used for research purposes (*i.e.* in understanding the growth dynamics of plantations) and as a complement to existing empirical techniques (see Section 8.4).

CHAPTER 8

FINAL DISCUSSION AND CONCLUSIONS

The 3-PG model has been widely tested and validated, and used for numerous applications involving several tree species, within a range of countries and locations. Validation studies have demonstrated that 3-PG is both robust and reliable, performing within an acceptable degree of confidence to predict growth in areas where trees have been grown (e.g. Sands and Landsberg, 2002; Landsberg *et al.*, 2003; Almeida *et al.*, 2004b; Dye *et al.*, 2004). The potential usefulness of 3-PG has been shown at Aracruz Celulose, Brazil where it is currently being implemented as the central component of a new GIS-based management system (Almeida *et al.*, 2003; Almeida *et al.*, 2004a; Almeida *et al.*, 2004b). Locally, the model has also been used to predict growth and water use of *Pinus Patula* (Dye, 2001) and *Eucalyptus* plantations (Dye *et al.*, 2004). Other applications include spatial applications of 3-PG using remotely sensed inputs and GIS (Coops *et al.*, 1998, Coops *et al.*, 2001; Coops and Waring, 2001a, Coops and Waring, 2001b; Tickle *et al.*, 2001 and White *et al.*, 2000).

Using these applications as a reference, the use of 3-PG in South Africa was proposed. The primary aims of this project were to see whether it is possible to adapt 3-PG to predict growth and yield (G&Y) for *E. grandis* under South African conditions, and to test whether model predictions are biologically reasonable and accurate in relation to observed data. Using a previously developed parameter set for *E. grandis* the performance of the model was examined using data from 31 ICFR *E. grandis* research trials within Southern Africa (see Section 2.3.4). Main findings showed that stand volume (SV) is under-predicted on medium (25 to 45 m³ ha⁻¹ yr⁻¹) and high (>45 m³ ha⁻¹ yr⁻¹) productivity sites, and over-predicted on the lower (<25 m³ ha⁻¹ yr⁻¹) productivity sites. Although predicted and observed volumes are highly correlated, leaf area index (LAI) greatly exceeded values normally observed over the rotation, thus suggesting the model gave the “right result but for the wrong reasons”.

These findings led to the formulation of a set of objectives to help develop the 3-PG model for use in South Africa (see Section 1.2). This thesis addressed these objectives

and answered various questions concerning the practical application of 3-PG in South Africa. Only the major conclusions are discussed below; more specific discussions are found in the relevant sections of each of the earlier Chapters.

8.1 IDENTIFYING KEY MODEL PARAMETERS (OBJECTIVE 1)

The sensitivity of predicted SV and LAI to the values of the species-specific parameters in 3-PG was examined in Chapter 3. These parameters tested characterise allometric relationships and biomass partitioning, canopy structure, branch and bark fractions, litterfall, canopy conductance and the effects of temperature, soil water and site nutrition on canopy quantum efficiency. The sensitivity of SV and LAI to variations in site and climatic inputs required by 3-PG was also examined (see Section 3.2.4). These analyses enabled the development of three distinct parameter sensitivity classes (see Sections 3.3.2 and 3.4.1): insensitive parameters (*i.e.* those that can be varied widely without affecting the outputs studied), sensitive parameters (*i.e.* those whose value strongly affects the outputs, and non-linear parameters (*i.e.* those for which the outputs depend in a non-linear manner on the parameter value). Because this study considered the variation of sensitivity of each parameter across a wide range of sites, it also identified potential site-dependence of parameter sensitivity (see Sections 3.3.2 and 3.4.4).

Results indicated that values currently assigned to insensitive parameters, with the possible exception of T_{max} , can be used in any subsequent re-parameterisation of 3-PG for *E. grandis*. However, closer attention needs to be paid to those parameters with moderate sensitivity and especially to those with the highest ranking. In addition, attention needs to be paid to non-linear parameters with low to moderate sensitivity, as a change in their value could make an insensitive parameter sensitive, and conversely. Parameters of moderate sensitivity, but with strong site-dependence also need close attention if the parameter set is to be applied across a wide range of site conditions. In summary, the following parameters require accurate determination because they have a moderate or high sensitivity ranking for SV or LAI: f_{N0} , a_S , n_S , η_{Rn} , η_{Rx} , α_{Cx} , ρ^* , Y , g_{Cx} , γ_{Fx} , σ_1 and p_{20} (see Section 3.3.2). In addition T_{max} and T_{opt} require close attention because they are highly non-linear and have a moderate sensitivity ranking.

