PARAMETERISATION OF THE 3-PG PROCESS-BASED MODEL IN PREDICTING THE GROWTH AND WATER USE OF *Pinus elliottii* IN SOUTH AFRICA

by
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Pietermaritzburg
2011

ABSTRACT

A simplified process-based model simulating growth and water use in forest plantations was utilised to predict the growth of *Pinus elliottii* in South African forest plantations. The model is called 3-PG (**P**hysiological **P**rinciples in **P**redicting **G**rowth) and predicted the growth of trees by simulating physiological processes that determine growth and water use, and the way trees are affected by the physical conditions to which they are subjected, and with which they react.

Pinus elliottii growth data recorded in 301 sample stands around South Africa were sourced from forestry companies. A selection procedure reduced the number of stands to 44, where 32 were used to parameterise 3-PG and 12 were reserved for testing the final model parameters. This was accomplished by matching model output to observed data. All stand simulations were initialised at age four years and continued to the maximum age of recorded growth.

A provisional set of parameter values provided a good fit to most stands and minor adjustments of the specific leaf area (σ), which was assigned a value of 5 $m^2.kg^{-1}$, were made, bringing about an improved fit. The predictions of mean DBH, Height, and TPH were relatively good, achieving R^2 of 0.8036, 0.8975, and 0.661 respectively, while predictions of stem volumes were worse (R^2 =0.5922, n=32). The 3-PG model over-predicted DBH in 20 stands, while modelled volume predictions improved substantially in thinned stands (R^2 =0.8582, n=14) compared to unthinned stands (R^2 =0.3456, n=18). The height predictions were generally good producing an R^2 =0.8975.

The final set of 3-PG parameter values was then validated against growth data from the 12 independent stands. The predictions of mean DBH, Height, and TPH were relatively good, achieving R^2 of 0.8467, 0.7649, and 0.9916 respectively, while predictions of stem volumes were worse (R^2 =0.5766, n=12).

The results of this study demonstrated the potential for 3-PG to respond to many growth factors and to predict growth and water use by trees with encouraging realism. Patterns of changing leaf area index *(L)* over time, responses to drought, and annual evaporation patterns all look realistic. Consequently, 3-PG is judged to have potential as a strategic forestry tool.

PREFACE

The work described in this dissertation was carried out in the Forestry Programme, University of KwaZulu-Natal from January 2003 to December 2010 under the supervision of Dr Peter Dye and the late Professor Janusz Zwolinski. This study represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any university. Where use has been made of the work of others, it is duly acknowledged in the text.

Signed:

....(Candidate)

Signed:

....(Supervisor)

LIST OF CONTENTS

ACKNOWLEDGEMENTS

It has been a great pleasure to be able to deal with such a fascinating subject. I trust that I managed to make a difference in the forestry industry. I express thanks to my supervisor, the late Professor Janusz Zwolinski, for putting consistent pressure on me to deliver, for his patience, friendship, mentorship and support during the study. Also to Dr Peter Dye, for providing guidance in all aspects of this study, without which any outcome from this study would not have been possible.

I am indebted to Trevor Morley, Duncan Wilson, Luke Esprey, Ben du Toit, Colin Smith, Marilyn Govender and Richard Kunz for their assistance with data sets and technicalities at various stages of this research. I am also indebted to all my valued comrades and personnel who contributed through support, especially Mrs Dianne Chellan.

I must thank the relevant forestry companies for granting me permission to access and make use of data in the MMRC database, and the Bioresource Engineering and Environmental Hydrology group of UKZN for providing weather data.

I must also thank the Council for Scientific and Industrial Research (CSIR) in providing financial support for this study.

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

SYMBOLS AND ACRONYMS

α_c	Canopy quantum efficiency coefficient (mol C (mol .photon^{-1}))
ϕ_p	Photosynthetically active radiation (mol.m^{-2})
ϕ_{pa}	Absorbed photosynthetically active radiation (MJ^{-2} or mol.m^{-2})
ϕ_{pau}	Utilisable $\phi_{p.a}$, determined by environmental constraints
ϕ_s	Short-wave incoming radiation (MJ^{-2})
θ_s	Available soil water (mm)
3-PG	Physiological Principles in Predicting Growth
ALT	Altitude or height above sea level (m)
ASW	Available soil water (mm)
BEEH	Bioresources Engineering and Environmental Hydrology
CAI	Current annual increment (m^3.ha^{-1}.year^{-1})
C_{pp}	Ratio P_N / P_G (0.45 ± 0.05)
DACST	Department of Arts, Culture, Science and Technology
DBH	Mean diameter at breast height (cm)
Dq	Quadratic mean diameter/ average stand diameter (cm)
DWAF	Department of Water Affairs and Forestry
ET	Evapotranspiration (mm.month^{-1})
FR	Fertility rating
g_c	Canopy conductance (m.s^{-1})
HD	Dominant height (m)
Hq	Quadratic mean height / mean tree height (m)
ICFR	Institute for Commercial Forestry Research
IF	Innovation Fund
k	Coefficient describing the relationship between stomatal and canopy conductance and VPD
KLF	Komatiland Forestry
L	Leaf area index (m^2.m^{-2})
Lat	Geographical reference point of latitude (decimal)
LF	Litterfall (Mg.ha^{-1})
Long	Geographical reference point of longitude (decimal)
MAP	Mean annual precipitation (mm)

MAT	Mean annual temperature (^{0}C)
MMRC	Mensuration and Modelling Research Consortium
N	Stem populations(trees.ha^{-1})
NECF	North East Cape Forests
NFAP	National Forestry Action Programme
NRF	National Research Fund
PAR	Photosynthetical active radiation (ϕ_p)
PBM	Process based models
P_G	Gross primary production (carbon fixed per unit time; mol.m^{-2} or Mg ha^{-1})
P_N or NPP	Net primary production (Mg.ha $^{-1}$). In 3-PG, P_N is assumed to be a constant fraction (C_{pp} = 0.47) of P_G
TAW	Total Available Water (mm)
TPH0	Initial stems per hectare at time of planting (trees.ha^{-1})
TPH00	Stems per hectare at age 4 four years (trees.ha^{-1})
TPH1	Final stems per hectare at time of last mensuration (trees.ha^{-1})
T_t	daily total atmospheric transmittance of solar radiation
UKZN	University of KwaZulu-Natal
VPD	Average monthly vapour pressure deficit (kPa)
Wf	Foliage biomass (t.ha^{-1})
Wr	Root biomass (t.ha^{-1})
Ws	Stem and branch biomass (t.ha^{-1})
W_{sx}	Mean stem mass (t.ha^{-1})
γ_F	Average monthly litterfall rate (Mg.ha^{-1}.month^{-1})
ΔT	is the daily range of air temperature (^{0}C)
$\Delta_T WF_L$	Average annual litterfall rate (Mg.ha^{-1}.year^{-1})
η_i	Carbon allocation coefficient for foliage (η_f), stems (η_s) and roots (η_r)
σ	Specific leaf area (m^2.kg^{-1})

1. INTRODUCTION

South Africa has had to rely almost exclusively on the development of exotic forest plantations to meet its demand for wood. The National Forestry Action Programme (NFAP) published by the South African Department of Water Affairs and Forestry (DWAF, 1997) stressed the need to significantly advance plantation productivity due to the projected demand for wood in the country.

Meeting this challenge requires not only wider adherence to the existing best management practices, but also a greatly improved understanding of the eco-physiological limits on tree growth, and how these may be modified through forest management strategies to maximise production. The task of improving yields is especially necessary, and also most difficult, for previously disadvantaged small-scale growers who mostly lack the technical tools to optimise their plantation management (DACST, Innovation Fund Proposal, 2002).

A further challenge to the forestry industry has been posed by the introduction of licensing of water-use in terms of the National Water Act No. 36 of 1998, and the need of the forestry sector to optimise its wood production within the limits of available water and other natural resources. South African forests are generally concentrated in the higher rainfall areas, which also provide a major proportion of the total quantity of water in the country's streams and rivers (Scott *et al.,* 1998).

Trends over the past century have shown that streamflows decline when catchments are converted from grassland or fynbos to forest plantations (Scott *et al.*, 1998). This is because evergreen trees maintain a higher rate of evapotranspiration due to a number of factors including an increase in *L* (ratio of total upper leaf surface of tree canopy divided by surface area of the land on which the tree grow) and canopy photosynthesis (evergreens maintains photosynthesis even in winter), and other species-intrinsic factors (Gholz *et al.,* 1990; Vose *et al.,* 1994).

However, current understanding of physiological and climatic controls on tree growth and water use is insufficient and thus preventing scientists from assessing the relative importance of forests, soils and weather conditions in constraining forest productivity and water use. The methods available to predict forest water use are also inadequate, and thus improved predictions are required to assess the hydrological impacts of forest plantations, and to minimise these in catchments where water resources are fully or over-utilised.

Most conventional forest growth models combine discrete site variables in a purely statistical sense, and little recognition is given to processes involving plant physiology or ecosystem functioning (Louw, 1999). Yield predictions derived from empirical measurements and relationships are increasingly viewed as being insufficient (Louw, 1999). As a result of increasing greenhouse gases in the atmosphere and atmospheric inputs of nitrogen altering stand nutrient budgets (Landsberg *et al*., 2000), it is likely that rates of forest growth and water use will be influenced in future rotations.

Considerable increase in management intensity (fertilisation, site preparation, competition control, and genetic improvement) is also likely to impact on plantation productivity (Landsberg *et al.,* 2000). As a result of these changes and developments, conventional predictions by empirically based growth and yield models are likely to become less reliable in the future.

Recent international research (McMurtrie *et al.,* 1994; Landsberg and Waring, 1997; Sands and Landsberg, 2002) has demonstrated that relatively simplified forest growth models can provide improvements in predictions of growth and water use, providing greater insights into optimum plantation management. Over the last two decades, there has been considerable progress in developing such process-based models (PBM's) to predict forest productivity, and earlier reviews of PBM's are reported by Landsberg and Waring (1997) and include McMurtrie *et al*., (1992), Weinstein *et al*., (1991), Running and Coughlan (1988), and Running and Gower (1991).

These process-based models aim to predict the growth of stands in terms of underlying physiological processes that determine growth and water use, and the way stands are affected by the physical conditions to which trees are subjected and with which they react. Several papers outline the perceived advantages of such models (Battaglia and Sands 1998; Louw, 1999).

The Council for Scientific and Industrial Research (CSIR) showed early interest in the 3-PG (**P**hysiological **P**rinciples in **P**redicting **G**rowth) model, a relatively simple process-based model that could potentially see practical application by the South African forestry industry. Two early evaluation studies (Gush, 1999; Dye, 2001) were promising, suggesting that the 3-PG model could be useful. A research proposal titled, "A *new decision-support software tool for tree growers and water resource managers: harnessing physiological information to improve productivity and water use assessment of forest plantation*", was then submitted to the Government-sponsored Innovation Fund (IF) managed by the National Research Foundation (NRF).The NRF is a grant-awarding science council that promotes the creation of new knowledge and products through research and development in all fields of science and technology. The IF supports large-scale collaborative research projects leading to technological innovation. The key objective of the IF is to contribute to economic growth and competitiveness through investment in technology innovations that lead to the establishment of new enterprises. The proposal was accepted, and funding was secured for a three-year period to develop a practical version of a process-based model for use by the forestry industry. A consortium of research partners was set up to achieve the goals of the project. The consortium included:

- the CSIR, specifically the Environmentek (now NRE) division;
- the Institute for Commercial Forestry Research (ICFR);
- the Mensuration and Modelling Research Consortium (MMRC);
- the University of KwaZulu-Natal (Forestry Programme) and,
- Brousse-James and Associates.

The project was planned to address various aspects of work necessary to develop the final product. This included a user requirements survey, a review of available process-based models, modifications to the model to adapt to South African requirements, model parameterisation for the major South African forest species, product design and development of a commercialisation plan. This dissertation is focused on 3-PG parameterisation for one of the major forest species planted in South Africa.

A review of available process-based models was performed early on in the project (Esprey, 2003a), and confirmed the impressions that the 3-PG model was indeed the most appropriate PBM to develop further in South Africa. Regarding the model parameterisation, it was decided to concentrate on parameterising the model for the major forest plantation species in this country, which were taken to be *Eucalyptus grandis*, *Pinus elliottii* and *Pinus patula.*

This research focused on *Pinus elliottii*, which is the second most commonly planted pine species in the country. This dissertation starts with the layout and the objectives of this study, while chapter two describes the silvicultural information on the species. In chapter three, a general overview of modelling in forestry is discussed, reflecting on the importance of forestry models and their relevance to the South African context. In chapter four, the process-based model “3-PG” is fully described through its general structure, data requirements and processes used to make predictions. Chapter five describes detailed methodology for stand selection around South Africa and the process of deciding and defining the parameters that would be required by the 3-PG (pre-parameterisation data requirements). Unlike in chapter four, where 3-PG initialisation data is illustrated, chapter six outlines the methodology used in the estimation of this pre-parameterisation data. Chapter seven outlines the results of the predictions and conclusions.

1.1 INNOVATION FUND PROJECT AND OBJECTIVES OF THIS STUDY

The Innovation Fund (IF) project was significant in providing the first opportunity for the collaborating organisations and scientists to pool their collective knowledge and work as a single team for the benefit of the South African forestry industry. It was the most ambitious application of forestry PBM in South Africa, reflecting the need to take into account the great diversity of climate, soil and tree species in our forestry regions. The IF project aimed at providing information that could be incorporated into a CD-based computer simulation tool that allows the user to operate 3-PG for any given location where *Pinus elliottii* grows. By simply selecting maps, it will be possible for the user to access temperature; rainfall and other required input data that are applicable to the selected *Pinus elliottii* site. By further stipulating the tree species, site conditions and management activities, a month-by-month computer simulation of a stand of trees was generated. Tree growers and strategic land-use planners would be provided with a decision-support software tool based on a relatively simple model of physiological processes governing growth and water use in plantations.

The products will guide growers towards improved plantation management, greater sustainable productivity, and optimal use of water, while assisting strategic planners with comparisons of forest water use and water use efficiency to alternative land use options. More specifically, the aims of this study were to:

- produce a set of parameters for the 3-PG model that predicted the growth and water use of *Pinus elliottii* over a representatively wide range of South African sites;
- evaluate the realism of model predictions;
- improve understanding of the parameterisation process for *Pinus elliottii*;
- provide a better understanding of what is limiting the growth rates of *Pinus elliotii* and,
- improve assessment of the usefulness of the 3-PG model to the South African industry.

2. PINUS ELLIOTTII IN SOUTH AFRICA

2.1 CHARACTERISTICS AND GROWTH CONDITIONS OF *PINUS ELLIOTTII* IN SOUTH AFRICA

2.1.1 *Pinus elliottii* Engelm. var. Elliottii

Pinus elliottii is indigenous to the United States of America, and its natural range extends from the coastal plain of southern South Carolina to central Florida and south-eastern Louisiana (Koch, 1972). The first attempted introduction of *Pinus elliottii* into South Africa took place in 1916 (Poyton, 1979). After *Pinus patula*, *Pinus elliottii* is now the most widely planted pine in South Africa. In many aspects, *Pinus elliottii* is the hardiest of the major pine species, growing on relatively shallow soils at lower mean annual precipitation (MAP) 850 mm, and showing high tolerance to relatively higher temperatures (Schulze *et al.,* 1997). *Pinus elliottii* is most versatile with a growth range (**Figure 1**) stretching from the Limpopo Province to the Western Cape. It is recommended for poorly drained soils in the Western Cape; shallow and dry sites in the Eastern Cape; KwaZulu-Natal and Mpumalanga, and also on hydromorphic soils on the coastal sands of Zululand (Schutz, 1994).

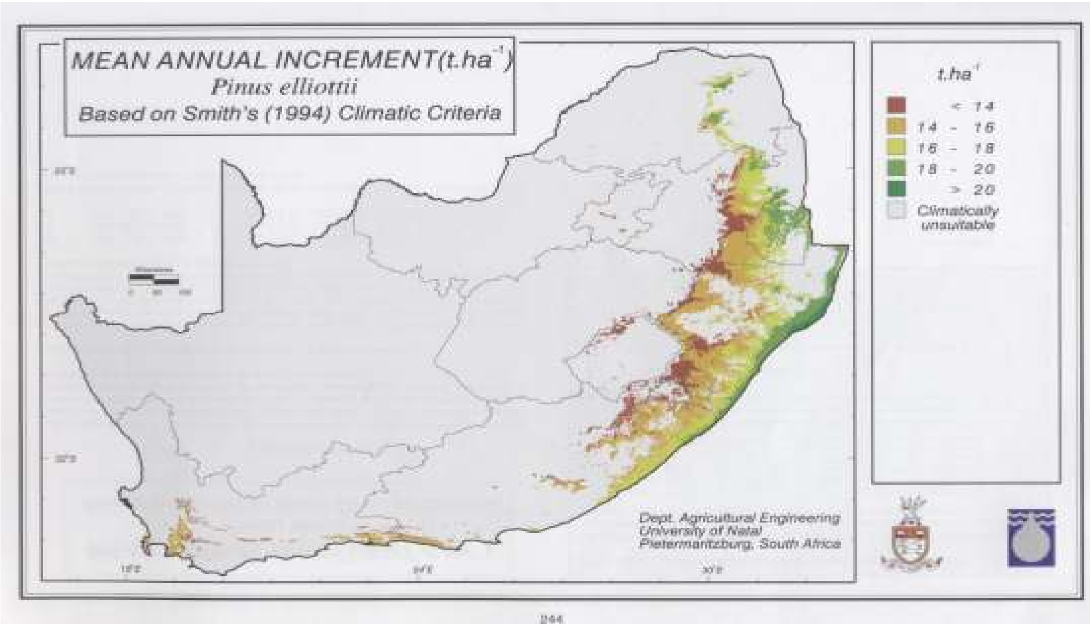

Figure 1: The potential *Pinus elliottii* growth areas in South Africa (Schulze *et al.,* 1997).

Pinus elliottii can grow to a maximum height of about 40 m, usually reaching an average height of 30 m in plantations (Marsh, 1978). According to Marsh (1978) it can be expected to achieve a diameter at breast height (DBH) of 30 to 42,5 cm between 30 to 35 years.

A general description of *Pinus elliottii* growth requirements in South Africa is provided in **Table 1**. These growth requirements may fluctuate slightly regionally. For instance, MAP may vary depending on the region and altitude. Optimum soil depth may vary with altitude but *Pinus elliottii* can grow reasonably in shallow soils. Region-specific information is available from various sources such as Marsh (1978), Schonau and Schulze (1984), Schutz (1994), Schulze *et al.,* (1997), Zwolinski and Hinze (2000).

Table 1: The general growth requirements for *Pinus elliottii* in South Africa (Zwolinski and Hinze, 2000; Morris and Pallett , 2000).

Altitude (m)	MAT* (^{O}C)	MAP* (mm)	Soil depth (mm)	Rooting depth (mm)	Pathogens	Initial Spacing (trees.ha^{-1})
<1500	>14	>700	>600	>300	*Armillaria mellea;* *Sphaeropsis sapinea*	1111-1736

* This is the accepted mean annual temperature (MAT) and MAP providing adequate growth but MAP may increase with altitude

2.1.2 Plantation area, and typical management of *Pinus elliottii*

In South Africa, *Pinus elliottii* collectively with other *Pinus* species such as *Pinus patula,* contribute about 52.2% to the overall forestry plantation area of 1.3 million hectares (DWAF, 2003). Typically, *Pinus elliottii* is thinned at two or three distinct ages depending on the intended product (sawtimber or pulpwood) and spacing between trees differs according to the silvicultural option. *Pinus elliottii* grown for pulpwood is not thinned, and reduction (if at all) in trees per hectare is due to natural mortality. The thinning regimes for trees grown for sawtimber typically occur at 8, 13, and 18 years of age in a rotation of 30 years.

The initial spacing for planting densities of 1372 trees per hectare (TPH) and 816 TPH is 2.7 m×2.7 m and 3.5 m×3.5 m respectively (Zwolinski and Hinze, 2000). Rotation age in pulpwood plantations varies from 15 years (in good sites) to 18 years (poor sites). Sawtimber and veneer *Pinus elliottii* stands are harvested at ages between 20 and 30 years, depending on tree performance and desired log size.

Post-harvest practices like burning are not recommended for *Pinus elliottii* as this promotes infection by *Rhizina undulata*. The species is susceptible to hail and damage by snow when still young, while aphids, rodents and some mammals feed on *Pinus elliottii*. More information covering different aspects of *Pinus elliottii* is reported by Morris and Pallett (2000) and Zwolinski and Hinze (2000).

3. MODELLING IN FORESTRY

3.1 OVERVIEW OF FORESTRY MODELLING

“A model is an abstraction or a simplified representation of some aspect of reality” (Vanclay, 1994, p.7). Forest models provide an efficient way to prepare resource forecasts, but a more important role may be their ability to explore management options and silvicultural alternatives. A good example as stated by Vanclay (1994) is that forest scientists may wish to know the long-term effects of particular silvicultural decisions, such as changing the thinning or pruning regimes and clear felling limits in harvesting. Growth models can scrutinize the probable outcomes, both with the intended and alternative regimes, thus allowing informed decision-making (Vanclay, 1994). Growth models may also have a broader role in forest management and in the formulation of forest policies, especially in developing countries like South Africa. If used in conjunction with other resources and environmental data, growth models can be expected to make predictions, formulate prescriptions and guide forest policy with accepted probability.

Figure 2 is a simplified representation of this process as shown by Vanclay (1994). It shows that growth models are a stepping-stone in the formulation of forest policy and management prescriptions, and that supplementary data and sufficient testing are also required. “The feedback loops are especially important, in the context of growth modelling and there should be sufficient feedback to ensure that inventory is adequate and model predictions are reliable across the range of resource conditions and management prescriptions entertained” (Vanclay, 1994, p.8).

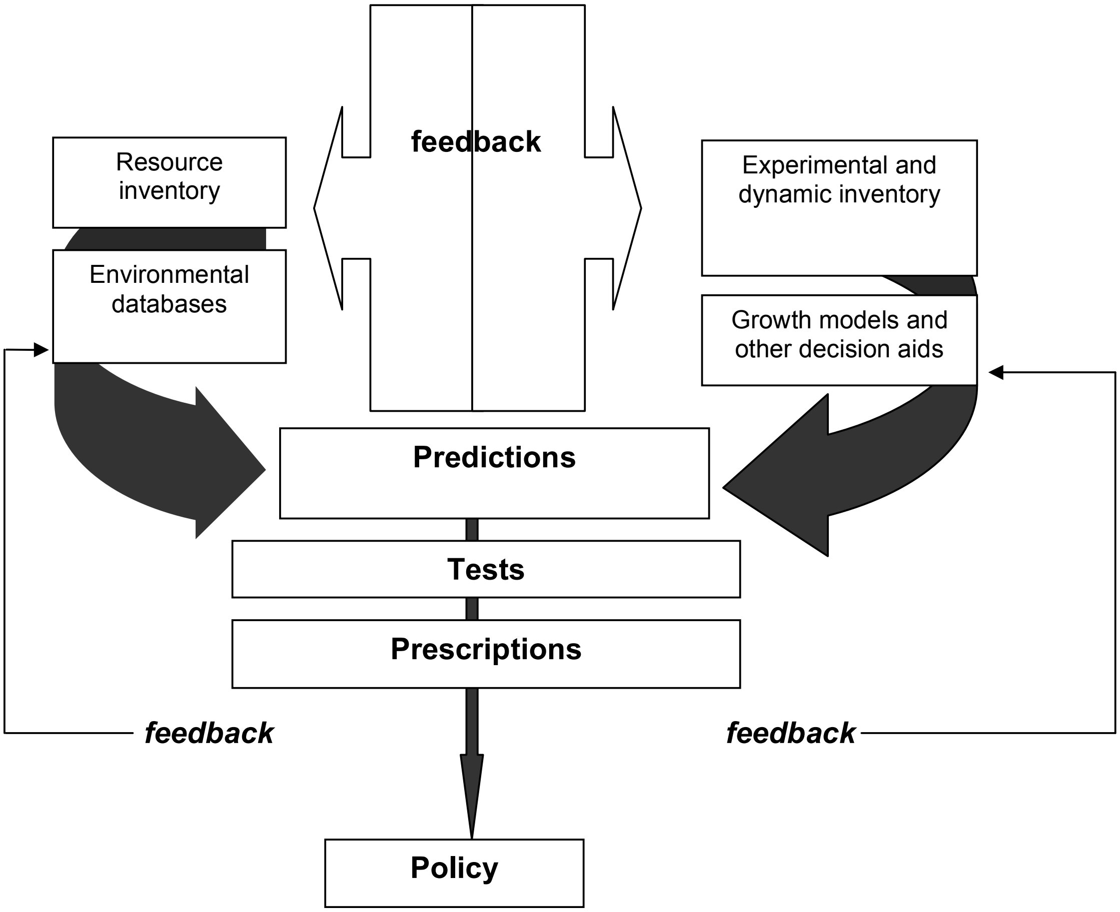

Figure 2: The role of growth models in decision-making, forest management and the formulation of forest policy (after Nix and Gillison, 1984) cited by Vanclay (1994).

3.2 THE RELEVANCE OF PROCESS-BASED MODELS TO THE SOUTH AFRICAN FORESTRY INDUSTRY

South Africa is a relatively dry country and subject to recurring droughts, which may last for several years. During a drought period an empirical growth model can fail to show such drought effects, leading to simulation inaccuracy. Morris (1995) showed how drought events could significantly affect tree growth. By contrast, PBM's have been proven to be able to track the effects of drought on trees because of their ability to simulate tree biological processes. Almeida *et al.*, (2004) showed how a PBM could be used to estimate the potential growth of trees, and separate the effect of management practices and climatic factors on growth rates. These authors also demonstrated the valuable role that PBM's can play as an operational or research tool that allows hypotheses testing regarding the way trees function and respond to environmental changes.

The South African forestry environment is biophysically complex. Required growth and water use models must therefore meet the following requirements proposed by Louw and Scholes (2001):

- predictions must have suitable spatial resolution for decision-making at operational "compartment" level, e.g. 5-100 ha;
- models must require relatively simple site and stand inputs that can be estimated from basic site classification systems or mensuration data available in typical forest inventories, but also that represent environmental factor interactions in a realistic fashion;
- model output must provide solutions to questions relevant to forest managers and researchers and,
- models must not rely solely on the empirical data, but must incorporate dynamic changes in the biophysical environment and silvicultural events that influence site growth potential. Models must therefore be "process-orientated" at some basic level.

The challenge is to adapt and enhance such process-based modelling systems (PBM's) to South African conditions and provide growers with a useful tool to meet their practical needs.

4. THE 3-PG MODEL

4.1 BACKGROUND

There are numerous process-based forestry models described in the literature. Several of these have been extensively used in a variety of forests and have become well established, e.g. FOREST-BGC (Running and Coughlan, 1988; Running and Gower, 1991); BIOMASS (McMurtrie *et al.,* 1992), PnET (Aber and Federer, 1992) and TREGROW (Weinstein *et al*., 1991). Esprey (2003a) reviewed a total of 17 forestry process-based models (PBM's) in order to select one that best met the IF project needs.

The selected model needed to be simple, yet with adequate physiological details that generate outputs describing plantation growth, yield and water use. In addition, the model needed to demonstrate flexibility, allowing modifications (such as access to groundwater) to be built into the model structure. The 3-PG model was selected because it met the selection criteria better than all other models considered. A detailed report of this model comparison exercise has been documented in Esprey (2003a).

4.2 OVERVIEW OF THE 3-PG MODEL

The 3-PG model was developed in an attempt to provide a relatively simple, practical PBM that could be used by foresters to improve their predictions of growth rates and water use of forest plantations. It was developed primarily to narrow the gap between conventional (mensuration based) growth and yield models and process-based (carbon and water balance) models. It is both simple and applicable to plantation management (Johnsen *et al.,* 2001).

The 3-PG model has been widely used in many different countries around the world, noticeably in Australia (Sands and Landsberg, 2002; Coops, *et al*., 2000), Brazil (Almeida, 2000; Almeida *et al*., 2003) and South Africa (Gush, 1999; Dye, 2001; Esprey and Sands, 2004). A detailed description of the model is available in Landsberg and Waring (1997), and a brief overview is outlined below.

4.3 THE 3-PG MODEL STRUCTURE

4.3.1 The 3-PG model input and output

The broad structure of 3-PG is illustrated in **Figure 3**. The model requires input information relating to weather, site and stand characteristics as shown in **Table 2**. These are required by the model prior to the start of a simulation. A network of interconnected mathematical equations (Landsberg and Waring, 1997; Sands and Landsberg, 2002) calculates the model outputs, which can be generated either at monthly or annual intervals.

They include stem (Ws), foliage (Wf) and root biomass (Wr) (t.ha^{-1}), stand volume (m^{3}.ha^{-1}), mean annual volume increment (m^{3}.ha^{-1}.year^{-1}), available soil water (θ_s ,mm), canopy leaf area index (m^{2}.m^{-2}) and many more described in later sections. A complete list of model outputs is presented in **Appendix 1**.

Table 2: Categories of input information required by 3-PG prior to simulation.

Weather	Rainfall (mm)	The actual monthly total rainfall.
	Radiation (MJ^{-2})	The actual monthly solar radiation to the stand.
	Temperature (^{0}C)	The monthly mean temperature.
	Vapour pressure deficit (kPa)	The monthly mean daylight vapour pressure deficit.
Site	Final soil water (mm)	The maximum available soil water content.
	Initial soil water (mm)	The minimum available soil water content.
	Soil texture	Depict the soil class of that site as clay, loamy etc.
	Fertility rating	An estimation of soil fertility for the site.
	Latitude (m)	The angular distance of a location north or south of the equator.
Stand	Trees per hectare (trees.ha^{-1})	Tree density per hectare at a given stand age.
	Initial biomass (t.ha^{-1})	The initial biomass of foliage, root and stems of a stand.
	Age of stand (years)	The age at which simulation will be started and terminated.

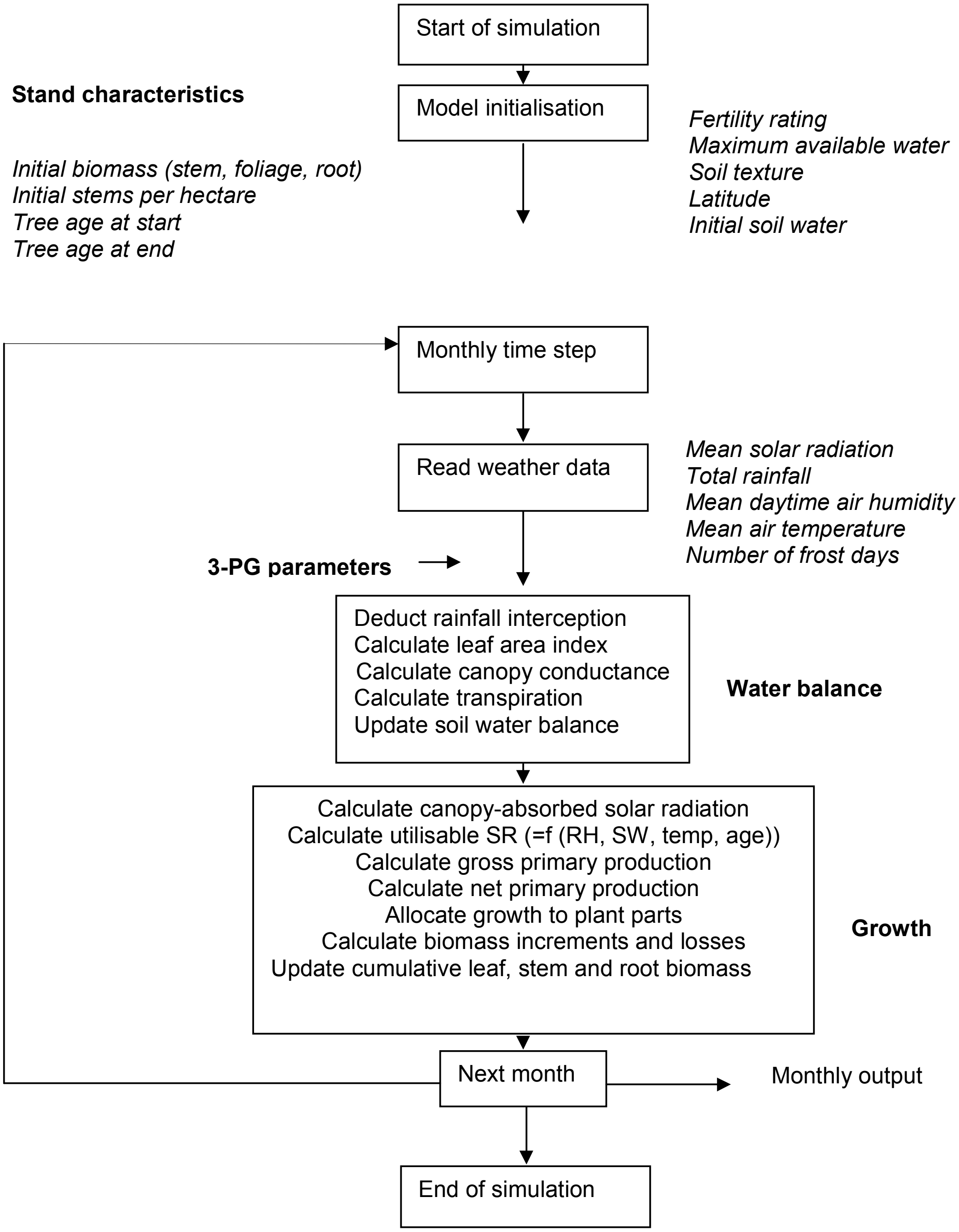

Figure 3: Flow diagram showing the structure of 3-PG (Dye, 2001).

4.3.2 Species parameters

The basic structure of 3-PG is considered to be generic or flexible (Esprey, 2003a) and applicable to all plantation forests. However, it needs to be parameterised for individual species, and this is accomplished either on the basis of field data or from information reported in the literature, or by comparing model output to observed data and adjusting parameter values in an iterative way. The model requires values for 49 parameters and these are listed in **Appendix 2.**

4.4 DETAILS OF SOME MAJOR 3-PG PROCESSES

Many authors provide a review of the 3-PG model processes and in this dissertation, reference is made to the original description provided by Landsberg and Waring (1997) and modifications of 3-PG made by Sands and Landsberg (2002, p 289-291). These authors provide comprehensive descriptions of the principal algorithms. Only some of the principal algorithms that have a major effect on growth and water use predictions are described below. **Figure 4** is a flow diagram illustrating how the 3-PG model processes are interrelated and affect each other to predict growth and water balance.

Sands and Landsberg (2002) describe 3-PG as consisting of five simple sub models namely:

- the assimilation of carbohydrates (gross primary production);
- the distribution of biomass between foliage, roots and stems (biomass allocation);
- the determination of stem numbers (stem mortality);
- the soil water balance and,
- the conversion of biomass into variables of interest to forest managers.

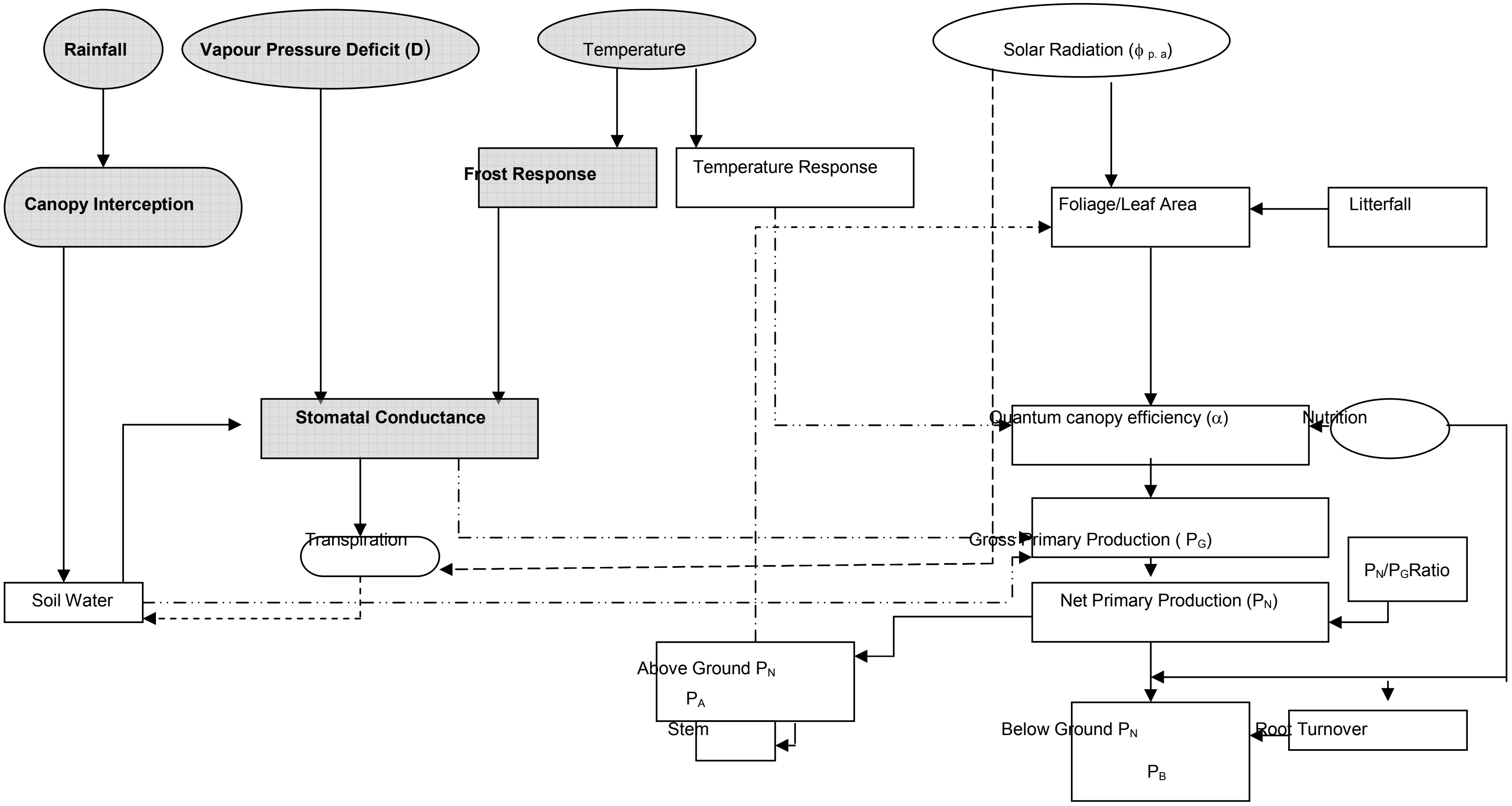

Figure 4: Flow diagram of 3-PG processes (Tickle *et al*., 2000a). The left-hand side of the diagram contains components affecting predominately the hydrological balance, while the right-hand side shows the carbon balance processes.

4.4.1 Assimilation of carbohydrates (Gross primary production)

The photosynthetically active radiation (PAR) ($\phi_{p;}$ (mol.m^{-2})) incident on the canopy is calculated from solar radiation or short-wave incoming radiation ϕ_s (MJ^{-2}) and an assumption is made that 1 MJ of solar radiation is equivalent to 2.3 mol.m^{-2} (Sands and Landsberg, 2002). The PAR (mol.m^{-2}) absorbed by the canopy is determined from L and ϕ_p through Beer's law. The gross primary production (P_G) is proportional to the absorbed PAR (ϕ_{pa}), with 1 mol C equivalent to 24 g_{DM} (Sands and Landsberg, 2002).

This proportionality factor, called canopy quantum efficiency (α_c) considers the environmental modifiers, which are detailed in Sands and Landsberg (2002). In the 3-PG model, the environmental modifiers provide a measure of the 'harshness' of the environment, and quantify the stresses experienced by the trees. Under no-stress conditions, these modifiers are unity, and absorbed PAR (ϕ_{pa}) is equal to utilisable PAR (ϕ_{pau}) (Landsberg and Waring 1997, p 212-214). The net primary production (NPP) is then calculated as a constant fraction (C_{pp}=0.47) of the gross primary production (P_G) (Sands and Landsberg, 2002).

4.4.2 Distribution of biomass (Biomass allocation)

Current growing conditions, principally available soil water, and vapour pressure deficit and site nutrition determines the allocation of NPP to roots at any model iteration. The model estimates carbon allocation using allocation coefficients (η_i) derived from the (allometric) equations that describe the observed relationships between the mass and size of the different parts of plants or trees. Allometric relationships for biomass allocation included in 3-PG are described in detail for different pine species in Landsberg and Waring (1997, p 218-219).

4.4.3 Stem mortality

The 3-PG model utilises the correlation between stem populations (*N)* and maximum achievable individual stem mass to determine changes in stem populations. Any reduction in stem population is calculated by means of the -3/2 self thinning law. It calculate the approximate mean stem mass W_{SX} ($kg_{DM}.tree^{-1}$) upper limit to the mean single tree stem mass (Ws), given the *N.* A detailed description of these relationships and technical implications is given in Landsberg and Waring (2002, p.216).

4.4.4 Soil water balance

In 3-PG, the soil water balance sub-model tracks monthly changes in soil water within a single soil layer. Monthly soil water extraction through transpiration is computed using the Penman-Monteith equation and precipitation (Landsberg and Gower (1997). The water balance model is discussed in detail in Waring and Landsberg (1997) and Landsberg and Gower (1997).

4.5 RECOMMENDED SOURCES OF DATA

Good data describing the changing biomass and structure of stands is a prerequisite for successful 3-PG simulations. Data describing, or leading to the calculation of tree biomass (foliage, stems and branches and roots), leaf area index (*L*) and rate of litterfall are important in arriving at a realistic model output. Esprey *et al*. (2004) classified sources of data typically required to parameterise 3-PG as biomass, field, literature, mensuration and physiological data represented by B, F, L, M or P class symbols respectively as shown in **Table 3**.

Table 3: Data source classes required for 3-PG parameterisation (Esprey *et al*., 2004).

Data source	**Class**	**Description**
Harvest biomass	B	Data from direct measurement of harvested trees, e.g. biomass data, leaf area, wood density
Field data	F	Data not routinely obtained from an inventory assessment, e.g. from soil samples, litterfall traps
Literature	L	Data obtained from literature
Mensuration	M	Data from an inventory assessment, e.g. measured stem height and diameter, data from statistical relationships
Physiological	P	Results of physiological experiments, e.g. gas-exchange analyses

The IF project was planned as a purely modelling and software development project and no provision was made for the collection of field data. The strategy was to take advantage of growth data stored in the Mensuration and Modelling Research Consortium (MMRC) database. Measured site information (particularly maximum available soil water, predominant soil texture and fertility rating) was largely unavailable for the selected sites, and so it was decided to obtain these from broad-scale correlations to geological types. All parameter values were therefore obtained from data reported in the literature or held in other databases.

5. METHODOLOGY

5.1 INITIAL STANDS

Growth data recorded for *Pinus elliottii* were required to set up simulations and to test the validity of parameter values and model output using independent data. Permission to utilise data housed in the MMRC database was obtained from the forestry companies Mondi, Komatiland forestry (KLF) and Sappi. This database comprised *Pinus elliottii* data from 296 permanent sample stands from the major forestry districts of the country. Additional data from a further five stands (two from Kwambonambi and Dukuduku in Coastal Zululand, and three from the farms Wildebees and Roseg in the North East Cape Forests (NECF)) were sourced, making 301 stands from which a sub-sample of stands was selected.

The strategy adopted for selecting stands for this study was based on the following criteria:

- a manageable total of about 40 stands;
- representative of the major forestry regions in South Africa;
- covering the range of growth conditions and site indices (a measure of site productivity). Variables considered to be important were mean annual precipitation (MAP); mean annual temperature (MAT); trees per hectare (TPH); altitude; soil types and geology and,
- preference for stands in which final growth measurements were conducted in mature stands in the latter half of a rotation period. Stands in which multiple growth surveys were performed, were also preferred.

5.2 STAND SELECTION PROCEDURE

This procedure was done in steps to minimise uncertainty and to be as systematic as possible.

Step 1: Delineation of major forestry regions where stands were found.
The first step in selecting a representative sample from the 301 stands was to divide these into subsets of more manageable numbers of stands for smaller regions. These were arbitrarily divided into the regions shown in **Table 4.**

Table 4: Geographical location of selected stands in the forest growing regions.

Region	**Latitude**	**Longitude**
Coastal Zululand	<28.5^0 S	>32^0 E
Natal midlands	27.5 - 31^0 S	<32^0 E
Mpumalanga – Highveld	27.5 - 26^0 S	>31^0 E
Mpumalanga – Lowveld	26 - 24.5^0 S	<31^0 E
North East Cape Forests	>31^0 S	<30^0 E
Limpopo	<24.5^0 S	<30^0 E

Step 2: Assessing distribution of stands by forestry regions of South Africa.

Within each region, all the districts or forest plantations in which the stands occurred were listed and plotted as illustrated in **Figure 5**.

Step 3: Assessing the range of upper and lower data extremes.

Quadratic mean tree diameter (Dq) was plotted against tree age to obtain an overall impression of variation in tree sizes with age (**Figure 6**). The MMRC database stands had associated estimates of Dq and quadratic mean height (Hq), while Zwolinski *et al*., (1998), estimated tree diameters in North East Cape Forests (NECF) stands from analyses of tree rings.

In Coastal Zululand, tree diameters at breast height were recorded in the field as stand mean diameters. This created inconsistency in available tree diameters. However, no effort was made to change mean diameters to Dq as there is little difference (approx. five percent variance) between Dq and mean diameters at breast height (D Wilson, 2004, pers. comm[1]). Stands were then selected along the upper and lower margins of the scatter of data points to ensure that productivity extremes were included (**Figure 6**).