8.2 PARAMETERISATION AND INITIALISATION OF 3-PG (OBJECTIVE 2)

Minimum data requirements for the parameterisation and initialisation of 3-PG are covered in Chapters 4 and 5. Conventional methods used for the parameterisation of models (see Section 4.1), specifically 3-PG, are reflected upon. An automated parameter estimation technique was examined and used for the estimation of selected parameters.

Species-specific parameters were categorised according to data source estimation and sensitivity classes (see Section 4.2). Data source class is based on the source of data used to estimate the parameters, namely: biomass harvested data, field data, mensuration data, physiological data, and data from the literature. Estimation class provides an indication of how parameters can be assigned values, and comprise default, observed and estimated classes. Sensitivity class indicates the broad sensitivity of model outputs to parameters, *i.e.* low, medium and high sensitivity. Guidelines for the parameterisation of 3-PG were developed on the basis of results from this parameter sensitivity analysis and published work for *E. globulus* (Sands and Landsberg, 2002).

Within Chapter 4 a distinction is made between parameter assignment and parameter estimation. Parameters describing allometric and age-dependent relationships were assigned values using observed data from biomass harvests. Critical parameters that could not be directly assigned using observed data were the ratio of foliage to stem allocation (*i.e.* p_2 and p_{20}), allocation of net primary production (NPP) to roots (η_{Rx} and η_{Rn}), optimum temperature for growth (T_{opt}) and maximum canopy quantum efficiency (α_{Cx}). These were estimated using parameter ESTimation (PEST, see Sections 4.2.2 and 4.3.2), by fitting model output to corresponding observed growth data. However, since no root data were available, default values were used for η_{Rx} and η_{Rn} . A default value for T_{opt} was also used because of its high correlation with α_{Cx} . Where parameter values could not be assigned directly from observed data, either because suitable data were unavailable, or unnecessary due to low sensitivity ratings, default values were taken from Landsberg and Waring (1997), Sands and Landsberg (2002) and Gush (1999).

As well as species-specific parameter values, mandatory inputs required by 3-PG include weather data, site-specific factors such as site fertility (FR) and physical properties of the soils, and stand initialisation data (see Section 5.1). Objective techniques to determine these site-specific factors and the initial values for the biomass pools were proposed in Chapter 5. Most of these data are readily available for sites where experimental trials exist, or where monitoring networks are in place. However, this is the exception rather than the rule, so alternative data and information sources are required.

Ideally, initial values for the biomass pools should be assigned using observed data. In the absence thereof other methods were developed (see Sections 5.4 and 5.4.1), based on a series of questions and actions dependent on what observed data are available. These include assigning values for stem mass using the allometric relationship with observed quadratic mean diameter (qDBH), or as given by an empirical function of basic stand variables or site index. Initial foliage biomass is inferred using an age-dependent relationship for specific leaf area (SLA) to convert typical values for LAI into foliage mass (see Section 5.4.2). Initial root biomass is determined as a fraction of the aboveground biomass (see Section 5.4.2). Techniques developed to empirically determine qDBH were tested using observed time-series for SV, stems per hectare (SPH), dominant height (dHT), qDBH and site index at five years of age (SI_5) over 48 sites planted to *E. grandis*. Results showed no significant differences between the three methods of prediction (see Section 5.4.1). This result is very promising because it suggests that any one of the methods can be used to predict qDBH adequately.

The need for accurate weather inputs (especially monthly rainfall (R)) and physical properties (especially soil texture, maximum available soil water (θ_{sv}) and FR) of the sites being modelled is emphasised. This is especially true if 3-PG is to be used to make predictions in response to climatic fluctuations. Actual observed data are therefore used where possible. Where such data are not available alternate data or surrogates are suggested (see Sections 5.1, 5.2 and 5.3).

8.3 VALIDATION OF 3-PG IN SOUTH AFRICA (OBJECTIVE 3)

Using the new 3-PG parameter set developed for *E. grandis* (Chapter 4) and methods to assign values to the mandatory input data (Chapter 5), the performance of 3-PG over a range of sites in South Africa was tested (Chapter 6). The importance of good quality observed data for model testing is emphasised. Despite a general shortage of quality data, the best use of existing ICFR data was made for four simple tests of the performance of 3-PG by comparing predicted *versus* observed SV using: (1) the parameter set developed by Gush (1999), compared with the newer *E. grandis* parameter set (see Sections 2.3.4 and 6.2); (2) the new parameter set and data sets independent of those used in the model parameterisation (see Section 6.3); (3) observed time-series data (see Section 6.4); and (4) data from a fertilised and irrigated experiment (see Section 6.5).