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[1] Dr D Wilson, Forestry Management Lecture: Forestry Programme, Private Bag X01, Scottsville 3201, South Africa

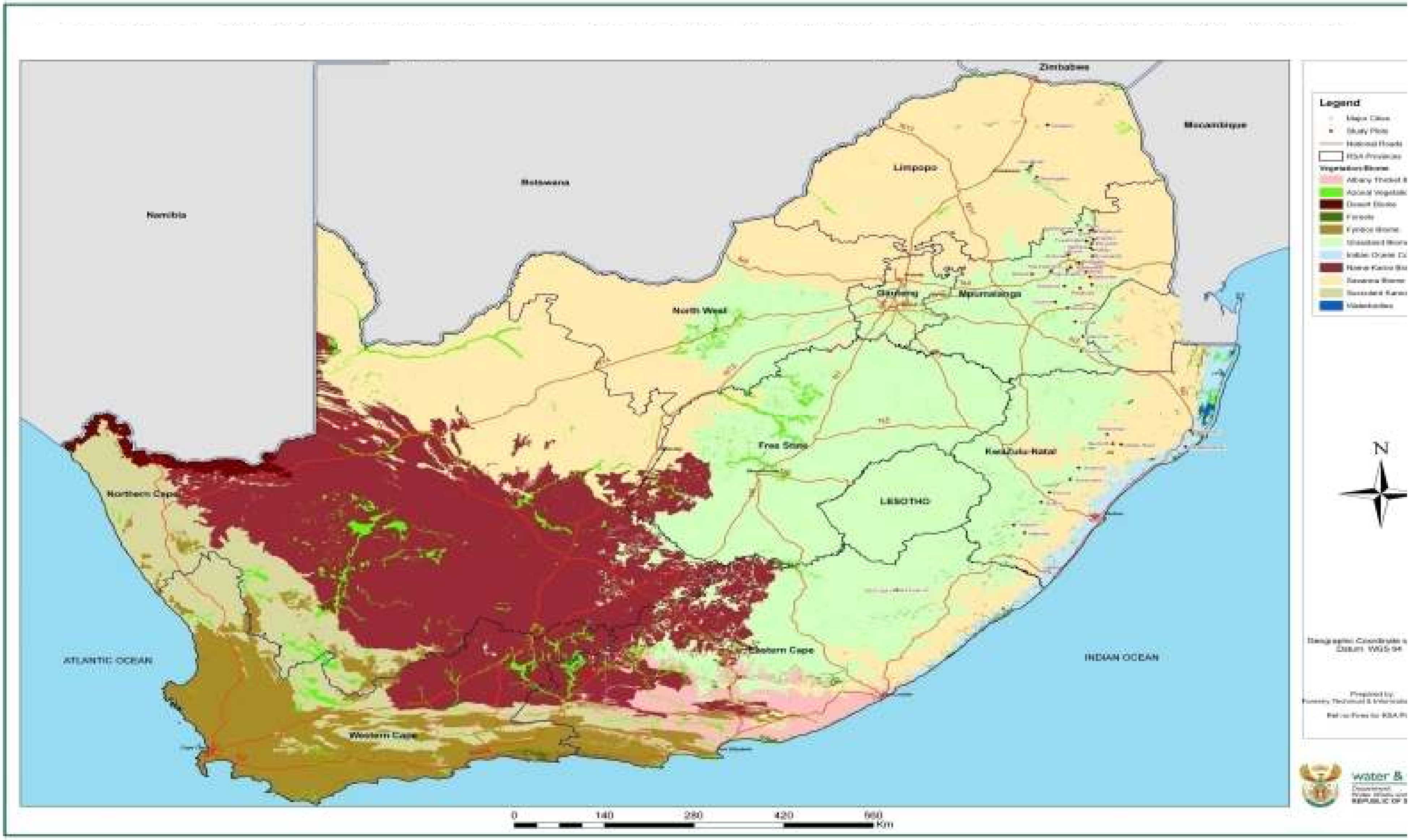

Figure 5: Geographical distribution of 301 selection stands from which 44 study stands were selected.

However, stands with unusually high or low stand densities were excluded. The acceptable range of stand densities was fixed at 1111 to 1400 trees per hectare, except in a few cases where stands represented a unique combination of site factors. Stands with trees older than 35 years were also excluded because, in South Africa, pine rotations are typically shorter than 35 years.

These criteria were intended to exclude stands that are not typical of regular commercial plantations of *Pinus elliottii*. This process trimmed the number of stands from 301 to 71. At least one stand from each district was selected to maximise the chance of sampling different climates and soils. In some districts, more than one stand was selected if substantial variations in growth or environmental gradient existed. The above process led to the selection of 44 stands.

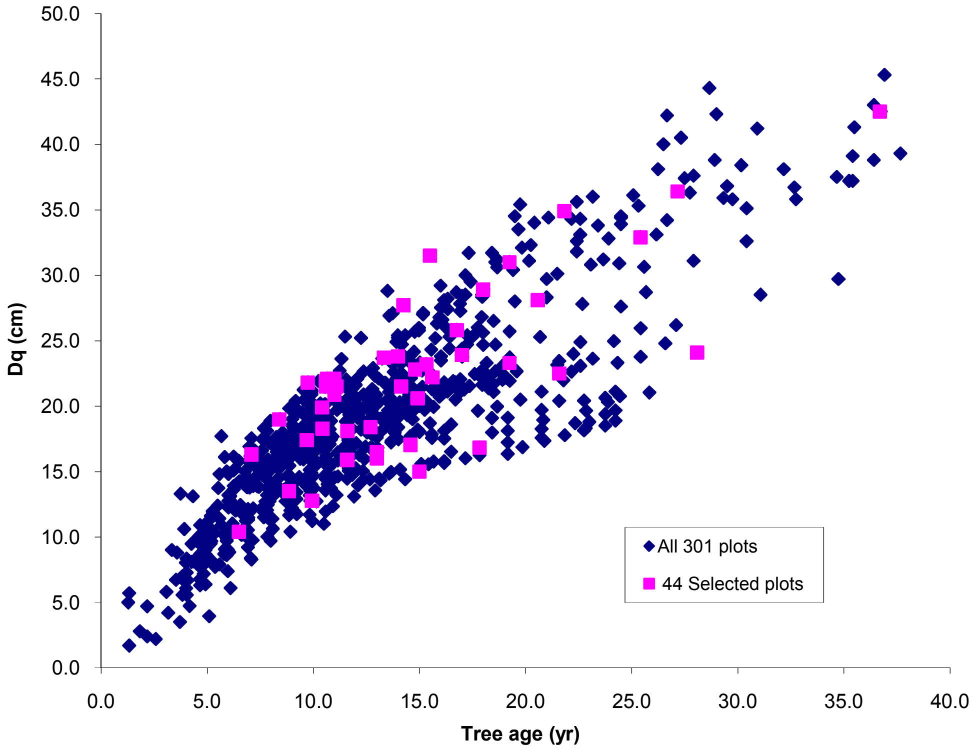

Figure 6: The relationship between quadratic diameter (cm) and tree age (years) for the final selection of 44 stands superimposed with the 301 original stands.

5.3 STAND INFORMATION AND FINAL SELECTION OF STANDS

Site and stand information was made available by various sources including the MMRC and the Bioresources Engineering and Environmental Hydrology (BEEH) group of the University of KwaZulu-Natal (UKZN). The information included soils and climatic data as shown in **Table 5**. In instances where weather and soil information were not available, or missing in the MMRC database, these were obtained from publications and through correspondence with relevant scientists. Once all the relevant data pertaining to each stand had been deemed to be correct and stage three had been completed, the parameterisation of the 3-PG model was initiated.

5.4 MODEL INITIALISATION DATA

5.4.1 Initial stem biomass

The 3-PG model requires initialisation data for biomass of stems and branches (Ws), foliage (Wf), and roots (Wr). Measured initial biomass data of stems and branches at age four were not available in any of the stands used in this study, and, as a result, had to be estimated from growth measurements later in the rotation. To obtain stem biomass (Ws), the volume and wood density of a tree has to be known. These are easy measurements to take, but for trees five years or younger, wood volume is small and is still seldom measured in the plantations.

In this study an effort was made to quantify Ws for very young trees (age < six years) by projecting the selected stand growth data backwards to age four years. As the first step in quantifying Ws, a site index model (Kassier and Kotze, 2000) was used to predict what the dominant tree height was at age four years for all selected stands. An initial age of four years was chosen since trees are well established at this age, with stable survival rates and canopies that are uniformly distributed.

Table 5: Location and major climatic and site variables for the selected stands of *P. elliottii* used in the study. (Refer to acronyms table for variables units. Soil categories are based on the South African Soil Classification, 1991; Dye, 2003)

Stand	Location	MAP	MAT	ALT	A-pan	Sol rad	Soil depth	Thinning	Long	Lat	Soil texture	Geology	Lithology	TAW	Fertility Rating
8	Babanango	876	16.2	1227	1735.9	255.2	726.1	unthinned	31.08389	28.42139	SaClLm	Pp	SHALE	136	0.6
11	Badplaas1	786	17.2	1163	1740.9	282.2	906.2	unthinned	30.48713	25.84091	SaCl	Vt	SHALE	110	0.3
27	Badplaas2	834	17.5	1158	1907.4	278.8	378.8	unthinned	30.70217	25.87489	SaLm	ZC	GNEISS	128	0.4
28	Barberton	886	18.8	902	1938.7	282.2	721.3	unthinned	30.84121	25.68177	SaClLm	Zka	GRANITE	111	0.5
12	Belfast	728	13.9	1852	1791.2	266.9	509.6	thinned	30.03010	25.63361	SaClLm	Pv	ECCA SANDSTONE	84	0.3
29	Bergvliet	1488	17.1	1408	1866.8	259.9	839.2	thinned	30.86322	25.10771	SaCl	Zne	GRANITE	111	0.5
13	Berlin	1407	17.1	1335	1879.9	268.4	849.7	thinned	30.78592	25.59733	SaCl	Zka	GRANITE	111	0.3
14	Blyde1	1502	15.9	1427	1871.5	271	711.3	thinned	30.84265	24.88527	SaClLm	Vbr	QUARTZITE	80	0.3
15	Blyde2	1933	16.2	1608	1847.3	254.1	711.3	thinned	30.87529	24.85961	SaClLm	Vw	SHALE	110	0.4
1	Boston	837	16.2	1278	1634.5	267	500.4	unthinned	30.15938	29.59131	ClLm	Pvo	SHALE	138	0.5
30	Brooklands	861	18.8	964	1931.3	276.7	897.2	thinned	30.87868	25.32800	SaClLm	Zne	GRANITE	111	0.5
16	Carolina	823	14.8	1612	1785.9	263.2	483.7	unthinned	30.35535	26.11721	SaClLm	ZC	GNEISS	128	0.3
42	Dukuduku	973	21.2	70	1706	NO DATA	300	thinned	32.2500	28.3500	Sa	O-S	BASAL CONGLOMARATE	187	0.8
39	Entabeni	1108	20.7	811	2126.4	286.8	763	thinned	30.25004	23.04698	SaClLm	Zgo	GNEISS	128	0.3
31	Franfort	1373	18.6	948	1882.4	272.9	859.1	thinned	30.89474	25.03477	SaCl	Vdi	DOLERITE	257	0.6
9	Golden Reef	866	17.7	821	1758.2	254.3	674.9	unthinned	31.27639	28.59167	SaClLm	ZB	GRANITE	309	0.5
2	Greytown	823	16.1	1235	1698.2	257.3	815	unthinned	30.68284	28.99920	SaClLm	Pv	ECCA SANDSTONE	84	0.5
3	Hlabeni	843	16.4	1212	1625.4	267.2	441.4	unthinned	29.77472	29.98889	ClLm	Jd	DOLERITE	165	0.6
4	Howick	1089	16.9	1042	1675.6	266.6	662	unthinned	30.2739	29.42235	ClLm	Pv	ECCA SANDSTONE	84	0.4
17	Jessievale	889	14	1738	1719.7	257	571.9	thinned	30.53097	26.21886	SaClLm	Rmp	QUARTZ MONZONITE	178	0.3
43	kwaMbonambi	1374	21	74	1706	NO DATA	300	unthinned	32.1830	28.6330	Sa	O-S	LIGNITE	187	0.8
18	Lothair	891	14.9	1599	1716	265.3	534.9	unthinned	30.63358	26.45564	SaClLm	Pv	ECCA SANDSTONE	84	0.3
19	Machadodorp	761	14.9	1682	1821.7	257.3	559.3	Thinned	30.29572	25.57806	SaClLm	Vsi	SHALE	110	0.3
5	Mahehle	853	16.5	1098	1594	262.9	786.8	unthinned	29.92500	30.12194	ClLm	Pvo	SHALE	160	0.5
6	Melmoth	764	18.3	875	1782.3	268.2	446.5	unthinned	31.16474	28.57960	SaClLm	ZB	GRANITE	309	0.5
20	Morgenzon	778	16.4	1573	1854.4	254.8	339	Thinned	30.70644	24.87857	SaClLm	Vt	SHALE	110	0.4
44	NEC plot 11	747	15.3	1307	1410	NO DATA	1800	unthinned	28"13'14	31"10'48	SaClLm	Pv	MUDSTONE	136	0.4
40	NEC plot 15	760	14.9	1337	1410	NO DATA	1800	unthinned	28"13'34	31"11'17	SaClLm	Pv	MUDSTONE	136	0.4
41	NEC plot 18	763	14.8	1349	1410	NO DATA	1800	unthinned	28"13'25	31"11'12	SaClLm	Pv	FELDSPATIC SANDSTONE	136	0.4
21	Nelshoogte	1048	14.1	1766	1919.7	282.3	721.3	unthinned	30.87047	25.81175	SaClLm	Zo	LAVA	NO DATA	0.4
32	NewAgatha	1171	18.7	1102	2032.3	281.6	1023.4	thinned	30.09717	23.94008	SaCl	VA	GRANITE	111	0.5
22	Ngodwana1	893	17.4	1197	1938.2	281.3	554	unthinned	30.52219	25.56974	SaClLm	Vt	SHALE	110	0.3
23	Ngodwana2	1025	17.1	1177	1916.5	259.6	449.2	unthinned	30.57018	25.52108	SaClLm	Vt	SHALE	110	0.4
10	Piet Retief	869	17.2	1230	1888.2	291.1	599.9	unthinned	30.71460	26.96282	SaClLm	Z-R	ULTRAMAFIC ROCKS	NO DATA	0.3
24	Roburnia	878	17.9	1166	1912.6	289.4	471.8	thinned	30.74150	26.71203	SaClLm	Zns	BASALT	128	0.4
7	Sevenoaks	835	16.8	1003	1686.5	261.4	747.9	unthinned	30.56299	29.19939	SaClLm	Pp	SHALE	136	0.6
33	Spitskop	1485	16.3	1490	1893.4	264.5	839.2	thinned	30.84542	25.17970	SaCl	Zne	GRANITE	111	0.5
25	Sudwala1	1011	15.4	1712	1895.7	254.8	611.3	unthinned	30.53551	25.30671	Cl	Vhd	ARENITE	136	0.6
34	Sudwala2	952	18.4	922	1924	276.1	433.9	unthinned	30.68371	25.43714	SaClLm	Vm	DOLOMITE	240	0.6
35	Tweefontien	1214	17.7	1118	1914.1	275.9	832.1	thinned	30.79441	25.06619	Cl	Vm	DOLOMITE	240	0.6
26	Uitsoek	802	17	1522	1945.7	279.1	839.2	unthinned	30.54199	25.29696	SaCl	Vt	SHALE	110	0.4
36	Wilgeboom	1152	18.7	899	1890	274.7	819.9	thinned	30.91632	24.89854	Cl	ZB	GRANITE	309	0.5
37	Witklip	1110	17.8	1064	1876.2	274.5	1016.1	thinned	30.88278	25.20793	SaClLm	Zne	GRANITE	111	0.5
38	Woodbush	1014	17.4	1568	2022	272.5	947.8	thinned	30.00745	23.75699	SaClLm	R-Vt	GRANITE	111	0.4
MINIMUM		**728**	**13.9**	**70**	**1594**	**244.1**	**271.8**								
MUXIMUM		**1933**	**21.2**	**1852**	**2126**	**291.1**	**1800**								

Tree height rather than DBH was used to estimate biomass at age four years. This was due to the fact that thinning events affect DBH to a far greater degree than height does and this is mainly attributed to competition (Pienaar *et al*, 1985). This competition determines which trees accumulate the most resources, which in turn are attributed to several intrinsic factors like the genetic fitness of the individual tree. The dominant height was estimated by using a Chapman and Richards's growth function (Puumalainen and Kotze, 1995):

$$HD_1 = HD_2 / \{[1\text{-exp} (ß_1{*}A_2)]/ [1\text{-exp} (ß_1{*}A_1]\} \wedge ß_2, \quad (1)$$

Where:

HD_1 = dominant height (m) at starting age (four years)

HD_2 = measured dominant height (m) at end age (years)

$ß_1$ = coefficient 1 (-0, 03251)

$ß_2$ = coefficient 2 (0, 99629)

A_1 = end age (years)

A_2 = starting age (four years)

The coefficients in **equation 1** above ($ß_1$ and $ß_2$) are generally suitable for all South African *Pinus elliottii* stands (Puumalainen and Kotze, 1995; Dye, 2003). Dominant heights at age four years were used to divide all 44 stands into three size classes. High, medium and low classes were assigned initial diameters and heights corresponding to the three site quality classes described in yield tables for this species (Kassier and Kotze, 2000). The mean heights and diameters were used to calculate mean volumes in each stand using the Schumacher and Hall model (Bredenkamp, 2000). This equation can be written as:

$$\ln V = b_0 + b_1 \ln (DBH + f) + b_2 \ln H \quad (2)$$

Where:

ln = natural logarithm to the base e

V = stem volume (m^3, under-bark), usually to 75 mm tip diameter

DBH = breast height diameter (cm, over-bark)

f = correction factor

H = tree height (m)

A calculated mean wood density of 378 kg.m^{-3} (A Zbonak, 2004, pers.comm[2]) for *Pinus elliottii* was used to convert the stem volume to stem dry mass. Finally, a relationship (R^2 = 0,9916) reported by Morris (1992) for *Pinus patula* in Swaziland was used to estimate the mass of branches and bark from stem DBH. This relationship is shown in **Figure 7**. The Ws were then estimated as the sum of branch, bark mass and stem mass. Suitable allometric data for *Pinus elliottii* could not be found in the literature.

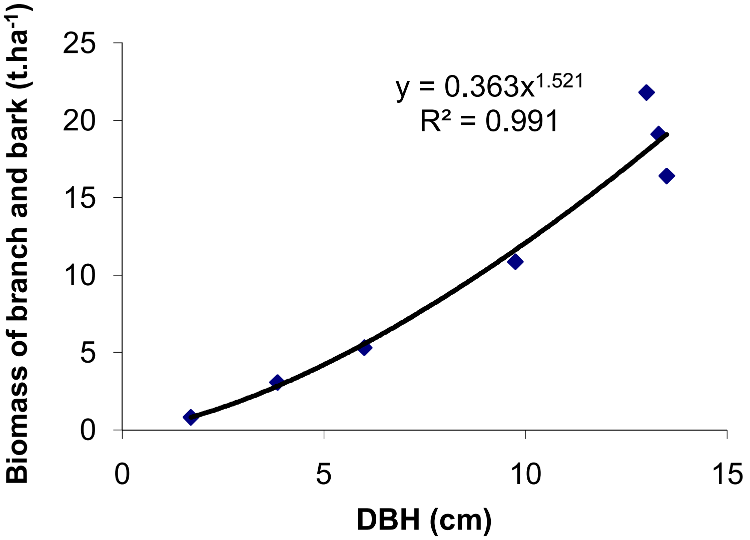

Figure 7: The relationship between DBH (cm) and the mass (t.ha^{-1}) of branches and bark for *Pinus patula* (Morris, 1992).

5.4.2 Initial foliage biomass

The value for Wf was estimated from mean DBH using the two equations given by Myers (1984) for *Pinus elliottii* that predict wood, bark and foliage. The difference in the two biomass-estimating equations was used to compute values of Wf. These relationships can be expressed as:

$$\text{Log } W_1 = -0.88096 + 1.03014 * \text{Log } (H*DBH^2), \qquad (3)$$

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[2] Dr Anton Zbonak, Council For Scientific And Industrial Research, Durban 4001, South Africa

$\text{Log } W_2 = -0.93767 + 1.03929 * \text{Log } (H*DBH^2)$, (4)

Where:

W_1 = dry mass of wood, bark, and foliage only ($t.ha^{-1}$),

W_2 = dry mass of wood and bark only ($t.ha^{-1}$),

Log = the logarithm to the base 10,

DBH (over-bark) = breast height diameter (cm),

H (m) = the total tree height.

Therefore:

$W_1 – W_2 = Wf$, where Wf is the dry mass of foliage.

5.4.3 Initial root biomass

No root data were available specific to *Pinus elliottii,* and therefore initial root biomass (Wr) at age four years was estimated as a fixed fraction of aboveground biomass as reported in Morris (1992) for *Pinus patula*. Morris (1992) found a close relationship (R^2 = 0,976; n=5) between root mass (>2 mm), DBH, and height:

$\text{Root Mass} = 2{,}75 + 0{,}00155 \, (DBH^2 * \text{Height})$, (5)

This relationship was used to estimate Wr at age four years for all the stands in this study. The 3-PG model assumes that the tree roots completely occupy the soil, and that differences in root mass do not influence the rate of soil water uptake.

5.4.4 Fertility rating

This is the most difficult site factor to assign a specific value. The basis for estimating fertility rating (FR) in this study was described using baseline fertility ratings proposed by Dr B. Du Toit (2004, pers. comm[3]). This method is based on organic matter content (OC) together with the soil type or form as the best estimate of soil fertility.

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[3] Ben Du Toit, Institute for Commercial Forestry Research, P.O. Box 100281, Scottsville 3209, South Africa

Fertility rating was estimated for each stand using organic matter content and altitude as shown in **Table 6** below. The rating (in bold) generally changes by one unit per organic matter content class, and by two units per altitude class (with the exception of the sites with extremely low levels of OC in the coastal sands).

Table 6: Baseline fertility ratings proposed for various land and soil types.