These tests showed that 3-PG predictions are relatively consistent with observed stand data. Analyses performed using time-series data showed model predictions accurately tracked observed growth in response to erratic and fluctuating weather conditions. Results from the initial model validation (see Section 2.3.4) showed production on high and low productivity sites was under- and over-predicted, respectively. Further results presented here (see Sections 6.3 and 6.4) show a similar, but less marked trend (*i.e.* over- and under-predictions are not as extreme), and individual biases are less than those from predictions made using the parameter set of Gush (1999).

Detailed observed time-series data from several sites enabled the biological realism of 3-PG to be examined. Results from this test generally showed that 3-PG can reflect reality reasonably accurately (see Sections 6.4.2 and 6.4.3). However, it is noted that some weather input data have a degree of error attached (see Sections 5.2 and 5.4). For instance, solar radiation (SR) data are long-term means and they would not reflect real conditions that exist during wet periods and dry periods. Similarly, there is no term in 3-PG that accounts for reflection within the canopy. Furthermore, the timing of rainfall events during a month is not accounted for by the actual R data. If long-term mean data are used as a surrogate for actual data then specific rainfall events will not be taken into account.

8.4 SOME APPLICATIONS OF 3-PG IN SOUTH AFRICA (OBJECTIVE 4)

It is believed that 3-PG can potentially play a useful role within the South African forestry industry, both as an operational and a strategic tool. Strategic applications may include the: (1) prediction of potential productivity on a site-by-site basis; (2) broad-scale productivity estimates of existing stands based on remote sensing and the spatial application of 3-PG; (3) identification of production constraints; and (4) estimation of C fluxes to help address sustainability issues. Operationally, 3-PG could complement empirically-based models (EBMs) or be used in conjunction with them as a hybridised product. EBMs are currently used to predict final standing volume for scheduling harvest operations.

Three of these potential applications of 3-PG were tested in this thesis. These are the determination of potential site productivity (see Section 7.2); the identification of factors constraining growth (see Section 7.3), and the use of 3-PG to predict stand volume at the end of the rotation (see Section 7.4). The results of using 3-PG for growth projection were compared with corresponding predictions made with locally developed, empirical models routinely used for growth projection. These applications were presented within the framework of the forestry site classification (FSC). Results showed that:

- 3-PG is able to make estimates of growth trends that are consistent with those used within the FSC. Furthermore, estimates other than potential mean annual increment (MAI) or SV were made (*i.e.* net primary production (NPP) and radiation use efficiency (GE)). This shows the considerable potential 3-PG has for strategic planning by the forest industry (*i.e.* projected wood supplies *etc*) and in research planning (refining existing site classifications). The model could be useful to predict growth in various areas where *E. grandis* is not grown, to assist in future decision making. Once 3-PG is parameterised for a range of species it may be useful for site-species matching.
- 3-PG can identify growth constraints on a site-by-site basis and distinguish between them. 3-PG was able to identify environmental and site limitations to

plantation growth, and how they vary in space and time. These results together with predictions of site productivity demonstrate the potential for 3-PG to be used to improve existing forest site classifications.

- The usefulness of 3-PG to predict volume at the end of the rotation (*i.e.* growth projection) was also tested. This exercise was in the form of a study where output from an empirical model were compared with predictions by 3-PG. Results showed that although the empirical models made accurate predictions of volume under static climatic conditions, under fluctuating weather conditions empirical estimates of volume were less accurate than those made with 3-PG. 3-PG can therefore be used operationally with minimum input data to predict growth using enumeration data. This is useful in saving time and cutting costs.

8.5 RECOMMENDATIONS FOR FUTURE RESEARCH

During this project many ideas came to mind regarding the manner in which 3-PG simulates processes and how these could be altered, along with modifications that could be made to improve predictions or provide additional outputs. 3-PG greatly simplifies complex processes and focuses on tree and stand growth development. For these reasons 3-PG is well suited for strategic and operational applications. Too many modifications would add more parameters making the model more complex and less desirable for use. The interested reader is referred to Almeida (2003) who outlines some modifications to 3-PG and recommendations for future research. Additional recommendations are presented as follows:

- It would be useful to consider how the ratio of net primary production and gross primary production (NPP/GPP) declines with age. This is not unreasonable as bigger trees have a higher proportion of respiring, non-photosynthetic tissue, than small trees. Allowing NPP/GPP to decline with age (rather than a fixed ratio used in 3-PG) may allow for the decline in production shown in observed data that is not predicted by 3-PG.
- A measurement protocol should be developed consistent with the guidelines pertaining to minimum data requirements for parameterising and testing the

model. Such a protocol will identify those field, physiological, *etc.*, data that should be collected, what variables should be measured (*e.g.* LAI, DBH, HT), and the frequency with which this should be done. This is especially important if 3-PG is to be parameterised for other commercial species.

- Through the application of techniques used to assign and estimate model parameters, together with experience gained from the parameterisation of 3-PG, a universal “*shortcut*” method to parameterise 3-PG for novel species needs to be developed. Such a method will allow any user of the model to develop a set of parameters for any new species.
- It would be useful to compare predictions of stand production using the parameter set developed here and those developed for *E. globulus* (Sands and Landsberg, 2002), *E. grandis* hybrids (Almeida *et al.*, 2004b) and *E. grandis x urophylla* (Stape *et al.*, 2004). Such a study would test whether 3-PG is able to distinguish between species and whether the differences are biologically reasonable. Furthermore, results would give an appreciation of why species perform they way they do.
- An objective, quantitative method to assign values to the site fertility rating (FR) is extremely important. Such a method would require a comprehensive review of existing nutritional trials in South Africa, in particular the relationship between nutritional response and physiological variables. Using ideas presented in see Section 5.3.2, and given observed data over a range of sites, it should be possible to develop an objective method to determine FR for South African conditions.
- It would also be instructive to test the possibility of linking a nutritional model such as SNAP (Paul *et al.*, 2002) to 3-PG.
- Additional tests of the use of 3-PG to predict potential site productivity and growth constraints are recommended for all site types included in the forest site classification. This would allow for the modification of site classes or the development of a more rational approach than is currently used. Such a study will identify the true potential and usefulness of the 3-PG model.
- Use 3-PGpjs (and the parameter set developed here) to verify (or ground truth) predictions made using the spatial version of 3-PG (3-PGS – not

covered in this thesis). This would be useful to test the accuracy of 3-PGS and identify gaps in our knowledge.

- Evaluate the extent to which 3-PG can account for climate change and use this adaptation to predict how species spatial range and productivity may change in response to global warming.
- Consider hybridising 3-PG with existing empirical models.

8.6 CONCLUSIONS

The challenges for this thesis were to see whether it was possible to adapt 3-PG to predict growth and yield of *E. grandis* under South African conditions, test that model predictions were consistent with observed growth data and were biologically reasonable, and to assess the practicality of using 3-PG as either a strategic or operational tool. These challenges were met by realising all the objectives (see Section 1.2). Results demonstrated that 3-PG is a useful tool to understand tree growth dynamics, to interpret between-site productivity differences, and to identify constraints which limit growth and how these change seasonally. It was also shown that 3-PG can be used to complement empirical models as an aid to forest planning and scheduling of harvest operations. Practically, 3-PG was also shown to be a useful strategic and operational tool.

An appreciation of the limitations of 3-PG, and of the minimum input data requirements for its use, was achieved. These led to the development of a prescription for the use of 3-PG in South African conditions. If it is accepted that 3-PG and the current *E. grandis* parameter set are to be used only in areas for which the model has been tested then it can be said that the model is working reasonably well, and within acceptable ranges. However, and despite the fact that the model is generic, if 3-PG is to be used in other countries within Africa then it will need to undergo additional, *i.e.* local, validation tests.

The use of process-based models (PBMs) in general, and 3-PG in particular, needs to be “*championed*” to the South African forest industry (see Esprey and Smith, 2005). This is necessary for two reasons. Firstly, the model and the manner with which it describes

physiological processes of growth need to be explained in layman's terms. This will demonstrate how and why a PBM can work better in a fluctuating environment than do empirically based models. Secondly the comparison between 3-PG and the local empirical models needs to be presented as an example of how 3-PG can be applied on an operational basis. It is accepted that much convincing is still required.