Altitude class	**Organic matter content class**			
	Extremely low (0.3%)	Low (0.4-0.9%)	Medium (1-3%)	High (> 3%)
Highveld (>1300 m)	**-**	**-**	**0.3**	**0.4**
Midlands (400-1300 m)	**-**	**-**	**0.5**	**0.6**
Coastal Zululand (<400 m)	**0.2**	**0.6**	**0.7**	**0.8**

5.4.5 Weather and soil data

Information was sourced from the MMRC database and included latitude, soil texture class, thinning details and year and month planted for all the stands. The School of Bioresources Engineering and Environmental Hydrology of the University of KwaZulu-Natal provided a database comprising both daily rainfall and maximum and minimum temperatures for use in this study. This database contained more than 100 rainfall and temperature recording stations in the forestry regions of South Africa. The closest recording stations to each selected stand were examined and one chosen that best matched the stand site (**Appendix 3**). This was decided primarily on the basis of altitude and coordinate similarity between meteorological stations and where the sample stand was located. Mean monthly vapour pressure deficits (VPD) were calculated using the following relationship (Dye *et al.,* 2001):

$$\text{VPD } (e_s - e_a) = (e_s\,(T_{max}) - e_s\,(T_{min}))/\,2 \qquad (6)$$

Where:

e_s = saturated vapour pressure (kPa)

e_a = actual vapour pressure (kPa)

T_{max} = maximum daily temperature (^{0}C)

T_{min} = minimum daily temperature (^{0}C)

Solar radiation (ϕ_s, MJ^{-2}) was likewise estimated from the monthly temperature data using the Bristow-Campbell (Bristow and Campbell, 1984) equation to estimate daily total atmospheric transmittance (T_t) of solar radiation:

$$T_t = A\ (1\text{-}\exp\ (\text{-}B^*\Delta T^C)) \qquad (7)$$

where ΔT is the daily range of air temperature, and A, B and C are empirical coefficients determined for a particular location from measured solar radiation data. These were assigned values of A = 0.7, B = 0.004, and C = 2.4, based on recommendations by Bristow and Campbell (1984), and from best fits to observed solar radiation data at Seven Oaks in the KwaZulu-Natal midlands (P Dye, 2004, pers. comm[4]).

The empirical coefficient A represents the maximum cloudless sky T_t characteristic of stand areas. It varies with altitude and pollution content of the air. B and C determine how soon maximum atmospheric transmittance (T_t) is achieved as ΔT increases. They demonstrate the partitioning of energy, which is characteristic of the region's arid or humid nature.

Some soils information was available in the MMRC database. However, estimates of soil depth, predominant texture and maximum available soil water capacity were taken from a new site classification scheme (C Smith, 2004, pers comm[5]) being developed by the Institute for Commercial Forestry Research (ICFR).

Initial soil water was arbitrarily assumed to be half of maximum water storage capacity. While the MMRC soils data may be more accurate of conditions at the sample stands, it was decided that the generalised information in **Table 5** (p. 25) should be used, since many future 3-PG modellers of *Pinus elliottii* will be relying on such freely available data.

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[4] Dr Peter Dye, Council for Scientific and Industrial Research, Private Bag X01, Scottsville 3209, South Africa

[5] Dr C. Smith, Institute for Commercial Forestry Research, P.O. Box 100281, Scottsville 3209, South Africa

5.4.6 Initial trees per hectare

The initial number of trees per hectare at time of planting (TPH0) in each stand was provided by the MMRC, as well as at the time of the later forest mensuration (TPH1). TPH at age four years (TPH00) was interpolated based on TPH for both ages. However, all predictions commenced at age four years, by which time most of the early mortality associated with tree establishment had already occurred.

The fractional decline in TPH due to natural mortality was estimated by calculating the TPH1/TPH0 fraction for all stands, which varied widely from 0.77 to 1. Most stands (>90%) produced a ratio centred on the mean that was calculated to be 0.90. It was therefore assumed, that in each stand, the trees per hectare at age four years was equal to the value determined by the TPH1/TPH0 fraction multiplied by 0.90.

5.4.7 Thinning regimes

The MMRC database identified which stands had been thinned. Where earlier thinnings were not shown, it was assumed that thinning took place at the standard rotation intervals shown by Kassier and Kotze (2000) for South African *Pinus elliottii* plantations.

5.5 ESTIMATION OF *PINUS ELLIOTTII* PARAMETERS

Sands (2002) comments on the process of assigning parameter values, and advises that as a general rule parameter values should always be assigned by direct measurement, either directly from available data, or indirectly, e.g. by regression analysis of experimental data or by correlation with other species (default).

Only when such data are unavailable should parameters be estimated by adjusting their values to optimise the fit of the 3-PG model output to observed data. The following section indicates how parameter values were estimated in this study and reference should be made to Landsberg and Waring (1997) for details on the principle parameter algorithms.

5.5.1 Foliage to stem ratios

Foliage to stem ratios (P_{FS}) describe the allocation of biomass to foliage and stem when the tree DBH is 2cm **(**p_2) and when it is 20cm (p_{20}). A study by Johnson (1990) on *Pinus elliottii* seedlings provided an acceptable estimation of the p_2 values for initial use in this study. He reported foliage to stem values of 0.92; 0.92; 0.97; and 0.93 for control; irrigated; fertilised and irrigated + fertilised treatments respectively. These were averaged to 0.93, which was the value initially used for the predictions. The foliage: stem partitioning at DBH = 20cm was assigned a value of 0.2, which was adopted from the value used by Dye (2001) for *Pinus patula*.

5.5.2 Allometric relationship of stem mass against diameter

The stem mass against diameter allometric relationship for a single tree is approximately estimated using **Equation 9** presented in Landsberg and Waring (1997, p.217-218). Parameter values for this relationship that are considered generic for most pine species are presented in Landsberg and Waring (1997, p.218). Since no specific values existed for *Pinus elliottii,* these generic values ($a_s = 0.04$; $n_s = 2.65$) were also used as defaults for this study.

5.5.3 Net primary production fractions allocated to roots

Johnson (1990) reported on the effect of fertigation on dry matter partitioning in young *Pinus elliottii*. Johnson (1990) found a relatively constant biomass allocation in one-year-old seedlings, with the stem accounting for about 51%, foliage 35% and roots getting 14% of NPP. Only fertilisation seemed to have shifted the proportion of dry-matter allocation to roots to 25%, which is contradictory to the general trend reported in other reports (Santantonio, 1989; Landsberg and Waring, 1997) that a greater fraction of biomass is allocated to roots if the nutritional status of the soil is low. Such inconsistencies were also evident in an honours study (Zola Sithole, Forestry Programme, University of Natal, 2002) by the author of this dissertation on the effect of site preparation on root growth of 11-year-old *Eucalyptus grandis.*

There was inconsistency in root biomass for all nutritional treatments. In the absence of definitive information on belowground allocations, the default value for the NPP fraction (maximum and minimum) that applies to roots was assumed to conform to other studies reported in the literature (Waring and Landsberg, 1997, p.219). The default values used for *Pinus elliottii* were taken to be 0.8 and 0.25; these values were originally used for *Eucalyptus globulus* (Sands and Landsberg, 2002) and for *Pinus patula* predictions by Dye (2001).

5.5.4 Cardinal temperature

The 3-PG model requires that the minimum, maximum and optimum monthly temperature for photosynthesis be specified. Schonau and Schulze (1984) conducted a South African study in which they used altitude for delineating areas of optimum growth for various *Pinus* species including *Pinus elliottii*. They defined a mean annual temperature of 14 ^{0}C for *Pinus elliottii* growth, 27 ^{0}C as the January mean temperature and 10^{0}C as the July mean temperature as the requirements for *Pinus elliottii* plantations. However, these do not necessarly describe the cardinal temperatures as required by the model. As a result, minimum, optimum, and maximum temperature values were taken as equivalents to 3, 23 and 35 ^{0}C respectively as adopted by Dye (2001) for *Pinus patula.*

5.5.5 Litterfall

The 3-PG model requires three parameter values regulating litterfall (LF). These are maximum litterfall rate; litterfall rate for young stands; and the litterfall rate midway between maximum litterfall rate and litterfall rate for young stands. Although parameter values for the above may be obtained from field data, it was not possible to do this in this study. Instead, estimates of these values were obtained from the literature. Jokela and Martin (2000) reported that needles constituted more than 90% of the annual pine litterfall, and they regarded litter to be entirely made up of needles. These authors found that treated (fertilised and weed control) *Pinus elliottii* stands had an annual mean litterfall rate that increased from about 4.25 Mg.ha^{-1}.year^{-1} at age six years to a steady state of 6.0 Mg.ha^{-1}.year^{-1} at ages 8-14 years.

In other slash pine plantations, the maximum annual litterfall production was 5.04 $Mg.ha^{-1}.year^{-1}$ for 22-year-old stands (Morris, 1992); 4.51 $Mg.ha^{-1}.year^{-1}$ for 21-year-old stands (Gholz *et al*., 1991); and 4.70 $Mg.ha^{-1}.year^{-1}$ for six-year-old stands with fertiliser and herbicide treatments (Dalla-Tea and Jokela, 1991). Cragg (1964), in a review of litter production by forests of the world, reported a total litterfall of 4.60 $Mg.ha^{-1}.year^{-1}$ for 10-year-old *Pinus taeda*. An average litterfall rate of 4.84 $Mg.ha^{-1}.year^{-1}$ was used in this study. The litterfall rates were converted to an average litterfall rate per month of 0.037 $Mg.ha^{-1}.month^{-1}$ using the following formula:

$$\gamma_F = (0.1\sigma/12L)\ \Delta_T WF_L) \qquad (8)$$

Where:

σ ($m^2.kg^{-1}$) is the specific leaf area of 3.1 and 0.1 is the conversion factor as recommended by Sands (2002), $\Delta_T WF_L$ is the average 4.84 $Mg.ha^{-1}.year^{-1}$ of all reported total annual litterfall values for *Pinus elliottii*, and L = 3.33 $m^2.m^{-2}$ was used in this formula (Raison *et al*., 1992; Dye, 2001; Sands and Landsberg, 2002).

5.5.6 Average monthly root turnover rate

Gower *et al*., (1994), reported that tropical/subtropical closed-canopy forests can acquire a mean belowground biomass of 2.81 $kg.m^{-2}$ with a maximum NPP of 0.22 $kg.m^{-2}.year^{-1}$ allocated to belowground. However, this is not a reliable estimate since the sample size used was small (n=1) and excluded roots greater than 5 mm in diameter. In other studies Gholz *et al.,* (1986) reported fine root production of seven-year-old *Pinus elliottii* and understory as 0.04 $kg.m^{-2}.year^{-1}$ and 0.32 $kg.m^{-2}.year^{-1}$, respectively, while for 27-year-old trees, a value of 0.19 $kg.m^{-2}.year^{-1}$ was reported. Gower *et al*., (1994) also reported fine root production for warm temperate evergreen needle-leaf forests to be 0.9 $kg.m^{-2}.year^{-1}$ or 0.075 $kg.m^{-2}.month^{-1}$. In view of the lack of data pertaining to root turnover rates in South Africa, 0.075 $kg.m^{-2}.month^{-1}$ was adopted in this study.

5.5.7 Canopy conductance

Ford *et al*., (1978) reported a canopy conductance (g_c) range of 0.01 to 0.03 $m.s^{-1}$ for *Pinus spp*. In this study the canopy conductance of 0.018 $m.s^{-1}$ (Landsberg and Gower, 1997) and boundary conductance of 0.3 $m.s^{-1}$ (Ford *et al*., 1978) was used in initial predictions for all stands. Furthermore, the model requires *L* for maximum stomatal conductance, which Kelliher *et al*., (1995) reported as 3.33 $m^2.m^{-2}$.

5.5.8 Specific needle (leaf) area of *Pinus elliottii*

A mean specific needle area (σ, all-sided) of 9.6 $m^2.kg^{-1}$ or 1/π of this value (3.1 $m^2.kg^{-1}$) for projected leaf area in two-year-old needles for *Pinus radiata* is reported in Raison *et al.,* (1992); Dalla-Tea and Jokela (1991), while Jokela and Martin (2000) reported an all-sided value of 10 $m^2.kg^{-1}$ (one-sided = 3.2 $m^2.kg^{-1}$) for *Pinus elliottii*. An average value of 3.15 $m^2.kg^{-1}$ was used as default for σ in this study.

5.5.9 Extinction coefficient for absorption of PAR by the canopy

The extinction coefficient (*k*) is usually defined as the logarithm of mean canopy transmittance of light divided by the canopy leaf area index (*L*). It is a good measure of the decrease in irradiance or alternatively can be taken as the rate of light interception per unit of leaf area. A *k* value range of 0.17-0.35 has been reported for *Pinus elliottii* (Steinberg *et al*., 1994; Delucia *et al*., 2002). These values are low in comparison with those reported by Jarvis and Leverenz (1983), and Cropper and Gholz (1993), which are 0.62 and 0.468 respectively for *Pinus elliottii*. A value of 0.5 proved to produce a good fit for *Pinus patula* (Dye, 2001) and was also used in this study.

5.5.10 Proportion of rainfall lost as interception

Canopy rainfall interception is the process by which incoming precipitation (P) is captured before reaching the earth's surface and stored to be eventually lost via evaporation back to the atmosphere. In 3-PG, rainfall interception is the quantity of water which never reaches the soil. The 3-PG model requires the proportion of precipitation (rainfall over most parts of South Africa) that is lost through this process. Ward and Robinson (2000) reported that canopies of conifers intercept about 30-35% of gross precipitation, while Dye and Versfeld (1992) in a study conducted in South Africa, reported a net interception loss (P minus through fall and stemflow) of 13% of gross precipitation for *Pinus patula*. The former estimate is less valid for South African conditions, and reflects typical northern hemisphere temperate forest values where rain and snow are frequent. The latter estimate is more suitable for South African plantations since here the rainfall frequency is lower than in the northern temperate forests. This proportion of 13% was assumed to hold for all predictions and it was adopted in this study.

5.5.11 Leaf area index for maximum rainfall interception

Various authors report on the *L* of this species, mainly for Australian and U.S. plantations. Vose *et al*., (1994), Dalla-Tea and Jokela (1991), Leverenz and Hinckley (1990) reported all-sided leaf area indices of 5.3-6.0 $m^2.m^{-2}$ (19-21-year-old trees); 0.9-1.5 $m^2.m^{-2}$; 1.5-7.2 $m^2.m^{-2}$ (six-year old trees) for *Pinus elliottii*, and 3.5-20 $m^2.m^{-2}$ for other different conifers. Gholz and Fisher (1982) in Vose *et al.,* (1994) reported a maximum *L* of 8 $m^2.m^{-2}$ for 10-12-year-old *Pinus elliottii* stands in Florida, while P. Dye (2004, pers. comm. recommended a maximum *L* of 4 $m^2.m^{-2}$ for South African pine plantations. Evidently *L* varies significantly in response to such environmental conditions as nutrition, temperature, water, light, and air pollution. This variation is confirmed by the above reported *L* values, which during the growing season may be as high as 72% (of the lowest recorded *L* values) for *Pinus elliottii*. In this study, *L* of 4 $m^2.m^{-2}$ was adopted to initialise the model.

5.5.12 Canopy quantum efficiency

The canopy quantum efficiency (% PAR actually utilised by trees) was initially taken as 0.0111 $molC.mol^{-1}$ PAR, a value reported by Cropper (2000) for *Pinus elliottii*. However, this value is small in comparison with that of 0.05 $molC.mol^{-1}$ PAR reported by Dye (2001) for *Pinus patula.* This value, which is 0.05 molC.mol-

1 PAR, was then used as a default. This value is recommended by Landsberg and Gower (1997) for most forests.

5.5.13 Basic density of wood

The age-related wood density was measured as the individual growth ring density (GRD) as shown in **Appendix 4**. A density range of 350-450 kg.m^{-3} was measured for seven different *Pinus elliottii* trees of ages one to seven years. This density range agreed with the densities of *Pinus elliottii* stands published in Pallett (2000). **Appendix 4** also shows the trends in wood density measurements as determined in this study. Notably, in almost all measured *Pinus elliottii* trees, the densities of the first two to three growth rings closest to pith were higher than in younger rings. This was attributed to a higher concentration of extractives in these growth rings. Extractives were not removed prior to density measurement, thus this trend is expected (A Zbonak, 2004, pers. comm.). The wood basic density was taken as an average density of seven 11-year old *Pinus elliottii* trees; and determined to be 378 kg.m^{-3} (0.378 t.m^{-3}).

5.5.14 Stem mortality

The 3-PG model automatically determines natural stem mortality through a mortality function using the procedure diagrammatically illustrated in Landsberg and Waring (1997, p.216). Default self-thinning parameter values adopted in Dye (2001) were used in initialising the 3-PG model. Model results were judged not to be sensitive to this function, because in South African plantations, tree density is generally not allowed to reach a point where self-thinning becomes significant.

5.5.15 Other parameters

Unless otherwise stated, the remainder of the species parameters required by the 3-PG model (**see Table 7**) were adopted from Dye (2001) or through initial fitting the model.

5.6 PARAMETERISATION PROCESS ASSUMPTIONS

It was assumed that:

- no additional soil water input into the rooting zone occurred from upslope or from water tables, and that trees were wholly reliant on rainfall for their water requirements. This is sometimes not the case;
- no solar radiation adjustment was needed for slope or aspect;
- solar radiation was estimated from monthly temperature extremes, and not from daily maximum and minimum temperature;
- no information on pruning, or on defoliation by insects, was available, and so such events were not taken into account;
- in the older saw-timber stands, early thinning information was sometimes unavailable, and had to be estimated from standard thinning schedules and,
- variations in diameter-height ratios due to applicable factors, e.g. altitude, were not taken into account.

5.7 PARAMETERISATION PROCEDURE

The values adopted as initial parameters are shown in **Table 7.** As many forestry researchers have reported, the goal of model parameterisation is to develop a reliable set of parameter values that provide good fits between simulated and observed outputs. Using the Excel 3PGpjs v.2.4 version of 3-PG, details of each stand were entered on a separate “single-site” worksheet. These data included initialisation data **(Appendix 5)**, site and stand factors, and silvicultural events (**Table 5,** p.25**)** while estimates of FR were based on **Table 6** (p.29). Each stand worksheet contained a table of observed stand data, generally the stand age, mean DBH, mean height and trees per hectare. The 3-PG model was run sequentially for all stands using a Microsoft Excel based version of the model (**Appendix 6**). The parameter estimation procedure that followed was similar to that used by Sands and Landsberg (2002). Several parameters governing allometric relationships and growth partitioning were varied manually to optimise their values to produce the best fit to observed mean diameter, mean height and stand volume. It must be noted that in this study Dq, Hq and TPH were the only available mensuration data in most stands, and, as a result, were used as the main calibration variables.

Table 7: Provisional parameter set adopted to initialise 3-PG growth simulations for *Pinus elliottii*.

3-PG Parameter	**Site or species specific**	**Default, fitted or observed**	**Value**	**Reference**
Allometric relationships and partitioning				
Ratio of foliage: stem partitioning at D = 2cm	Species	Observed	0.93	Johnson (1990)
Ratio of foliage: stem partitioning at D = 20cm	Species	Default	0.2	Dye (2001)
Constant in stem mass v diam. Relationship	Species	Default	0.04	Landsberg and Waring (1997)
Power in stem mass v diam. Relationship	Species	Default	2.65	Landsberg and Waring (1997)
Maximum fraction of NPP to roots	Species	Default	0.8	Sands and Landsberg (2002)
Minimum fraction of NPP to roots	Species	Default	0.25	Sands and Landsberg (2002)
Temperature modifier				
Minimum temperature for growth	Species	Default	3 ^{O}C	Dye (2001)
Optimum temperature for growth	Species	Default	23 ^{O}C	Dye (2001)
Maximum temperature for growth	Species	Default	35 ^{O}C	Dye (2001)
Soil water modifier				
Moisture ratio deficit which gives fq = 0.5	Site	Default	0.5	Landsberg and Waring (1997)
Power of moisture ratio deficit in fq	Site	Default	5	Landsberg and Waring (1997)
Age modifier				
Maximum stand age used to computer relative age	Species	Default	80 years	Landsberg and Waring (1997)
Power of relative age in fage	Species	Default	4	Landsberg and Waring (1997)
Relative age to give fage = 0.5	Species	Default	0.95	Landsberg and Waring (1997)
Litterfall and root turnover				
Maximum litterfall rate	Both	Observed	0.037 1 month^{-1}	Cragg (1964)
Litterfall rate at t = 0	Both	Default	0.0011 month^{-1}	Dye (2001)
Age at which litterfall rate has median value	Both	Default	24 month	Dye (2001)
Average monthly root turnover rate	Both	Default	0.021 month^{-1}	Gower *et al.*,(1994); Dye (2001)
Conductance				
Maximum canopy conductance	Species	Observed	0.018 m.s^{-1}	Landsberg and Gower (1997)
L for maximum stomatal conductance	Species	Observed	3.33	Kelliher (1995
Defines stomatal response to VPD	Species	Default	0.05 1/mBar	Dye (2001)
Canopy boundary layer conductance	Both	Observed	0.3 m.s^{-1}	Ford *et al.*,(1978)

3-PG Parameter	**Site or species specific**	**Default, fitted or observed**	**Value**	**Reference**
Fertility effects				
Value of m when FR = 0	Species	Default	0	Dye (2001)
Value of Fn when FR = 0	Species	Default	1	Dye (2001)
Power of (1-FR) in Fn	Species	Default	0	Dye (2001)
Stem mortality				
Maximum stem mass per tree at 1000 trees/ha	Both	Default	300 kg.tree^{-1}	Sands and Landsberg (2002)
Power in self thinning law	Both	Fitted	1.5	This study
Fraction of mean foliage biomass per tree on dying trees	Both	Fitted	0	This study
Fraction of mean root biomass per tree on dying trees	Both	Fitted	0.2	This study
Fraction of mean stem biomass per tree on dying trees	Both	Fitted	0.2	This study
Canopy structure and processes				
Specific leaf area at stand age 0	Species	Default	5 m^2 kg^{-1}	Dye (2001)
Specific leaf area for mature aged stands	Species	Observed	3.2 m^2 kg^{-1}	Dalla-Tea and Jokela (1991); Raison *et al.*,(1992); Jokela and Martin (2000)
Age at which specific leaf area = ½(s0+s1)	Species	Default	2.5 years	Dye (2001)
Extinction coefficient for absorption of PAR by canopy	Species	Observed	0.5	Stenberg *et al.*,(1994); DeLucia *et al.*, (2002); Dye (2001)
Age at full canopy cover	Species	Default	0 years	Dye (2001)
Maximum proportion of rainfall intercepted by canopy	Species	Observed	0.13	Dye and Versfeld (1992)
L for maximum rainfall interception	Species	Default	6	Gholz and Fisher (1982); Dye (2001)
Canopy quantum efficiency	Species	Observed	0.0111 molC.molPAR^{-1}	Cropper (1999)
Ratio NPP/GPP	None	Default	0.47	Dye (2001)
Branch and bark fraction				
Branch and bark fraction at stand age 0	Species	Default	0.75	Dye (2001)
Branch and bark fraction for mature aged stands	Species	Default	0.19	Dye (2001)
Age at which branch and bark fraction = ½(pBB0+ pBB1)	Species	Default	7 years	Dye (2001)
Basic density				
Maximum basic density – for older trees	Both	Observed	0.378 t.m^{-3}	This study
Ratio of basic density for young trees/density of old trees	Both	Default	0.4 t.m^{-3}	Sands and Landsberg (2002)
Age at which r = ½ density of old and young trees	Both	Default	7 years	Dye (2001)
Conversion factors				
Intercept of net radiation v solar radiation relationship	Species	Fitted	-90 W.m^{-2}	This study

3-PG Parameter	**Site or species specific**	**Default, fitted or observed**	**Value**	**Reference**
Slope of net radiation v solar radiation relationship	Both	Fitted	0.8	This study
Molecular weight of dry matter	Species	Fitted	24 gDMmol^{-1}	This study
Conversion of solar radiation to PAR	Both	Fitted	2.3 molMJ^{-1}	This study

6. EVALUATION OF 3-PG PREDICTIONS

The estimation of parameters was done manually (no automation selection of parameters was used). The predicted data of stands were produced by using a common set of parameters adjusted to improve the fit. All runs commenced from age four years, and terminated after the last growing year recorded for that particular stand. The 3-PG model predictions of mean DBH, height and tree density were compared to the last mensuration data recorded in each stand.

6.1 STATISTICAL ANALYSIS

For each set of predicted and observed values calculated, the following statistics in Stape (2004) was obtained to evaluate the model performance: model efficiency (EF), root mean square error (RMSE) the slope (*a)* and intercept (*b)* coefficients of the linear relation between predicted (*P*) and observed (*O*) values, and the coefficient of determination (R^2). It is recommended that the best model should have EF and R^2 close to the unity (one), RMSE close to zero (relative to the mean values of O and P values), and *a* and *b* not significantly different from 0 and 1, respectively (Stape, 2004). However R^2 which denotes the proportion of variance between observed and modelled values was used as the main indicator of best fit.

6.2 RESULTS

6.2.1 Parameterisation of 3-PG for *Pinus elliottii* growth

The final parameter set producing best fit of modelled outputs to observed values were produced by 3-PG after several fitting exercise. This information of 32 stands is shown in **Table 8**. It must be noted that the model was started at age four years and run until the age corresponding to the time of the last mensuration . The results were then analysed and **Table 9** summarises the overall statistical relationships of the modelled variables for 32 stands.

Table 8: An overall comparison of observed (O) and predicted (P) mean DBH (cm), stand volume ($m^3.ha^{-1}$), mean height (m) and tree per hectare ($tree.ha^{-1}$) for 32 study stands.

Location	Age of stand	O DBH	P DBH	O Volume	P Volume	O Height	P Height	O TPH	P TPH
Babanango	11.0	20.9	19.4	247	236	15.0	14.4	1327	1326
Badplaas	10.0	12.8	14.6	68	114	9.4	10.2	1609	1608
Barberton	10.4	18.3	17.5	139	134	13.0	12.4	1133	1131
Belfast	6.5	10.4	12.9	8	22	4.7	8.1	619	619
Bergvliet	10.4	19.9	21.8	150	210	14.9	16.0	888	900
Berlin	25.4	32.9	37.4	340	459	27.5	29.0	375	400
Blyde2	14.3	27.7	29.3	155	202	17.4	21.5	406	400
Carolina	9.7	17.4	13.6	130	87	10.4	9.4	1508	1548
Dukuduku	13.0	16.5	18.0	131	190	No data	13.1	1333	1371
Entabeni	7.1	16.3	15.1	39	37	9.1	9.9	606	613
Frankfort	10.7	22.1	23.8	169	225	16.3	17.6	738	750
GoldenReefs	14.6	15.9	21.5	165	361	15.9	16.4	1406	1405
Greytown	8.4	19.0	13.8	124	63	10.8	9.4	1169	1168
Hlabeni	13.1	20.3	17.6	202	166	13.8	12.7	1250	1313
Jessievale	21.8	34.9	32.8	311	295	22.8	24.7	381	400
KwaMbonambi	20.3	21.2	28.9	217	617	18.3	22.8	700	986
Lothair	11.1	19.83	18.1	122	127	11.5	12.9	984	983
Mahehle	15.1	21.5	19.5	259	199	16.8	14.3	1150	1149
Melmoth	12.7	18.4	21.9	143	266	14.3	16.3	1035	1062
Morgenzon	9.8	21.8	17.9	148	141	12.0	12.8	944	1110
NECF Stand 15	17.0	23.9	21.1	362	257	18.8	15.7	1149	1148
NECF Stand 18	13.0	17.6	18.3	121	166	11.8	13.2	1181	1180
Nelshoogte	14.9	20.6	23.2	160	282	17.5	17.4	738	954
New Agatha	14.0	23.8	24.4	187	227	16.3	18.1	706	705
Ngodwana1	17.8	16.8	17.7	94	141	16.0	12.6	709	750
Roburnia	20.6	28.1	35.8	220	396	21.8	27.5	431	400
Seven Oaks	14.8	22.8	23.2	235	296	16.0	17.4	983.3	995
Sudwala	18.0	28.9	27.4	435	426	20.8	21.1	854	853
Tweefontien	27.2	36.4	43.6	471	775	32.7	35.0	350	399
Uitsoek	19.3	23.3	28.1	146	234	18.8	20.8	488	500
Wilgeboom	11.0	22.1	23.8	140	207	15.2	17.5	663	700
Witklip	19.3	31.0	32.5	275	309	23.0	24.5	419	425

Table 9: Statistics describing the relationship between observed and predicted mean DBH (cm), mean height (m), trees per hectare ($tree.ha^{-1}$) and stand volume ($m^3.ha^{-1}$) at age four years for 32 study stands.

Attribute	Slope	Intercept	R^2	RMSE	EF
Mean DBH	1.0450	-1.3225	0.8036	2.9488	0.0664
Mean Height	1.0689	-0.1812	0.8975	2.7227	0.7285
Trees per Hectare	0.9846	45.3940	0.9661	62.5426	0.9577
Stand Volume	1.1658	23.2400	0.5922	98.3300	-0.2460

A final set of parameter values gave a relatively good fit to most stands with the exception of some stands located in the Natal Midlands (Greytown, Melmoth and Babanango), Coastal Zululand and the North East Cape Forests (NECF) stands. The 3-PG model produced a good fit of TPH (R^2 = 0.9661, n=32) in all stands with the exception of the KwaMbonambi, Morgenzon, and Nelshoogte stands. This emphasised the accuracy with which 3-PG simulate thinning regimes in reality. The 3-PG model over-predicted DBH in 20 stands with a maximum over-prediction of 35% in a Golden Reefs stand. A prediction with R-squared value of 0.5922 (n=32) for stem volume was observed. It is evident that the scatter of data points was greatest in the stand volume predictions (**Figure 8b**). In some stands there were more scatter/outliers, with the KwaMbonambi and Tweefontein stands producing maximum over-predictions of 65% and 39% for stem volume respectively.

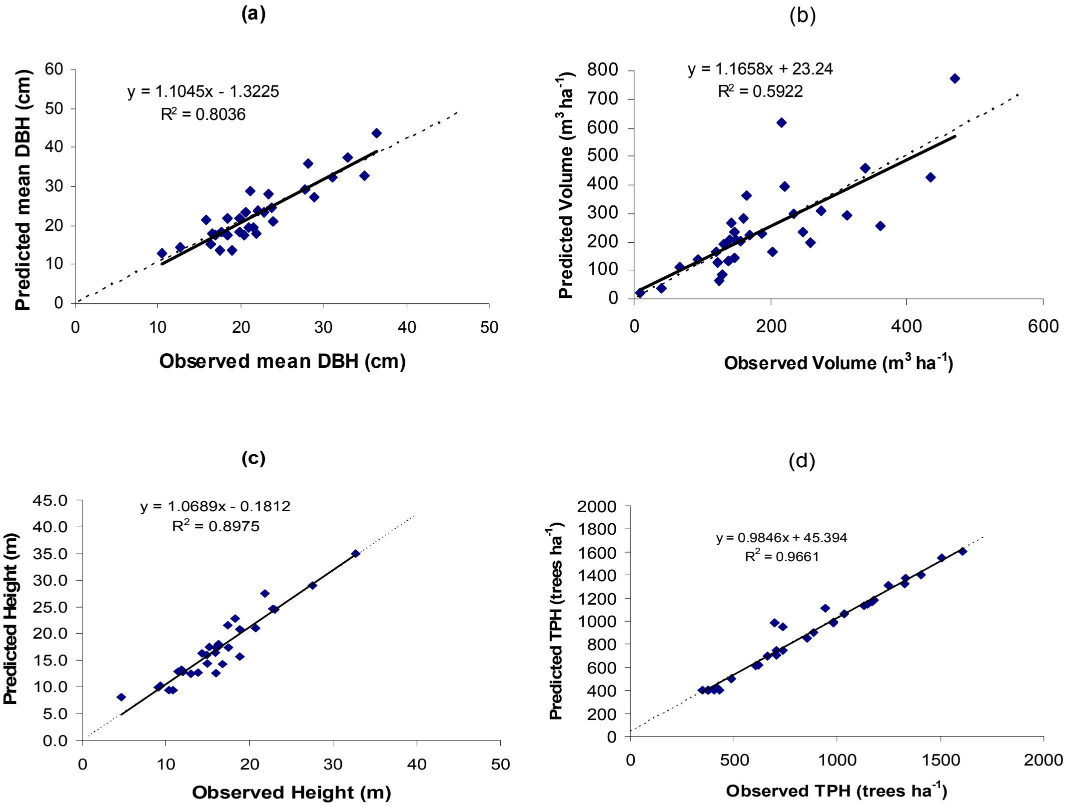

Figure 8: Comparison of observed and predicted DBH (cm), stand volume ($m^3.ha^{-1}$), height (m) and trees per hectare ($tree.ha^{-1}$) for 32 stands. Observed and predicted points shown as (♦), (▬) is the regression line and (.....) is a 1:1 line.

This might be because in 3-PG, calculated volumes are sensitive to diameter and height dimensions, especially when there are larger, older trees (Tickle *et al*., 2000). Tickle *et al.,* (2000) on 3-PG modelling of various *Eucalyptus spp*., found only a strong relationship (R^2 =0.86, n=22) between predicted and observed stand volume when two old stands with the largest trees were removed. When included in simulations, these two stands worsen the relationship to R^2 =0.58 (n=24).

In a 3-PG sensitivity analysis study on *Eucalyptus grandis* by Esprey, *et al*., (2004), this sensitivity of stand volume had been observed. Esprey, *et al*., (2004) demonstrated that the stand volume was sensitive to the ratio of net to gross primary production, basic wood density and other parameter classes other than those related to diameter and height dimensions.

Nonetheless various other studies on *Pinus spp*, produced similar realism as reflected in **Figure 8**. Similar good 3-PG predictions were reported in Landsberg *et al.,* (2000 and 2003); Sands and Landsberg (2002); and Dye (2001). A few outliers considerably influenced the overall 3-PG performance (RMSE, EF, and R^2) and these are briefly examined below to investigate the possible reasons.

6.2.1.1 Model over-predictions

The data from a stand in Coastal Zululand (Kwambonambi, 28 32’ 07” S and 32 07’53” E) is the likely explanation of the trend in the model over-predictions. According to the records, the Kwambonambi stand was planted in 1937 and was not thinned over the next 20 years. The 3-PG model over-predicted growth (DBH and Height) in this Kwambonambi stand (**Figure 9**), especially after year eight and there are several possible hypotheses to explain this discrepancy which are listed below.

- Poor weed control. The effectiveness of weed control in the 1930s is unknown, but may have been poorer than what is typical of modern day PSP (Permanent Sample Stand), especially in Zululand where weed growth can be very rapid (P Dye, 2004, pers. comm.). There is evidence of this poor weed control in a paper by Pienaar and Harrison (1989). It is rather unusual that the trees per hectare declined rapidly after age eight, when modelled DBH and height departed markedly from observed values. This suggests that increased competitive stresses from weeds may have occurred around this time (Dye 2003, p.24). In addition, this site has poor historical silvicultural management, which, at some stage, resulted in competition reduced mortalities (Piennar and Harrison,1989).

- Pruning. No information on the occurrence of pruning was available for this stand. If pruning did take place, it would have reduced the leaf area index and possibly the growth rate (Jarvis and Leverenz, 1983; Dye, 2003; p.23).
- Low FR. Coastal sands can be very nutrient poor, and are susceptible to nutrient leaching following significant rains (Pienaar and Harrison, 1989); P Dye, 2004, pers. comm.). A high FR of 0.8 is suggested for this soil type (**Table 6**, p.29), but this may be an overestimate. Experimentally reducing the fertility ratio greatly reduces the difference between observed and predicted stand volume (Landsberg *et al.,* 2000).
- *Pinus elliottii* seedlings planted in the late 1930s may have been less productive than the genetically improved seedlings used in more modern times.

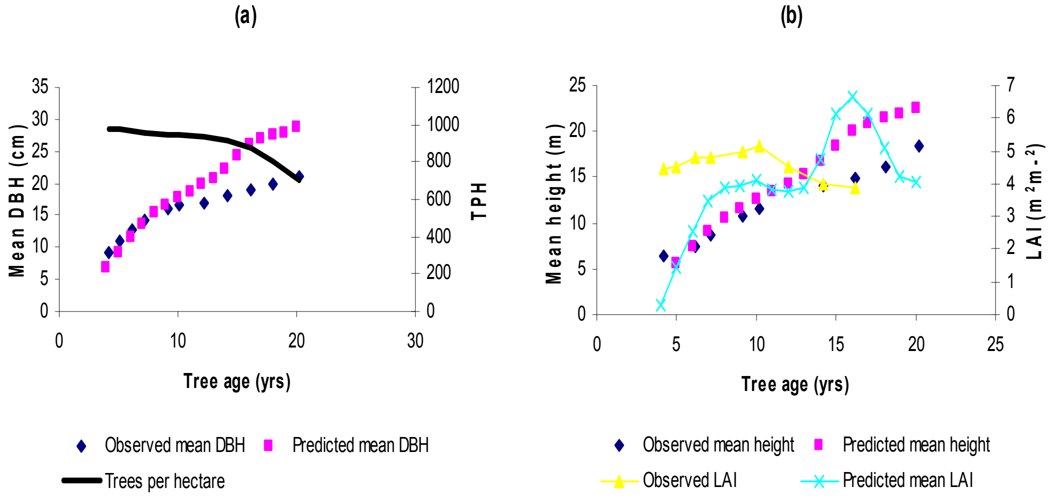

Figure 9: Model over-prediction of DBH (cm) after age eight shown in graph (a), while in (b) observed and predicted height (m), LAI ($m^2.m^{-2}$) are depicted for the KwaMbonambi stand from 1937 to 1957.

The first two hypotheses discussed above may also explain why 3-PG over-predicts volumes in the Tweefontein, Roburnia and Golden Reefs stands. These are again older stands of trees in which small differences in diameter and height have a large effect on calculated volumes. There is also a greater period for management interventions and environmental effects to alter growth trajectories. When these stands were removed during the calibration, the stand volume predictions improved. Although the parameterisation approach used in this study was different from Tickle *et al*., (2000), they observed similar model behaviour when they removed the outlier(s).

They argued that this behaviour is a result of the inclusion of the outlier(s) in the development of the single set of parameter values. This resulted during their calibration, when the model was tuned for each stand individually and then a single set of parameter values were generated by using the mid-point of the range used for each variable (Tickle *et al*., 2000, p. 9).

6.2.1.2 Model under-predictions

The NECF stand 15 and Mahehle and Greytown stands all show higher growth rates than those predicted by the 3-PG model. Observed data from the Mahehle stand indicates that the under-prediction was already substantial by year eight, suggesting that site conditions were more favourable for growth than assumed by 3-PG.

This may involve such site factors as the soil depth and texture, available soil water, the fertility rating, or an additional influx of water into the rooting zone from upslope. The maximum available soil water estimate for the Greytown stand was a relatively low 84 mm, which is likely to significantly retard modelled growth.

There is also great uncertainty over the availability of groundwater for trees because observations in road-cutting commonly show that the permeability and depth of subsoil’s is spatially highly variable (P Dye, 2004, pers. comm.). Deeply weathered subsoil’s would store greater amounts of water, and promote a higher rate of growth by trees able to access this water (P Dye, 2004, pers. comm.).

The estimation of initial biomass is also likely to be a significant source of error. In this study, a site index equation was used to estimate initial biomass. During this exercise, tree growth was projected backward to when trees were younger (four years). This approach assumes that growth late in the rotation is always correlated to initial biomass, but this is not always the case.

In the Mahehle stand, a severe drought was recorded in 1992 and 1993, which is reflected in the modelled growth of the trees. In such cases, a high initial biomass may develop into a relatively low final yield because of the suppression of intervening growth by drought. The NECF stand 15 was not grown for commercial purposes and was one of the most productive sites in NECF stands (CAI= 21.3 $m^3.ha^{-1}.year^{-1}$). Surely with the NECF stand 15, the predictions discrepancy lies with the initial biomass estimation which in this study was correlated directly to final biomass of the NECF stand 15. A further reason for evaluating the manner in which the initial biomass was estimated, was that there was some circularity in using final observed yields to estimate starting biomass, which was then influential in simulating final yields.

As an alternative, it was decided to investigate the usefulness of starting all predictions at age three years. This when the variation in mean diameter and height across stands is even less than at age four years and by assuming a uniform initial tree size for all the stands. **Table 10** below describes the statistical results of starting the predictions at three years.

Table 10: Statistics describing the relationship between observed and predicted mean DBH (cm), mean height (m), trees per hectare ($tree.ha^{-1}$) and stand volume ($m^3.ha^{-1}$) at age three years for 32 study stands.

Attribute	Slope	Intercept	R^2	RMSE	EF
Mean DBH	1.0763	-1.0394	0.7696	3.1106	0.6262
Mean Height	1.0498	0.1757	0.875	2.8328	0.7061
Trees per Hectare	0.9702	50.761	0.9497	71.7177	0.9445
Stand Volume	1.1029	22.413	0.5325	104.9032	-0.4181

A comparison of **Table 9** and **Table 10** shows that a poorer overall match was achieved (R^2 = 0.53, n= 32, RMSE= 98.33 compared to R^2 = 0.59, n=32, RMSE= 104.90 at age four) by assuming a fixed starting stem, branch and foliage mass at age three years. This result illustrates the importance of an accurate initial biomass.

6.2.2 Validation against 12 independent test stands

The validity of the parameter values obtained through a fitting process using the 32 stands described in earlier sections were then tested on an independent set of data from 12 other stands. The predictions of mean DBH, Height, and TPH were relatively good, with R^2 of 0.8467, 0.7649, and 0.9916, respectively. However, stem volumes again were over-predicted in eight out of the 12 stands (**Table 11 and Figure 10**). Noticeably, the stem volumes in both 32 simulation stands and 12 independent stands were the most varying growth variable.

Table 11: A comparison of observed (O) and predicted (P) mean DBH (cm), stand volume ($m^3.ha^{-1}$), mean height (m) and trees per hectare ($tree.ha^{-1}$) for 12 independent stands.

Location	Age of stand	O DBH	P DBH	O Volume	P Volume	O Height	P Height	O TPH	P TPH
Badplaas2	11.6	15.9	19.1	67.6	140.6	10.5	13.7	924.0	923.3
Blyde1	15.5	31.5	27.6	293.2	219.5	21.0	20.4	481.0	499.6
Boston	10.6	21.5	17.9	158.9	133.3	11.9	12.8	1055.0	1054.3
Brooklands	15.3	23.2	27.2	97.4	157.6	16.5	19.7	381.0	399.9
Howick	10.6	21.9	16.0	236.4	106.1	14.7	11.2	1183.0	1182.2
Machadodorp	16.8	22.7	20.1	422.8	295.6	19.3	15.1	1443.0	1440.9
Ngodwana2	21.6	22.5	25.5	348.7	448.6	21.3	19.6	1076.0	1074.1
Piet Retief	11.6	18.1	17.0	166.9	174.4	12.3	12.3	1472.0	1479.9
Roseg11	15	20.1	20.1	226.0	447.3	15.8	18.6	1230.0	1228.6
Spitkop	13.3	23.7	24.0	179.5	242.5	17.3	17.8	638.0	774.6
Sudwala2	8.9	13.5	15.1	70.9	107.8	10.0	10.6	1401.0	1399.3
Woodbush	36.7	42.5	49.9	469.6	841.1	28.3	40.3	306.0	299.4

In the 3-PG model the tree diameter and trees per hectare are derived from the stem mass (W_{sx}) after NPP has been partitioned into roots first and subsequently to stem and foliage (Landsberg and Waring, 1997; Tickle *et al.*, 2000). In light of the above fact, these results were unexpected since it was anticipated that stand volume predictions would be accurate, provided predictions for mean DBH, Height and TPH were realistic.

However, stand volume, as earlier alluded, is sensitive in particular to α_c, and similarly the α_c strongly influences *L* (Esprey *et al*., 2004). This is likely the reason why the stand volume predictions were not realistic enough.

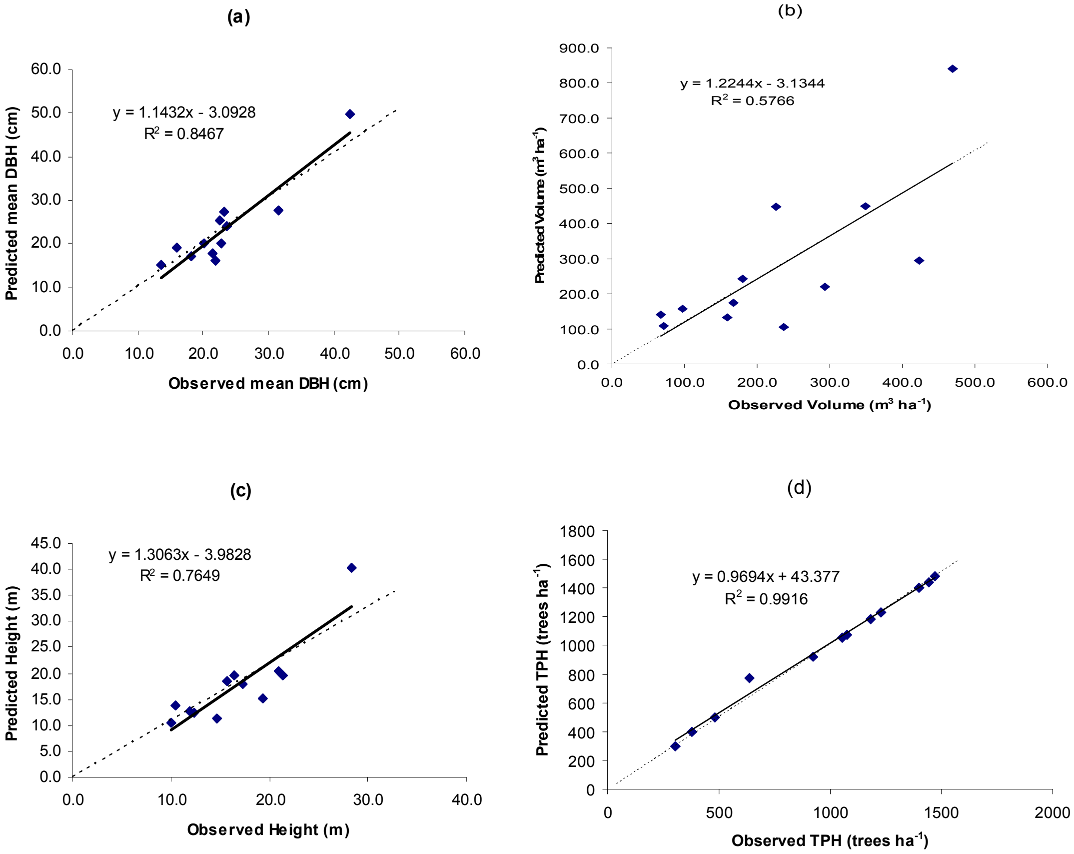

Figure 10: Comparison of observed and predicted DBH (cm), stand volume (m^3.ha^{-1}), height (m) and trees per hectare (tree.ha^{-1}) for 12 stands. Observed and predicted points shown as (♦), (▬) is the regression line and (…..) is a 1:1 line.