Several spin-offs from this study were also achieved. These are the development of a set of guidelines useful for the parameterisation of 3-PG, the appraisal and use of automated parameter estimation techniques, and objective methods to initialise the 3-PG model.

The primary aim of this project was to become fully acquainted with 3-PG. This conscious effort to understand the model and the physiological processes represented, resulted in a greater appreciation of 3-PG. Finally, this project has also been hugely beneficial in that it has led to a greater understanding and appreciation of the role physiological processes play in determining growth. This would not have been possible without the use of a 3-PG.

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APPENDICES 1-5

APPENDIX 1

**Description of 3-PG parameters, their symbols
and 3PGpjs names**

Description of parameter	Symbol	3PGPJS name	Units
Biomass partitioning and turnover			
<i>Allometric relationships & partitioning</i>			
Ratio of foliage:stem partitioning at $B = 2$ cm	p_2	<i>pFS2</i>	-
Ratio of foliage:stem partitioning at $B = 20$ cm	p_{20}	<i>pFS20</i>	-
Constant in stem mass ν diam. relationship	a_S	<i>stemConst</i>	-
Power in stem mass ν diam. relationship	n_S	<i>stemPower</i>	-
Maximum fraction of NPP to roots	η_{Rx}	<i>pRx</i>	-
Minimum fraction of NPP to roots	η_{Rn}	<i>pRn</i>	-
<i>Litterfall & root turnover</i>			
Litterfall rate at $t = 0$	γ_{F0}	<i>gammaF0</i>	month ⁻¹
Litterfall rate for mature stands	γ_{Fx}	<i>gammaF1</i>	month ⁻¹
Age at which litterfall rate has median value	$t_{\gamma F}$	<i>tgammaF</i>	month
Average monthly root turnover rate	γ_R	<i>Rttover</i>	month ⁻¹
Growth modifiers			
<i>Temperature modifier</i>			
Minimum temperature for growth	T_{min}	<i>Tmin</i>	°C
Optimum temperature for growth	T_{opt}	<i>Topt</i>	°C
Maximum temperature for growth	T_{max}	<i>Tmax</i>	°C
<i>Frost modifier</i>			
Number of days production lost for each frost day	k_F	<i>kF</i>	days
Fertility modifiers			
Value of m when $FR = 0$	m_0	<i>m0</i>	-
Value of f_N when $FR = 0$	f_{N0}	<i>fN0</i>	-
Power of $(1-FR)$ in f_N	n_{fN}	<i>fNn</i>	-
<i>VPD modifier</i>			
Defines stomatal response to VPD	k_D	<i>CoeffCond</i>	mbar
<i>Soil water modifier</i>			
Moisture ratio deficit which gives $f_0 = 0.5$	c_0	<i>SWconst</i>	-
Power of moisture ratio deficit in f_0	n_0	<i>SWpower</i>	-
<i>Age modifier</i>			
Maximum stand age used to computer relative age	t_x	<i>MaxAge</i>	yr
Power of relative age in f_{age}	n_{age}	<i>nAge</i>	-
Relative age to give $f_{age} = 0.5$	r_{age}	<i>rAge</i>	-
Conductance			
Maximum canopy conductance	g_{cx}	<i>MaxCond</i>	$m\ s^{-1}$
Canopy LAI for maximum canopy conductance	L_{cx}	<i>LAIgcx</i>	$m^2\ m^{-2}$
Canopy boundary layer conductance	g_b	<i>BLcond</i>	$m\ s^{-1}$
Stem mortality and self-thinning			
Seedling mortality rate ($t = 0$)	γ_{N0}	<i>gammaN0</i>	yr ⁻¹
Mortality rate for older stands (large t)	γ_{N1}	<i>gammaNx</i>	yr ⁻¹
Age at which $\gamma_N = \frac{1}{2}(\gamma_{N0} + \gamma_{N1})$	$t_{\gamma N}$	<i>tgammaN</i>	yr
Shape of mortality response	$n_{\gamma N}$	<i>ngammaN</i>	-
Maximum stem mass per tree at 1000 trees/ha	w_{Sx1000}	<i>wSx1000</i>	kg/tree
Power in self thinning law	n_N	<i>thinPower</i>	-
Fractions of foliage, root and stem biomass pools per tree on each dying tree	m_F	<i>mF</i>	-
	m_R	<i>mR</i>	-
	m_S	<i>mS</i>	-