6.2.3 Evaluation of model predictions for all 44 stands

6.2.3.1 General trends in leaf area index

The 3-PG model produced realistic values (**Figure 11**) of leaf area index *L* (all sided) and relatively similar values to those indicated in reports by (Vose *et al.,* 1994) where *L* of 5.3 $m^2.m^{-2}$ and 1.9 $m^2.m^{-2}$ was reported for trees aged four and 21 years respectively.

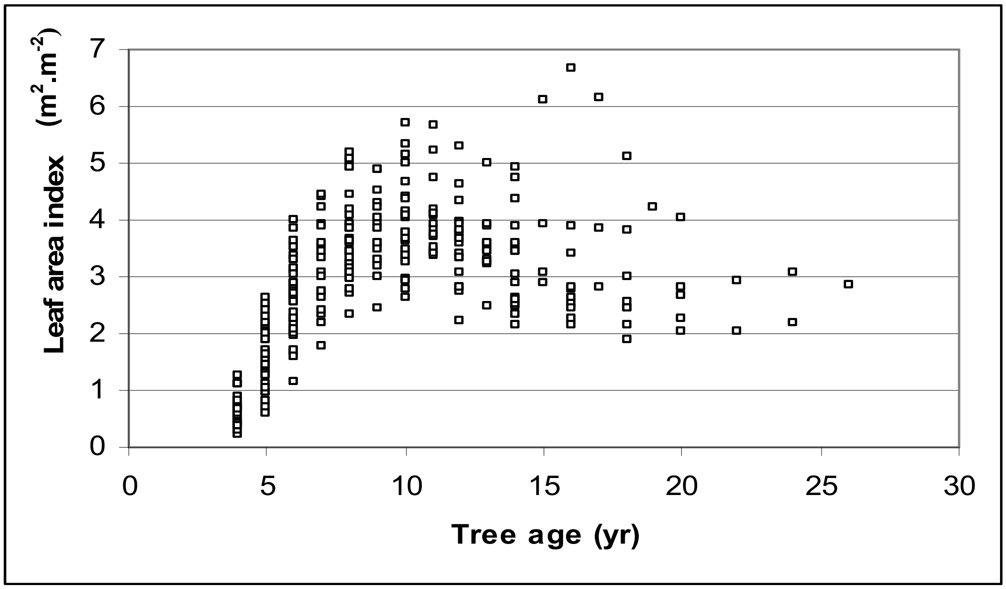

Figure 11: *Pinus elliottii* leaf area index ($m^2.m^{-2}$) predicted in each year for all 44 study stands. Predicted points for each stand are shown as (□).

This trend of realism is further supported by *L* prediction results from *Pinus abies* studies (Landsberg *et al.*, 2003) which produced R^2 values of 0.95 and 0.86 for the control and fertilised stands respectively.

6.2.3.2 Thinned versus unthinned stands

The 3-PG model predictions in 18 unthinned stands against 14 thinned stands produced different outcomes in growth variables, especially for DBH and stem volume. The DBH and stem volume were poorly predicted in unthinned stands, with no marked difference in stem height and trees per hectare (**Figure 12**). In

Landsberg *et al.,* (2003) such observations are supported, where both stand volume and basal area predicted values increased after stands were thinned.

Table 12: Statistics in the relationships between observed and predicted mean DBH (cm), mean height (m), trees per hectare (tree.ha^{-1}) and stand volume (m^{3}.ha^{-1}) of the unthinned stands.

Attribute	Slope	Intercept	R^2	RMSE	EF
Mean DBH	0.8528	3.2745	0.4398	3.3936	0.9720
Mean Height	1.0176	0.2298	0.7390	1.9366	0.9839
Trees per Hectare	0.8821	164.9300	0.9290	87.2059	0.9939
Stand Volume	0.7695	87.8420	0.2850	121.890	0.6573

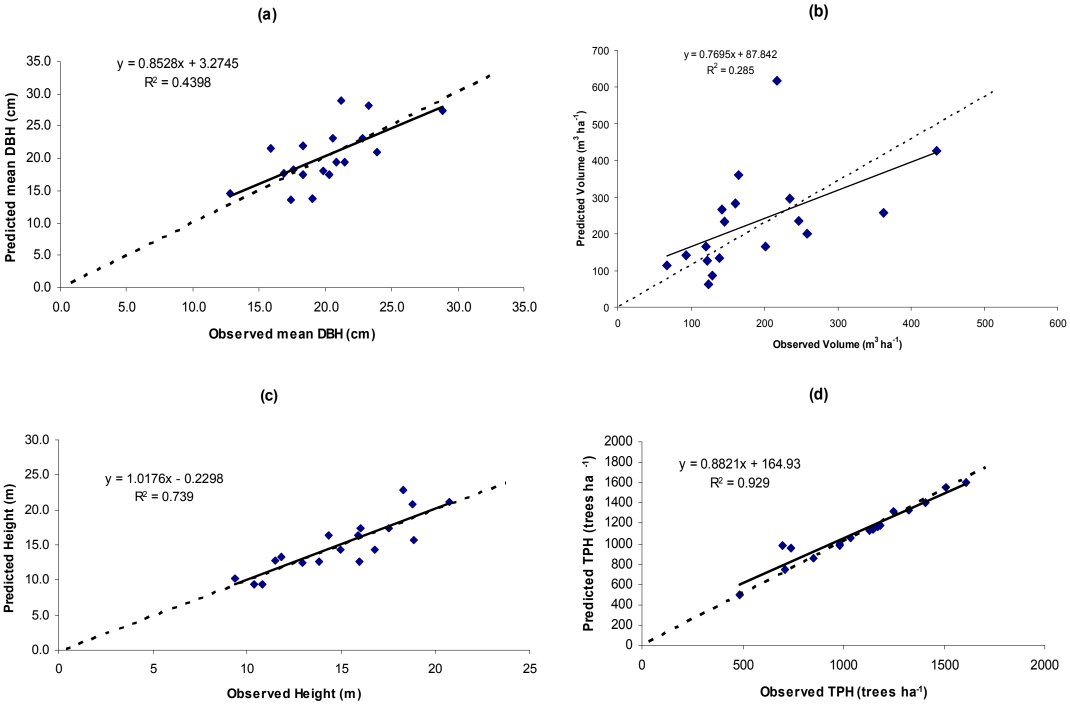

Figure 12: Comparison of observed and predicted DBH (cm), stand volume (m^{3}.ha^{-1}), height (m) and trees per hectare (tree.ha^{-1}) for unthinned stands only. Observed and predicted points shown as (♦), (▬) is the regression line and (….) is a 1:1 line.

However, in the thinned stands, the predictions were improved (**Figure 13**).

Table 13: Statistics in the relationships between observed and predicted mean DBH (cm), mean height (m), trees per hectare (tree.ha^{-1}) and stand volume (m^3.ha^{-1}) for thinned stands.

Attribute	Slope	Intercept	R^2	RMSE	EF
Mean DBH	1.1297	1.3915	0.8916	5.0016	0.9356
Mean Height	1.0174	1.8720	0.9668	6.0789	0.9434
Trees per Hectare	1.0637	16.6110	0.9802	6.0789	0.9835
Stand Volume	1.4708	24.3080	0.8897	150.257	0.8732

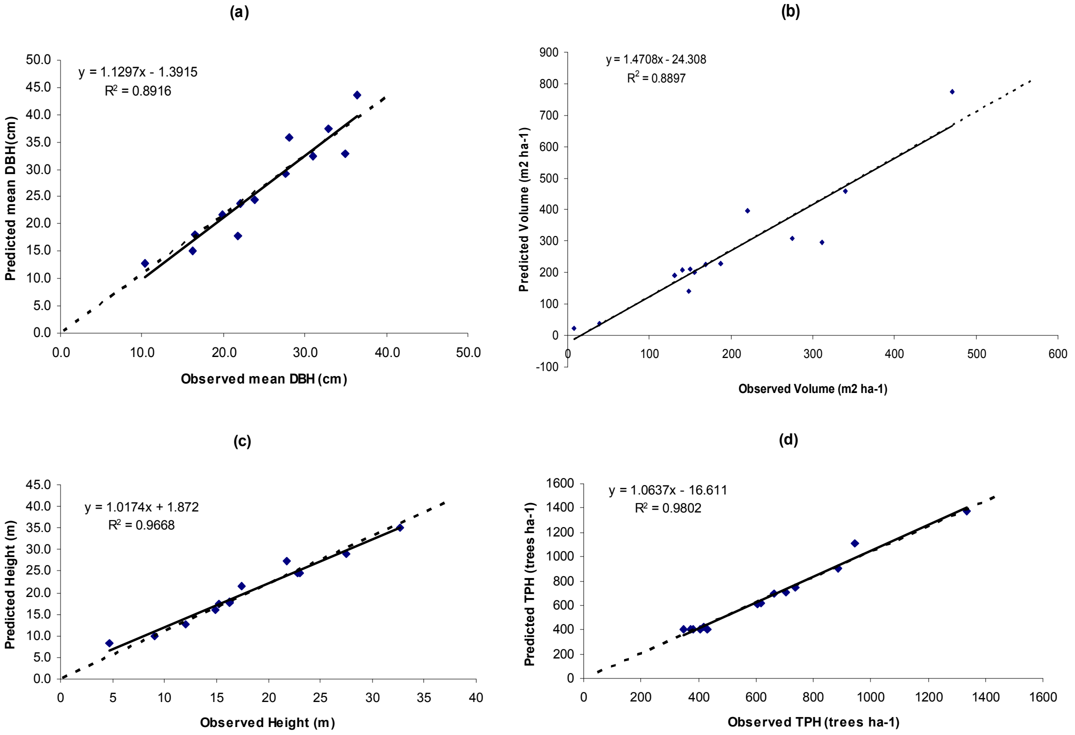

Figure 13: Comparison of observed and predicted DBH (cm), stand volume (m^3.ha^{-1}), height (m) and (tree.ha^{-1}) for thinned stands only. Observed and predicted points shown as (♦), (▬) is the regression line and (…) is a 1:1 line.

There are several possible reasons that explain the differences in predictions between thinned and unthinned stands. These differences are discussed below.

Competition: In unthinned stands, fewer bigger trees suppressed the smaller ones and this drastically affected the diameter and volume distribution across the unthinned stands. In thinned stands, this competition was less prominent among the trees because of the “smoothing effect” of thinning.

Starting biomass method: As previously stated, this approach assumes that late rotation growth is correlated to initial biomass, but this is not always the case. Thinned stands also comprised five old stands (Woodbush, Tweefontien, Berlin, Jessivale and Roburnia), all of which are older than 20 years.

These stands increased diameter and tree volumes, most likely because of the logarithmic assumptions by 3-PG in (Landsberg and Waring, 1997). For example, the 3-PG model calculates mean DBH from the average stem mass, which in turn is used to calculate basal area and height (Dye, 2003, p.19).

6.2.3.3 The effect of drought

The effects of drought conditions in 1992 and 1999 on current annual increments calculated for the Mahehle stand, located in the Natal Midlands, are shown in **Figure 14.** This figure illustrates the ability of 3-PG to account for changing growth conditions. For example, 3-PG predicted low CAI when rainfall was lowest an indication that drought suppressed growth. This stand was unthinned and notice that after year eight the 3-PG simulate a sharp decline in growth indicating a possible decrease in tree density and a drought event suppressed growth in year nine and growth recovered in year 10.

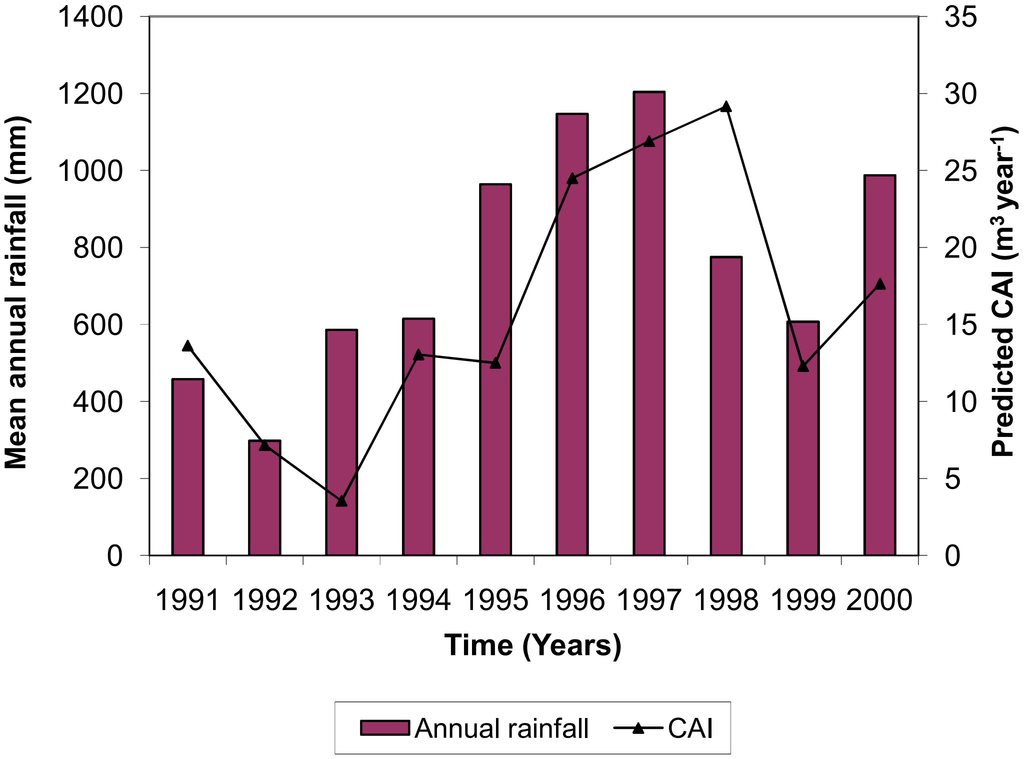

Figure 14: A predicted phase of growth from 1991 to 2000 by 3-PG using the actual rainfall (mm) and simulated current annual increment (m^3.year^{-1}) recorded for Mahehle.

6.2.3.4 General trends in evapotranspiration

Figure 15 shows annual ET is much less than annual rainfall at age five years, but this difference declines with age as *L* increases (peaks around 8-15 years, see figure 11, p.52) and the canopies develop to their full extent. Without thinning, the canopy remains well developed, and ET accounts for most of the rainfall in every year. In some years, ET can exceed rainfall by utilising stored soil water from the previous year. Transpiration is not much less than ET in all years, indicating that canopy rainfall interception is a minor hydrological process compared to transpiration. These results indicate similar observation in Dye *et al*, (2001).

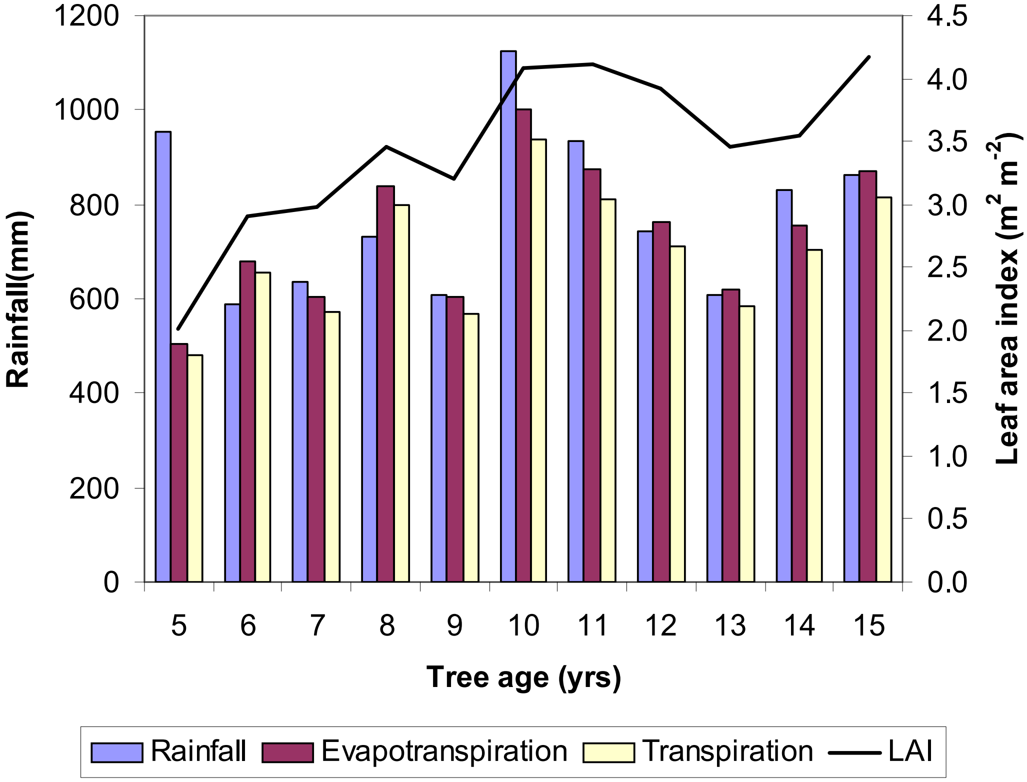

Figure 15: Annual variation in rainfall (mm), and simulated evapotranspiration (mm), transpiration (mm) and leaf area index (m^2.m^{-2}) in an unthinned stand at Seven Oaks.

Figure 16 below shows predictions for a stand at Jessievale that was thinned at age eight and 13 years. The canopy *L* in this stand is well developed by age five years, and thus most rainfall is lost as ET. There is little difference between ET and transpiration up to the first thinning at age eight years (P Dye, 2004, pers. comm.). After this first thinning, *L* is sharply reduced, but recovers until the second thinning at age 13 years again reduces it. The *L* remains low for the remainder of the rotation. Reductions in *L* are clearly correlated to reductions in ET and transpiration.

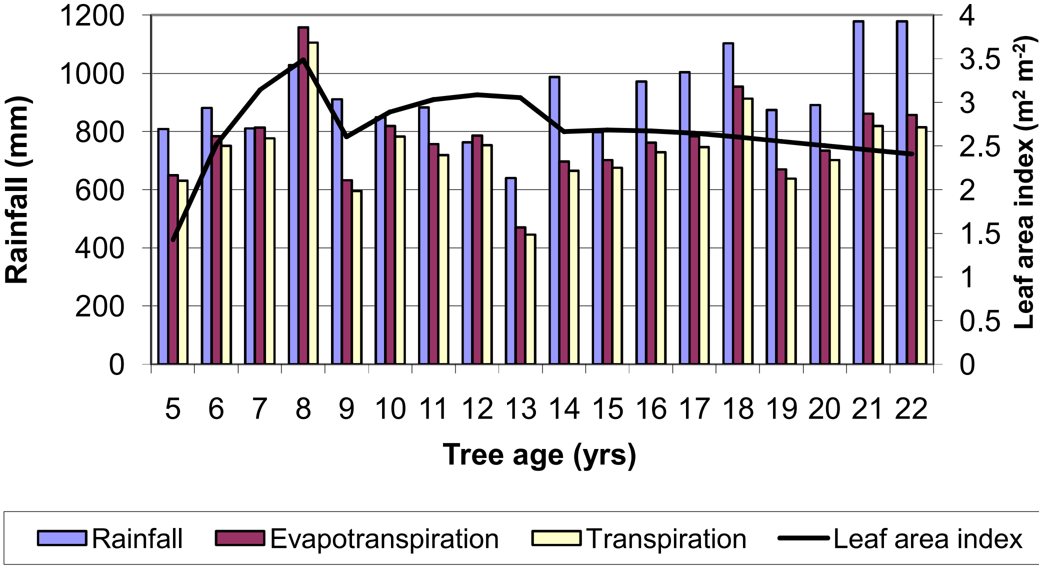

Figure 16: Annual variation in rainfall (mm), and simulated evapotranspiration (mm), transpiration (mm) and leaf area index ($m^2.m^{-2}$) in a thinned stand at Jessievale.

6.2.3.5 Annual evapotranspiration

Annual evapotranspiration (ET) is a significant physiological property of forest stands. The rate of transpiration, which is the dominant process in forest evapotranspiration, is governed by stomatal resistances, which also regulate CO_2 uptake, assimilation and growth. Thus, if simulated annual ET is unrealistic then the 3-PG model is also likely to incorrectly simulate growth processes. Unrealistic ET rates will also lead to errors in the simulated soil water balance, causing problems in the estimation of plant water stress, growth and transpiration. Finally, annual ET is inversely related to annual water yields at a catchment scale. For all these reasons, it is important to examine the realism of 3-PG simulated annual ET estimated for the sample plots.

In this section, trends in 3-PG predicted annual ET are reviewed, and an attempt is made to identify which properties of site and stands are important in determining annual ET. This was done simply by analyzing trends of simulated ET in 13 representative stands and investigating correlation to various site and stand factors. The representative 13 stands (**Table 14**) were selected from Mpumalanga, KwaZulu-Natal, and Limpopo and represented varying site (altitude, rainfall, soil etc) and stand (TPH, age, management regime) factors. Half of the stands were unthinned pulpwood stands, while the remainder were thinned sawtimber stands.