Description of parameter	Symbol	3PGrJS name	Units
Canopy structure and processes			
<i>Specific leaf area</i>			
Specific leaf area at stand age 0	σ_0	SLA0	$\text{m}^2 \text{kg}^{-1}$
Specific leaf area for mature aged stands	σ_1	SLA1	$\text{m}^2 \text{kg}^{-1}$
Age at which specific leaf area = $\frac{1}{2}(\sigma_0 + \sigma_1)$	t_σ	tSLA	yr
<i>Rainfall interception</i>			
Maximum fraction of rainfall intercepted by canopy	i_{Rx}	MaxIntcptn	-
LAI for maximum rainfall interception	L_{ix}	LAI _{max-Intcptn}	$\text{m}^2 \text{m}^{-2}$
<i>Light interception, production and respiration</i>			
Extinction coefficient for PAR absorption by canopy	k	k	-
Age at full canopy cover	t_c	fullCanAge	yr
Maximum canopy quantum efficiency	α_{Cr}	alpha	-
Ratio NPP/GPP	Y	Y	-
Wood and stand properties			
<i>Branch & bark fraction</i>			
Branch and bark fraction at stand age 0	p_{BB0}	fracBB0	-
Branch and bark fraction for mature aged stands	p_{BB1}	fracBB1	-
Age at which $p_{BB} = \frac{1}{2}(p_{BB0} + p_{BB1})$	t_{BB}	tBB	yr
<i>Basic density</i>			
Minimum basic density – for young trees	ρ_0		t m^{-3}
Maximum basic density – for older trees	ρ_1	rhoMax	t m^{-3}
Age at which $\rho = \frac{1}{2}$ density of old and young trees	t_ρ	tRho	yr
<i>Stem height allometric relationship</i>			
Constant in stem height relationship	a_H	aH	-
Power of DBH in stem height relationship	n_{HB}	nHB	-
Power of stocking in stem height relationship	n_{HN}	nHN	-
<i>Stem volume allometric relationship</i>			
Constant in stem volume relationship	a_V	aV	-
Power of DBH in stem volume relationship	n_{VB}	nVB	-
Power of stocking in stem volume relationship	n_{VN}	nVN	-
Conversion factors			
Intercept of net radiation v solar radiation relationship	Q_a	Qa	W m^{-2}
Slope of net radiation v solar radiation relationship	Q_b	Qb	-
Molecular weight of dry matter		gDM_mol	g mol^{-1}
Conversion of solar radiation to PAR		molPAR_MJ	mol MJ^{-1}

APPENDIX 2

Names and description of 3PGpjs output variables

Description of output variables	Symbol	3PGJS name	Units
Site and management attributes			
Soil class		SoilClass	-
Fertility rating	FR	FR	-
Maximum available soil water	θ_{sr}	maxASW	mm
Minimum available soil water	θ_{sn}	minASW	mm
Climatic factors			
Day length (sunrise to sunset)	h	DayLength	s d ⁻¹
Mean number of frost days per month	d_F	FrostDays	d month ⁻¹
Mean daily incident solar radiation	Q	SolarRad	MJ m ⁻² d ⁻¹
Mean daily temperature	T_a	Tav	°C
Mean day-time VPD	D	VPD	mbar
Mean monthly precipitation	R_P	Rain	mm month ⁻¹
Applied irrigation	R_I	Irrig	mm month ⁻¹
Stand attributes			
Stand age	t	StandAge	yr
Stand stocking	N	StemNo	trees ha ⁻¹
Stand basal area	A	BasArea	m ² ha ⁻¹
Stand volume excluding branch & bark	V	StandVol	m ³ ha ⁻¹
Stand-based mean DBH	B	avDBH	cm
Mean annual volume increment		MAI	m ³ ha ⁻¹ yr ⁻¹
Peak MAI of stand to the current stand age		MAIx	m ³ ha ⁻¹ yr ⁻¹
Stand age at which MAI peaked		ageMAIx	yr
Long-term average stem biomass growth rate		ltStemGR	kg ha ⁻¹ yr ⁻¹
Canopy attributes			
Specific leaf area	σ	SLA	m ² kg ⁻¹
Fraction of ground area covered by canopy	ζ	CanCover	-
Canopy LAI	L	LAI	m ² m ⁻²
Peak canopy LAI up to the current stand age		LAIx	m ² m ⁻²
Stand age at which LAI peaked		ageLAIx	yr
Biomass pools			
Foliage biomass	W_F	WF	t _{DM} ha ⁻¹
Root biomass	W_R	WR	t _{DM} ha ⁻¹
Stem biomass, including branches and bark	W_S	WS	t _{DM} ha ⁻¹
Total biomass		TotalW	t _{DM} ha ⁻¹
Mean stem biomass per tree	w_S	AvStemMass	kg _{DM} /tree
Basic density	ρ	Density	t _{DM} m ⁻³
Fraction of stem biomass as branch and bark	P_{BB}	fracBB	-
Accumulated litter fall		TotalLitter	t _{DM} ha ⁻¹
Growth modifiers			
Age-dependent modifier	f_{age}	fAge	-
VPD-dependent modifier	f_D	fVPD	-
Temperature-dependent modifier	f_T	fTemp	-
Frost-dependent modifier	f_F	fFrost	-
Soil water-dependent modifier	f_θ	fSW	-
Nutrition-dependent modifier	f_N	fNutr	-