Table 14: Site information of the 13 stands selected to assess trends in 3-PG predicted annual ET. (Refer to page XIV for acronyms)

Stand	Location	MAP	MAT	ALT	A-pan	Solar radiation	Soil depth	Thinning	Long	Lat	Soil texture*	Geology	Lithology	TAW	Fertility Rating
		(mm)	(^{0}C)	(m)	(mm)	(MJ^{-2})	(mm)		(Decimal)	(Decimal)					
8	Babanango	876	16.2	1227	1735.9	255.2	726.1	unthinned	31.08389	28.42139	SaClLm	Pp	SHALE	136	0.6
11	Badplaas1	786	17.2	1163	1740.9	282.2	906.2	unthinned	30.48713	25.84091	SaCl	Vt	SHALE	110	0.3
28	Barberton	886	18.8	902	1938.7	282.2	721.3	unthinned	30.84121	25.68177	SaClLm	Zka	GRANITE	111	0.5
29	Bergvliet	1488	17.1	1408	1866.8	259.9	839.2	thinned	30.86322	25.10771	SaCl	Zne	GRANITE	111	0.5
14	Blyde1	1502	15.9	1427	1871.5	271	711.3	thinned	30.84265	24.88527	SaClLm	Vbr	QUARTZITE	80	0.3
16	Carolina	823	14.8	1612	1785.9	263.2	483.7	unthinned	30.35535	26.11721	SaClLm	ZC	GNEISS	128	0.3
42	Dukuduku	973	21.2	70	1706	NO DATA	300	thinned	32.2500	28.3500	Sa	O-S	BASAL CONGLOMARATE	187	0.8
39	Entabeni	1108	20.7	811	2126.4	286.8	763	thinned	30.25004	23.04698	SaClLm	Zgo	GNEISS	128	0.3
31	Franfort	1373	18.6	948	1882.4	272.9	859.1	thinned	30.89474	25.03477	SaCl	Vdi	DOLERITE	257	0.6
9	Golden Reef	866	17.7	821	1758.2	254.3	674.9	unthinned	31.27639	28.59167	SaClLm	ZB	GRANITE	309	0.5
2	Greytown	823	16.1	1235	1698.2	257.3	815	unthinned	30.68284	28.99920	SaClLm	Pv	ECCA SANDSTONE	84	0.5
3	Hlabeni	843	16.4	1212	1625.4	267.2	441.4	unthinned	29.77472	29.98889	ClLm	Jd	DOLERITE	165	0.6
17	Jessievale	889	14	1738	1719.7	257	571.9	thinned	30.53097	26.21886	SaClLm	Rmp	QUARTZ MONZONITE	178	0.3

*(Soil categories are based on the South African Soil Classification, 1991)

- *ET vs. Rainfall*

Figure 17 shows a plot of annual rainfall against 3-PG simulated annual ET. ET is mostly below the 1:1 line but it can exceed rainfall by as much as 150 mm when high rainfall is experienced in the previous year, leading to carryover of soil water. Annual ET hardly exceeds 1200 mm, which seems to be the upper limit. Annual rainfall limits annual ET in years where rainfall is below 800 mm, but not in years where annual ET exceeds 1000 mm, this is an observation in line with *Pinus elliottii* ET data reported in Riekerk (1982) and 3-PG has been able to reflect this upper limit.

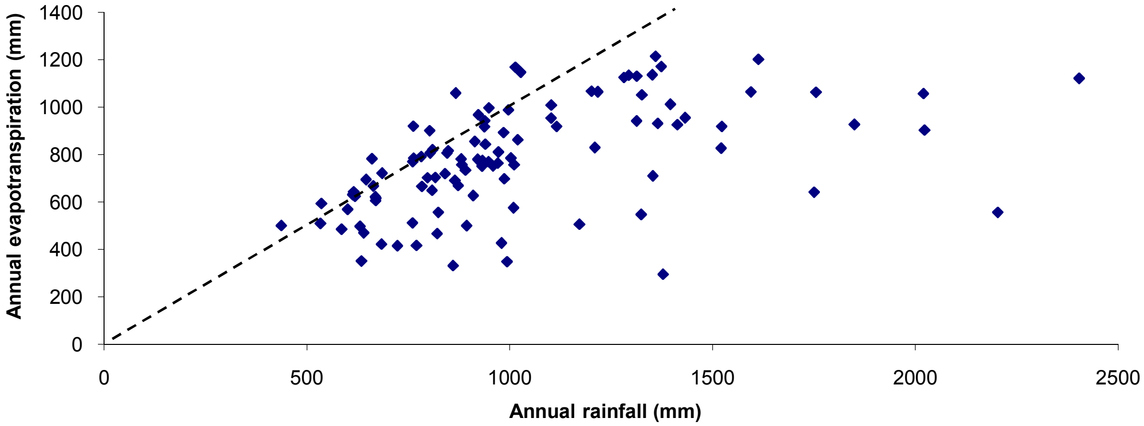

Figure 17: Plot of annual rainfall (mm) and 3-PG simulated annual evapotranspiration (mm) in multiple years for 13 stands (n=99). The line (…..) is a 1:1 line.

- *ET vs. Tree age*

In **Figure 18** below, it is clear from the pattern of data points that younger trees (5-6 years) are associated with a relative low ET while the peak annual ET is highest at around age 7-10 years. This shows clearly how simulated annual ET varies with tree age. In Lesch and Scott (1997) this pattern is ascribed to low ET rates due to smaller canopy cover and *L* which only reaches it maximum extent around 10-12 years as reported by Gholz and Fisher (1982) in Vose *et al.,* (1994). It is hypothesized that this ET trend follows changes in *L* of the stands (See section 6.2.3.1)

Figure 18: The 3-PG model simulated annual evapotranspiration (mm) for 13 stands. An age-related pattern of 3-PG simulated annual evapotranspiration (n=99) is clearly distinguishable with a peak occurring around age 10-12 years and a decline later in the rotation.

- *ET vs. L*

When a plot of ET and *L* with annual rainfall represented as size of the symbols, LAI seems to be the main determinant of ET rates than rainfall according to Figure 19. This presents a clear correlation between ET and *L*. In **Figure 19**, some young trees (5-6 yrs) with low *L* do not respond to high rainfall as much as those with high *L*. This trend is also evident in mature trees (9-13 yrs) where trees with high *L* show high ET rates than those with similar rainfall amounts. In older trees (14-24 yrs) this observation is clearer, where *L* is definitely having a controlling and limiting effect on ET values. Older trees with stable *L* (around 2- 2.5 $m^3.m^{-3}$) have relatively the same ET rates irrespective of the amount of rainfall. These 3-PG results are in line with Figure 18 and those observed in section 6.2.3.4.

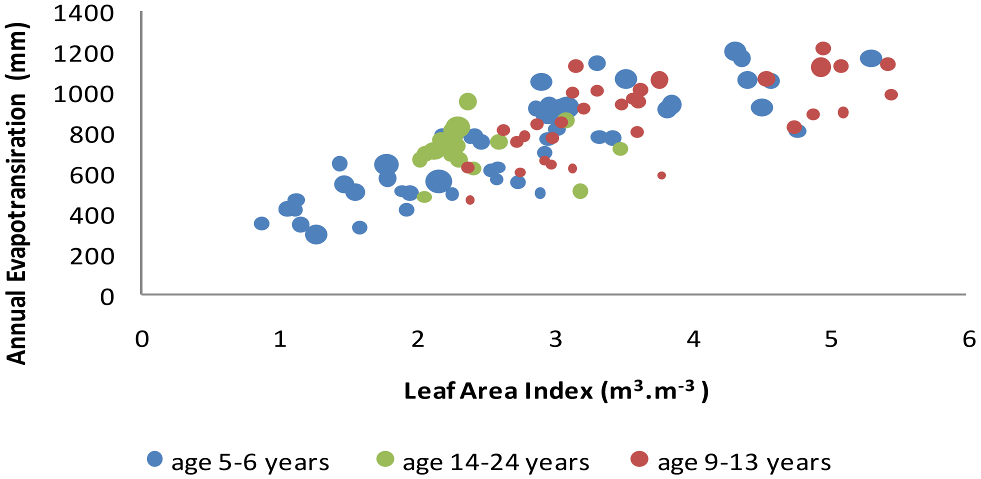

Figure 19: Plot of 3-PG simulated annual evapotranspiration (mm) and leaf area Index ($m^2.m^{-2}$) for 5-24 year-old stands.

- ET vs. thinning

To further investigate trends in model-predicted ET, the influence of stand density (TPH) on simulated annual ET was investigated in more stands as shown in **Figure 20**. The general trends in **Figure 20** show that simulated annual ET drop in the year of thinning, although recovery of *L* is rapid and the effect may disappear in subsequent years. This pattern is clearly seen in some stands, especially Morgenzon, Frankfort, Wilgeboom, New Agatha and Jessievale where first thinning produced a sharp decline in simulated annual ET and *L*. These observations are comparable with results in Lesch and Scott (1997) where thinning decreased ET and improved catchments stream flows. However in five other sawlog stands (Berlin, Dukuduku, Witklip, Tweefontien and Roburnia) the pattern was less clear or absent. In all stands the *L* response to second thinning was less significant than the first thinning. There are several possible factors for these observations which can include site and stand factors like climate, thinning timing and duration, seasons, and *L.* Landsberg and Waring (1997, pp 220-221) illustrated that trends in *L* are affected by different environmental constraints (VPD, ASW and frost etc). The 3-PG model has been able to show that thinning effect on annual ET is evident in the year of thinning, but short lived as it quickly recovers in subsequent years.

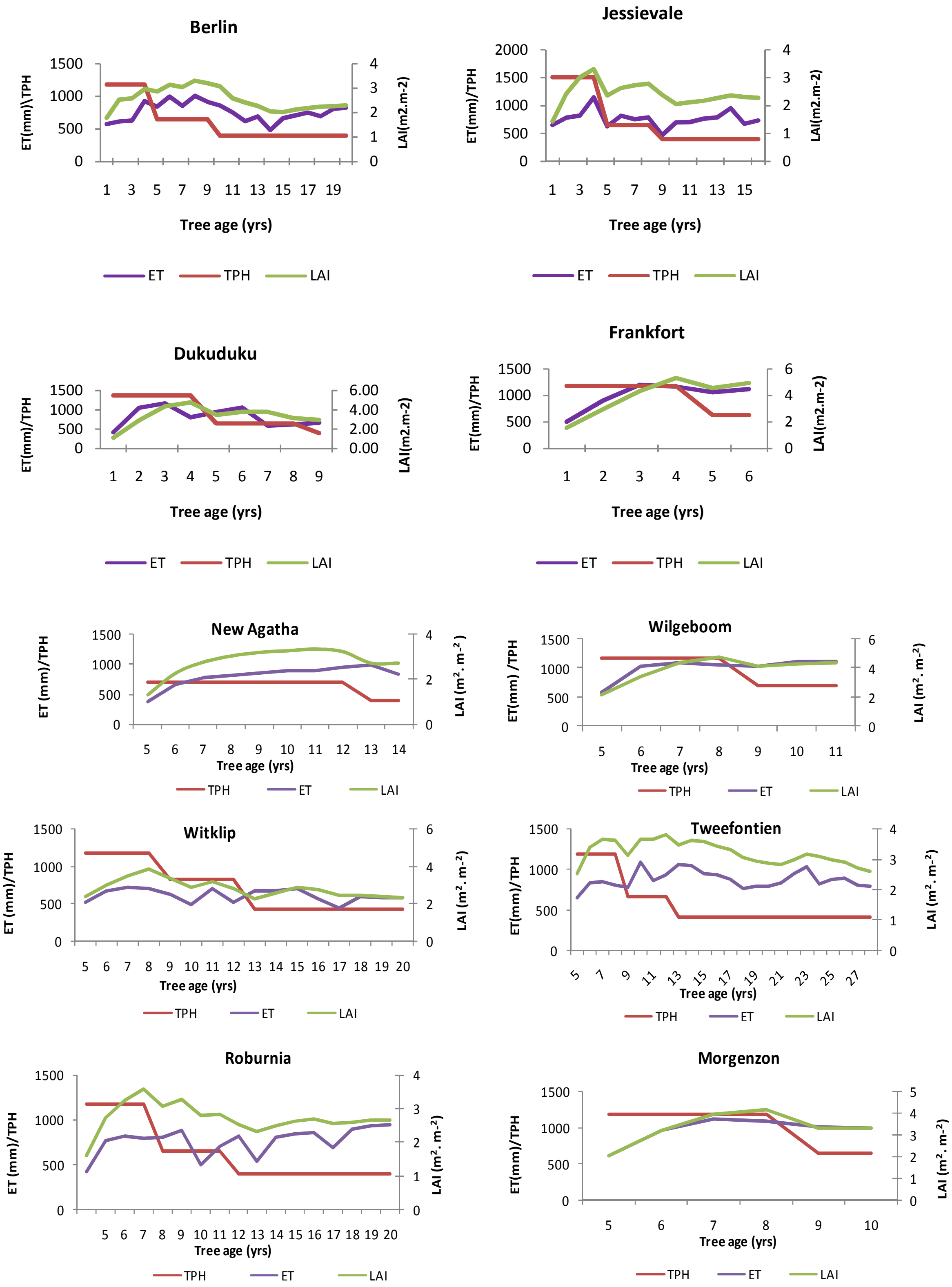

Figure 20: Plot of 3-PG simulated annual evapotranspiration (mm), leaf area index ($m^{2\cdot}m^{-2}$) and stand density (TPH).

- Conclusion

Predicting ET is complex and the hydrological balance in all versions of 3-PG, as described by Landsberg and Waring (1997) is simplistic (Sands and Landsberg, 2002). However, this simple graphical analysis shows that 3-PG appears to predict annual ET in a realistic way, responding to variation in annual rainfall, tree age, leaf area index and thinning treatments in a logical way. Other factors such as canopy defoliation by insects, site fertility, understorey development could also have significant impacts on annual ET but could not be investigated here.

The recent introduction and use of new techniques for measuring ET above forest stands allows 3-PG predicted ET to be tested against field measurements. This is recommended for further study to verify that 3-PG model output is realistic.

7. DISCUSSION AND CONCLUSION

Despite the necessary simple approach towards parameterisation of 3-PG, the results of this study have demonstrated the potential for 3-PG to describe many growth-limiting factors and to predict growth with encouraging realism. Patterns of changing *L* over time, responses to drought, and annual ET patterns all look realistic. The same realism was evident in a preceding study by Dye *et al.,* (2001) on predictions of *Pinus patula* using 3-PG. Both these studies have endeavoured to accomplish the first parameterisation of pine species in South Africa. Furthermore, these studies have been in line with the intentions of the IF in this regard. By the same token, and with particular regard to this study, the realism of predictions is also thought to have been restricted by the assumptions made in this study's parameterisation process (p.38).

It is recognised that forestry planners require greater accuracy in predicting stand volumes, and the 3-PG model has the potential to meet this need. However, for this accuracy in predictions to be possible, this study further stressed that the initialisation data must be based on the recorded values, and estimations of these values must be avoided as far as possible.

In addition, the 3-PG model version applied was not exhaustive in terms of actually considering several elements, which might affect the resultant predictions (it excluded actual silvicultural management events). A new version of 3-PG (Sim-a-Tree) is currently under development by the IF team, and many improvements over the spreadsheet version used here are being introduced. These improvements include a daily time step, improved estimation of solar radiation and VPD, simulation of pruning events, and many other modifications reported by Dye (2003). Furthermore, this study has established that achieving success with 3-PG modelling will require the following:

The use of all input data to set up predictions. The following strategy is recommended:

- obtain on-site soil data for each stand to be predicted. Soil depth, texture and organic carbon contents are frequently available from past soil surveys;

- assess trees per hectare and mean height after post-planning rates have declined and when the young trees are fully established. Mortality rates are variable, and are influenced by many factors (e.g. site preparation, quality of planting process, seedling quality, insect damage, rainfall and evaporative conditions following planting, frost incidence, weed prevalence, method of slash management, fungal pests, soil compaction, etc.) that are probably impossible to ever model using a process-based approach. Since a realistic starting biomass is essential, it would be useful to start all predictions at the time of an early field inventory. Such early data would ensure that starting biomass is accurate, and would provide an early indication of site quality, which would guide estimations of fertility rating and maximum ASW;
- in stands unthinned, predict through to the end of rotation and,
- in thinned stands, use pre-thinning surveys to re-initialise simulation. Volume estimation becomes increasingly sensitive to errors in diameter and height estimation, as trees grow larger.

2. Experience that must be gained in parameterising 3-PG over a wide range of sites.

This will obviously take time as more and more compartments are modelled and predictions compared to field observations. This process will encourage understanding of what site factors limit growth, and lead to new insights when explanations for discrepancies are found.

3. Diverse model applications.

The following model applications would be relatively easily introduced into current forestry operations to provide useful data:

- providing a year-by-year assessment of growth increments achieved over a wide range of compartments in order to update estimates of yields and improve planning of wood flow to the mills;
- predicting growth from mid-rotation surveys until harvest time, thus dispensing with pre-harvest stand inventories;

- evaluating potential growth rates on new afforestation sites where no prior afforestation has occurred. Good soil description and weather input data should lead to realistic predictions of growth and yields and,
- drought risk assessment.

4. Realistic measurements or estimation of species and site-specific parameter values.

The accuracy and credibility of the 3-PG modelling will not reach it potential as long as all model parameters are not accurately determined. Methods to measure site and species specific parameters need to be devised soon for *Pinus elliottii* and other forestry species.

It will be to the advantage of the South African forestry industry if these reflect the local measurements. Once these methods have been devised, it is important that they are correctly implemented because some of the site and stand factors are acutely sensitive to changes in these parameters. Furthermore, studies that strengthen our understanding of physiological processes and, subsequently 3-PG parameter values, need to be commissioned.

The greatest challenge to fostering the use of 3-PG by the South African forestry industry is to improve our ability to measure or estimate the required parameters and site factors for any given forest compartment. This will come with experience in 3-PG modelling, and will take time to accumulate. However, once obtained, it will lead to a huge improvement in our understanding of what limits tree growth rates, and the accuracy with which we can predict growth and yields.

Future research needs to focus on a smaller range of diverse sites where good site and growth information is available. Predictions at these sites should be validated by accurate monthly measurements of stand structure (especially diameter, height growth and *L*), and correlated to regular field measurements (e.g. tree water status, sap flow rates and canopy conductance) describing the physiological status of the trees. Such studies will lead to further refinements in species parameters developed in this study (**Table 15**) and to further insights into site constraints on tree growth that will greatly improve our ability to predict growth and yields in *Pinus elliottii* stands.

In conclusion, this study demonstrated that 3-PG has potential as a predictive tool. However, although 3-PG predicts growth realistically, there are still some concerns and uncertainty based on this study. It is thus concluded that although the results have been proven to be sound, 3-PG must, for now, be used solely as a strategic tool. In addition, this study has been able to:

- produce parameter sets for the 3-PG model that predicts the growth and water use of *Pinus elliottii* over a representatively wide range of South African sites and,
- improve the understanding of the parameterisation process for *Pinus elliottii* through inferences made in various sections of this document.
- improve the assessment of the usefulness of the 3-PG model in South Africa.

However, this study has not been able to:

- provide a better understanding of what factors limit the growth rates of trees using 3-PG. This is because the essence of this study and the research course taken was to solely develop 3-PG parameters that will produce the best fit for *Pinus elliottii* predictions in South Africa. As alluded earlier, the factors that limit the growth of trees still need primary research, which will eventually be incorporated in similar modelling studies such as this one.

Table 15: Final 3-PG parameter set developed for *Pinus elliottii*.

Parameter name	3PG- Name	Units	Value
Allometric relationships and partitioning			
Foliage: stem partitioning ratio @ D=2 cm	pFS2	-	0.93
Foliage: stem partitioning ratio @ D=20 cm	pFS20	-	0.2
Constant in the stem mass v. diam. Relationship	StemConst	-	0.04
Power in the stem mass v. diam. Relationship	StemPower	-	2.65
Maximum fraction of NPP to roots	pRx	-	0.8
Minimum fraction of NPP to roots	pRn	-	0.25
Litterfall and root turnover			
Maximum litterfall rate	gammaFx	1/month	0.037
Litterfall rate at t = 0	gammaF0	1/month	0.001
Age at which litterfall rate has median value	tgammaF	month	24
Average monthly root turnover rate	Rttover	1/month	0.075
Temperature modifier (fT)			
Minimum temperature for growth	Tmin	Deg. C	4
Optimum temperature for growth	Topt	Deg. C	23
Maximum temperature for growth	Tmax	Deg. C	35
Frost modifier (fFRost)			
Days production lost per frost day	kF	days	1
Soil water modifier (fSW)			
Moisture ratio deficit for fq = 0.5	SWconst	-	0.5
Power of moisture ratio deficit	SWpower	-	5
Fertility effects			
Value of 'm' when FR = 0	m0	-	0
Value of 'fNutr' when FR = 0	fN0	-	1
Power of (1-FR) in 'fNutr'	fNn	-	0
Age modifier (fAge)			
Maximum stand age used in age modifier	MaxAge	years	80
Power of relative age in function for fAge	nAge	-	4
Relative age to give fAge = 0.5	rAge	-	0.95
Stem mortality and self-thinning			
Mortality rate for large t	gammaNx	%/year	0.01
Seedling mortality rate (t = 0)	gammaN0	%/year	0.15
Age at which mortality rate has median value	tgammaN	years	0.5
Shape of mortality response	ngammaN	-	1
Max. stem mass per tree @ 1000 trees/hectare	wSx1000	kg/tree	340
Power in self-thinning rule	thinPower	-	1.5
Fraction mean single-tree foliage biomass lost per dead tree	mF	-	0
Fraction mean single-tree root biomass lost per dead tree	mR	-	0.2
Fraction mean single-tree stem biomass lost per dead tree	mS	-	0.2
Specific leaf area			
Specific leaf area at age 0	SLA0	m2/kg	5
Specific leaf area for mature leaves	SLA1	m2/kg	5
Age at which specific leaf area = (SLA0+SLA1)/2	tSLA	years	2.5
Light interception			
Extinction coefficient for absorption of PAR by canopy	K	-	0.5
Age at canopy cover	fullCanAge	years	0
Maximum proportion of rainfall evaporated from canopy	MaxIntcptn	-	0.13

Parameter name	3PG- Name	Units	Value
L for maximum rainfall interception	LmaxIntcptn	-	8
Production and respiration			
Canopy quantum efficiency	Alpha	molC/molPAR	0.05
Ratio NPP/GPP	Y	-	0.47
Conductance			
Maximum canopy conductance	MaxCond	m/s	0.02
L for maximum canopy conductance	Lgcx	-	3.33
Defines stomatal response to VPD	CoeffCond	1/mBar	0.05
Canopy boundary layer conductance	BLcond	m/s	0.2
Branch and bark fraction (fracBB)			
Branch and bark fraction at age 0	fracBB0	-	0.75
Branch and bark fraction for mature stands	fracBB1	-	0.19
Age at which fracBB = (fracBB0+fracBB1)/2	tBB	years	5
Basic Density			
Minimum basic density – for young trees	rhoMin	t/m3	0.36
Maximum basic density - for older trees	rhoMax	t/m3	0.4
Age at which rho = (rhoMin+rhoMax)/2	tRho	years	7
Stem height			
Constant in the stem height relationship	aH	-	0.210
Power of DBH in the stem height relationship	nHB	-	1.224
Power of trees per hectare in the stem height relationship	nHN	-	0.081
Stem volume			
Constant in the stem volume relationship	aV	-	9.848
Power of DBH in the stem volume relationship	nVB	-	3.381
Power of trees per hectare in the stem volume relationship	nVN	-	1.288
Conversion factors			
Intercept of net v. solar radiation relationship	Qa	W/m2	-90
Slope of net v. solar radiation relationship	Qb	-	0.8
Molecular weight of dry matter	gDM_mol	gDM/mol	24
Conversion of solar radiation to PAR	molPAR_MJ	mol/MJ	2.3

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9. APPENDICES

Appendix 1: Names and description of 3-PG output variables.