Description of output variables	Symbol	3PGPJS name	Units
Physiological modifier of canopy conductance	ϕ	<i>PhysMod</i>	-
Biomass production and allocation			
Gross primary production in current period	P_g	<i>GPP</i>	$t_{DM} \text{ ha}^{-1}$
Net primary production in current period	P_n	<i>NPP</i>	$t_{DM} \text{ ha}^{-1}$
Total solar radiation intercepted by canopy		<i>RadInt</i>	$\text{MJ m}^{-2} \text{ month}^{-1}$
Canopy quantum efficiency after modifiers	α_C	<i>alphaC</i>	mol mol^{-1}
Light utilisation efficiency based on total biomass	ε	<i>Epsilon</i>	$\text{g}_{DM} \text{ MJ}^{-1}$
Light utilisation efficiency based on stem biomass	ε_S	<i>StemEpsilon</i>	$\text{g}_{DM} \text{ MJ}^{-1}$
Stem volume increment in current period		<i>CVI</i>	$\text{m}^3 \text{ ha}^{-1}$
FR modifier of root biomass allocation	m	<i>m</i>	-
Fraction of NPP allocated to roots	η_R	<i>pR</i>	-
Fraction of NPP allocated to stems	η_S	<i>pS</i>	-
Fraction of NPP allocated to foliage	η_F	<i>pF</i>	-
Ratio of foliage to stem biomass allocation	p_{FS}	<i>pFS</i>	-
Current leaf litterfall rate	γ_F	<i>gammaF</i>	month^{-1}
Litter fall in current period		<i>Litter</i>	$t_{DM} \text{ ha}^{-1}$
Stem mortality			
Max. mean tree stem mass at current stocking	w_{Sn}	<i>wSmax</i>	kg tree^{-1}
Density independent mortality rate	γ_N	<i>gammaN</i>	month^{-1}
Number of stems dying in current period		<i>Mortality</i>	trees ha^{-1}
Water use			
"Supplemental" irrigation to maintain $\theta_s \geq \theta_{sn}$		<i>supIrrig</i>	mm
Fraction of rainfall intercepted by canopy	i_R	<i>fRainInt</i>	-
Rainfall intercepted by canopy in current period		<i>RainInt</i>	mm
Canopy conductance	g_C	<i>CanCond</i>	m s^{-1}
Water use efficiency	ω	<i>WUE</i>	$\text{g}_{DM} \text{ mm}^{-1}$
Evapotranspiration rate in current period	E_T	<i>EvapTransp</i>	mm
Monthly transpiration rate in current period		<i>Transp</i>	mm
Available soil water	θ_s	<i>ASW</i>	mm

APPENDIX 3

Sands, P.J. and Landsberg, J.J. (2002). Parameterisation of 3-PG for plantation grown *Eucalyptus globulus*. *Forest Ecology and Management*. 163: 273-292.

APPENDIX 4

Esprey, L.J., Sands, P.J. and Smith, C.W. 2004.

Understanding 3-PGPJS using a sensitivity analysis. *Forest*

***Ecology and Management* 193:235-250.**

APPENDIX 5

Campion, J.M., Esprey, L.J. and Scholes, M.C. (2005).

Application of the 3-PG model to a *Eucalyptus grandis* stand

subjected to varying levels of water and nutritional

constraints. *Southern African Forestry Journal*. 203: 3-14.

Please note that appendices 3, 4 and 5 have inadvertently been omitted from this bound version of the dissertation. These appendices are referenced in the text and can be found in the appropriate journal.