Description	Output name	3-PG name	Units
Site and management attributes			
Name of site given on site data sheet	Site name	Site name	
Fertility rating	Fert. Rating	FR	
Minimum available soil water (for supplemental irrigation)	Min ASW	minASW	mm
Applied irrigation	Annual irrigation	Irrig	mm/ha/ years
Stand attributes			
Current stand age	Stand age	Stand age	Years
Stand trees per hectare	Trees per hectare	StemNo	trees/h
Stand basal area	Basal area	BasArea	m^2/ha
Stand volume, main stem excluding bark	Stand volume	StandVol	m^3/ha
Stand-based mean DBH	Mean DBH	avDBH	Cm
Current mean annual stem volume increment	MAI	MAI	m^3/ha/ years
Peak MAI of stand to the current stand age	Peak MAI	MAIx	m^3/ha/ years
Stand age at which MAI peaked	Age at peak MAI	ageMAIx	Yr
Current canopy Leaf area index (mean annual value if output is annual)	L	L	
Peak Leaf area index of canopy up to the current stand age	Max L	Lx	
Stand age at which L peaked	Age at max L	ageLx	Yr
Fraction of ground area covered by canopy	Fract. Canopy cover	CanCover	
Biomass pools and canopy attributes			
Foliage biomass	Foliage DM	WF	tDM/ha
Root biomass	Root DM	WR	tDM/ha
Stem biomass, including branches and bark	Stem DM	WS	tDM/ha
Total biomass	Total DM	TotalW	tDM/ha
Mean stem biomass per tree	Mean stem mass	AvStemMass	kgDM/tree
Fraction of above ground woody biomass as branch and bark	Fract. as bark and branch	fracBB	
Specific leaf area	SLA	SLA	m2/kg
Annual outputs			
Light utilisation efficiency based on above ground biomass	Above ground epsilon	abvgrndEpsilon	gDM/MJ
Light utilisation efficiency based on total biomass	Total epsilon	totalEpsilon	gDM/MJ
Annual total evapotranspiration	Annual ET	cumEvapTransp	mm/ years
Annual total transpiration	Annual transp.	cumTransp	mm/ years
Annual total supplemental irrigation	Annual suppl. Irrigation	cumIrrig	mm/ years

Description	Output name	3-PG name	Units
Annual total net primary production	Annual NPP	cumNPP	tDM/ha/ years
Annual total leaf litterfall	Annual litterfall	CumLittfall	tDM/ha/ years
Growth modifiers			
Age dependent modifier	fAge	fAge	
VPDdependent modifier	fVPD	fVPD	
Temperature dependent modifier	fTemp	fT	
Frost dependent modifier	fFrost	fFrost	
Soil water dependent modifier	fSW	fSW	
Nutrition dependent modifier	fNutr	fNutr	
Physiological modifier of canopy conductance	Phys. modifier	PhysMod	
Fertility dependent modifier of root biomass partitioning	M	m	
Biomass production and partitioning			
Net primary production	Monthly NPP	NPP	tDM/ha/month
Canopy quantum efficiency after application of modifiers	Canopy alpha	alphaC	mol/mol
Fraction of NPP partitioned to roots	pR	pR	
Fraction of NPP partitioned to stems	pS	pS	
Fraction of NPP partitioned to foliage	pF	pF	
Ratio of foliage to stem biomass partitioning	pFS	pFS	
Leaf litterfall rate	Litterfall rate	Littfall	1/month
Monthly total leaf litterfall	Litterfall	delFloss	tDM/ha/month
Water use			
Available soil water	ASW	ASW	Mm
Monthly supplemental irrigation (to maintain minASW)	Monthly supp. irrig.	monthlyIrrig	mm/month
Monthly evapotranspiration rate	Monthly ET	EvapTransp	mm/month
Monthly transpiration rate	Monthly transp.	Transp	mm/month
Canopy conductance	Canopy conductance	CanCond	
Climatic factors			
Day length (sunrise to sunset)	Daylength	DayLength	s/day
Mean number of frost days per month	Frost days	FrostDays	Days/month
Mean daily incident solar radiation	Solar rad.	SolarRad	MJ/m/day
Mean daily temperature	Mean temp.	Tav	C
Mean daily VPD	VPD	VPD	mBar
Mean monthly rainfall	Rainfall	Rain	mm/month

Appendix 2: Description of 3-PG parameters.

3-PG Parameter	**3-PG symbol**	**3PGPJS name**	**Site or species specific**	**Units**
Allometric relationships and partitioning				
Ratio of foliage: stem partitioning at D = 2 cm	P_2	pFS2	Species	-
Ratio of foliage: stem partitioning at D = 20 cm	P_{20}	pFS20	Species	-
Constant in stem mass v diam. Relationship	a_S	stemConst	Species	kg
Power in stem mass v diam. Relationship	n_S	stemPower	Species	-
Maximum fraction of NPP to roots	h_{Rx}	pRx	Species	-
Minimum fraction of NPP to roots	h_{Rn}	pRn	Species	-
Temperature modifier				
Minimum temperature for growth	T_{min}	Tmin	Species	deg. C
Optimum temperature for growth	T_{opt}	Topt	Species	deg. C
Maximum temperature for growth	T_{max}	Tmax	Species	deg. C
Frost modifier				
Number of days production lost for each frost day	k_F	Kf	Species	
Soil water modifier				
Moisture ratio deficit which gives fq = 0.5	c_θ	SWconst	site	-
Power of moisture ratio deficit in fq	n_θ	SWpower	site	-
Age modifier				
Maximum stand age used to computer relative age	-	MaxAge	Species	years
Power of relative age in fage	n_{age}	nAge	Species	-
Relative age to give fage = 0.5	r_{age}	RAge	Species	-
Litterfall and root turnover				
Maximum litterfall rate	γ_{Fx}	gammaFx	Both	$month^{-1}$
Litterfall rate at t = 0	γ_{F0}	gammaF0	Both	$month^{-1}$
Age at which litterfall rate has median value	$t_{\gamma}F$	tgammaF	Both	month
Average monthly root turnover rate	${}_{\gamma}R$	Rttover	Both	$month^{-1}$
Conductance				
Maximum canopy conductance	g_{Cx}	MaxCond	Species	$m\ s^{-1}$
Canopy L for maximum canopy conductance	L_{Cx}	Lgcx	Species	-
Defines stomatal response to VPD	k_g	CoeffCond	Species	$mBar^{-1}$
Canopy boundary layer conductance	g_B	BLcond	Both	$m\ s^{-1}$
Fertility effects				
Value of m when FR = 0	M_0	M0	Species	-
Value of fN when FR = 0	f_{N0}	fN0	Species	-
Power of (1-FR) in fN	nfN	fNn	Species	-
Stem mortality				
Maximum stem mass per tree at 1000 trees/ha	w_{Sx1000}	wSx1000	Both	kg $tree^{-1}$
Power in self thinning law	n_N	thinPower	Both	-

3-PG Parameter	3-PG symbol	3PGPJS name	Site or species specific	Units
Fraction of mean foliage biomass per tree on dying trees	m_F	mF	Both	-
Fraction of mean root biomass per tree on dying trees	m_R	mR	Both	-
Fraction of mean stem biomass per tree on dying trees	m_S	mS	Both	-
Canopy structure and processes				
Specific leaf area at stand age 0	Σ_0	SLA0	Species	m^2 kg^{-1}
Specific leaf area for mature aged stands	Σ_1	SLA1	Species	m^2 kg^{-1}
Age at which specific leaf area = ½(s0+s1)	t_σ	Tsla	Species	Years
Extinction coefficient for absorption of PAR by canopy	K	K	Species	-
Age at full canopy cover	t_{cc}	fullCanAge	Species	Years
Maximum proportion of rainfall intercepted by canopy	I_x	MaxIntcptn	Species	-
L for maximum rainfall interception	L_{Ix}	LmaxIntcptn	Species	-
Canopy quantum efficiency	A	Alpha	Species	molC mol^{-1} PAR
Ratio NPP/GPP	Y	Y	species	-
Branch and bark fraction				
Branch and bark fraction at stand age 0	p_{BB0}	fracBB0	species	-
Branch and bark fraction for mature aged stands	p_{BB1}	fracBB1	species	-
Age at which branch and bark fraction = ½(pBB0+ pBB1)	t_{BB}	tBB	species	Years
Basic density				
Maximum basic density – for older trees	r_x	rhoMax	both	t m^{-3}
Ratio of basic density for young trees/density of old trees	r*	rhoRatio	both	-
Age at which r = ½ density of old and young trees	t_r	tRho	both	Years
Conversion factors				
Intercept of net radiation v solar radiation relationship	Q_a	Qa	species	W m-^{2}
Slope of net radiation v solar radiation relationship	Q_b	Qb	species	
Molecular weight of dry matter		gDM_mol	species	gm mol^{-1}
Conversion of solar radiation to PAR		molPAR_MJ	species	mol MJ^{-1}

Appendix 3: A list of districts in which study stands were selected, indicating which rainfall and temperature stations were used for each simulation (See List of Acronyms for units) .

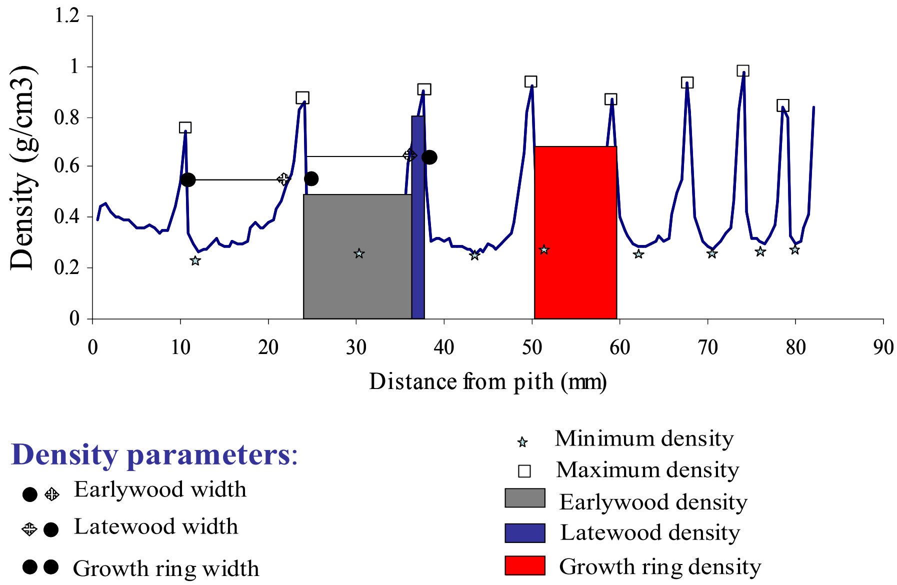
Stand	Location*	Long	Lat	Rainfall station	Temperature station	Rainfall		Temperature	
						Long	Lat	Long	Lat
1	**Boston**	30.15938	29.59131	Naauwpoort	Little Harmony, Richmond	3012	2959	3019	2956
2	Greytown	30.68284	28.99920	Springgroove estate	Hazyview,Kranskop	3044	2900	3052	2858
3	Hlabeni	29.77472	29.98889	Lilydale, Donnybrook	Swartberg, Sheltervale	2958	3000	2908	3006
4	**Howick**	30.27390	29.42235	Inanda Dam	Natal est, Thornvill	3052	2942	3024	2945
5	Mahehle	29.92500	30.12194	The Grange, Umzimkulu	The Grange, Umzimkulu	2958	3015	2958	3015
6	Melmoth	31.16474	28.57960	Mtunzini (MAG)	Entumeni Mill	3145	2857	3118	2854
7	Seven Oaks	30.56299	29.19939	White mountain, Dalt	Seven Oaks-Ryhill	3039	2920	3037	2914
8	Babanango	31.08389	28.42139	Speedwell	Riversbend est, Nkwa	3100	2841	3132	2843
9	Golden Reef	31.27639	28.59167	Hudson AR, Eshowe	Eshowe Bos	3128	2854	3128	2853
10	**Piet Retief**	30.71460	26.96282	Piet Retief	Piet Retief	3048	2700	3045	2700
11	Badplaas1	30.48713	25.84091	Middlemam	Nelspriut: Brondal	3048	2538	3051	2521
12	Belfast	30.03010	25.63361	Belfast (Pol)	Belfast	3003	2542	3002	2539
13	Berlin	30.78592	25.59733	Berlin Bos	Barberton (Agric)	3045	2533	3101	2547
14	**Blyde1**	30.84265	24.88527	Blyde(Bos)	Vaalhoek	3050	2450	3047	2444
15	Blyde2	30.87529	24.85961	Blyde(Bos)	Lydenburg, Rosenkrans	3050	2450	3037	2454
16	Carolina	30.35535	26.11721	Carolina (mun)	Carolina(mun)	3007	2604	3007	2604
17	Jessievale	30.53097	26.21886	Jessievale(Bos)	Songimvelo	3031	2614	3054	2602
18	Lothair	30.63358	26.45564	Wolwenkop cascades	Athole Proefplaas	3044	2646	3035	2636
19	**Machadodorp**	30.33499	25.59235	Machadodorp	Elandshoek	3015	2540	3028	2536
20	Morgenzon	30.70644	24.87857	Rietspruit	Lydenburg Rosenkrans	3056	2459	3037	2454
21	Nelshoogte	30.87047	25.81175	Nelshoogte(Bos)	Friedenheim	3050	2550	3059	2526
22	Ngodwana1	30.52219	25.56974	Heights	Barberton Koffiekor	3056	2556	3058	2545
23	**Ngodwana2**	30.57018	25.52108	Badplaas Vygeboom dam	Barberton Koffiekor	3037	2552	3058	2545
24	Roburnia	30.74150	26.71203	Roburnia (Bos)	Piet Retief	3045	2640	3048	2700
25	Sudwala1	30.53551	25.30671	Elandhoek	Coetzeestroom	3042	2530	3045	2538
26	Uitsoek	30.54199	25.29696	Friednheim, Nissv	Friedenheim	3058	2528	3059	2526
27	**Badplaas2**	30.70217	25.87489	Badplaas (Pol)	Badplaas (Vygeboomdam	3034	2558	3039	2554
28	Barberton	30.84121	25.68177	Barberton (Agric)	Barberton (Agric)	3101	2547	3101	2547

Stand	Location	Long	Lat	Rainfall station	Temperature station	Rainfall		Temperature	
						Long	Lat	Long	Lat
9	Bergvliet	30.86322	25.10771	Bergvliet	DR DE Wet(Sabi)GorgeBos	3053	2504	3053	2503
30	**Brooklands**	30.87868	25.32800	Brooklands (Bos)	Nelspriut	3045	2514	3058	2527
31	Franfort	30.89474	25.03477	Frankfort(Bos)	DR DE Wet(Sabi)GorgeBos	3053	2502	3053	2503
32	NewAgatha	30.09717	23.94008	SERALA (Bos)	TOURS	3005	2401	3017	2405
33	**Spitskop**	30.84542	25.17970	Spitkop (Bos)	Nelspriut: Brondal	3050	2509	3051	2521
34	**Sudwala**	30.68371	25.43714	Bornmansdrift	Barberton Koffiefor	3058	2543	3058	2545
35	Tweefontien	30.79441	25.06619	Tweefontien (Bos)	Lydenburg	3047	2503	3028	2506
36	Wilgeboom	30.91632	24.89854	Wilgeboom (Bos)	DR DE Wet(Sabi)GorgeBos	3057	2456	3053	2503
37	Witklip	30.88278	25.20793	Witklip	Nelspriut: Brondal	3024	2512	3051	2521
38	**Woodbush**	30.00745	23.75699	SERALA (Bos)	TOURS	3005	2401	3017	2405
39	Entabeni	30.25004	23.04698	Roodewal	Levubu	3002	2300	3017	2305
40	NECF stand 15	28^{0}13’34”	31^{0}11’17”	Ugie	Ugie	2816	3113	2816	3113
41	NECF stand 18	28^{0}13’25”	31^{0}11’12”	Ugie	Ugie	2816	3113	2816	3113
42	Dukuduku	32.25	28.35	Cape St Lucia	Cape st lucia	3224	2830	3224	2830
43	kwaMbonambi	32.183	28.633	Kwa-Mbonambi	Cape st lucia	3211	2838	3224	2830
44	NECF stand 11	28^{0}10’48”	31^{0}13’14”	Ugie	Ugie	2816	3113	2816	3113

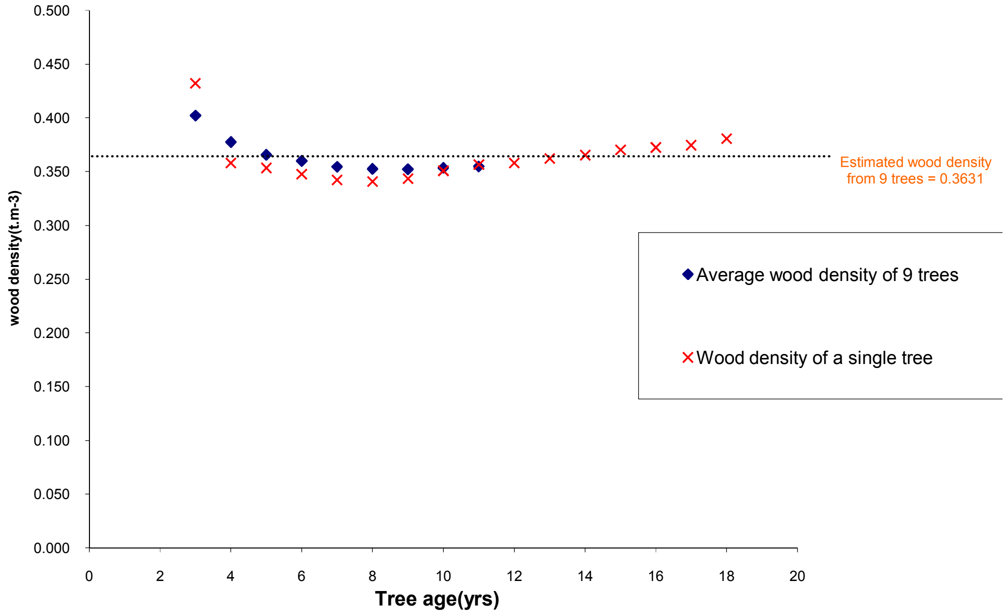
*Stands in bold were used as test stands.

Appendix 4: Estimation method used to determine wood density of *Pinus elliottii* (A. Zbonak, 2004, pers. Comm*).

A. Schematic below shows wood density estimation



B. *Pinus elliottii* wood density value determination



Appendix 5: Starting biomass of branch and bark ($t.ha^{-1}$), (foliage, Wf ($t.ha^{-1}$); stem, Ws ($t.ha^{-1}$), and roots, Wr ($t.ha^{-1}$) of respective 44 stand location, age (years), Dq (cm), Hq (m), TPH ($tree.ha^{-1}$), Stand volume ($m^3.ha^{-1}$), DBH (cm), and Stem mass ($t.ha^{-1}$).

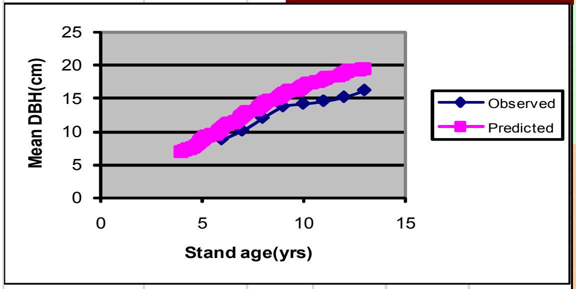
Location	Age	Dq	Hq	TPH0	TPH1	Mortality	Stand volume at age 4	DBH at age 4	Stem mass at age 4	Branch and bark	Ws	Wr	Wf	Mean height	Dominant height at age 4
Babanango	11.0	20.9	15.0	1327	1327	0.00	11.87	8.900	4.486	10.113	14.599	3.483	2.491	4.500	6.09
Badplaas1	10.0	12.8	9.4	1609	1609	0.00	3.97	6.200	1.499	5.796	7.295	3.009	0.966	2.700	4.15
Badplaas2	11.6	15.9	10.5	1527	924	0.14	5.58	7.600	2.108	7.930	8.633	2.682	1.151	2.700	4.08
Barberton	10.4	18.3	13.0	1146	1132	0.01	6.02	7.600	2.277	7.930	10.083	3.091	1.328	3.700	5.51
Belfast	6.5	10.4	4.7	816	604	0.14	2.01	6.200	0.760	5.796	5.639	2.478	0.422	2.700	3.01
Bergvliet	10.4	19.9	14.9	1372	1015	0.14	12.27	8.900	4.638	10.113	12.686	3.017	2.215	4.500	6.34
Berlin	25.4	32.9	27.5	1372	1015	0.14	12.27	8.900	4.638	10.113	12.686	3.017	2.215	4.500	6.00
Blyde1	15.5	31.5	21.0	1372	481	0.14	12.27	8.900	4.638	10.113	12.686	3.017	2.215	4.500	6.50
Blyde2	14.3	27.7	17.4	1372.0	1015	0.14	7.21	7.600	2.726	7.930	9.165	2.756	1.384	3.700	5.75
Boston	10.6	21.5	9.3	1081	1055	0.02	3.95	7.600	1.492	7.930	9.196	2.939	0.925	2.700	3.89
Brooklands	15.3	23.2	16.5	1372	381	0.14	9.78	8.900	3.698	10.113	11.877	2.901	1.851	3.700	5.15
Carolina	9.7	17.4	10.4	1629	1508	0.07	4.01	6.200	1.518	5.796	6.771	2.788	0.906	2.700	4.69
Dukuduku	13.0	16.5	11.7	1333	1333	0.00	3.29	6.200	1.242	5.796	7.038	2.964	0.801	2.700	4.16
Entabeni	7.1	16.3	9.1	816	604	0.14	4.29	7.600	1.621	7.930	8.215	2.597	0.823	3.700	5.41
Frankfort	10.7	22.1	16.3	1372	1015	0.14	12.27	8.900	4.638	10.113	12.686	3.017	2.215	4.500	6.80
Golden Reef	14.6	17.0	15.9	1406	1406	0.00	7.39	7.600	2.794	7.930	10.724	3.216	1.649	3.700	5.15
Greytown	8.4	19.0	10.8	1184	1169	0.01	6.22	7.600	2.353	7.930	10.153	3.102	1.371	3.700	5.53
Hlabeni	15.6	22.2	16.3	1377	1018	0.14	7.24	7.600	2.736	7.930	9.173	2.757	1.389	3.700	5.03
Howick	10.6	21.9	14.7	1545	1183	0.26	13.82	8.900	5.222	10.113	11.342	2.665	2.145	4.500	6.17
Jessievale	21.8	34.9	22.8	1738	1285	0.14	9.14	7.600	3.454	7.930	9.790	2.860	1.753	3.700	5.50
kwaMbonambi	28.1	24.1	22.6	988	988	0.00	2.44	6.200	0.920	5.796	6.717	2.909	0.593	2.700	4.63
Lothair	11.1	21.5	12.0	1599	1183	0.14	3.94	6.200	1.490	5.796	6.266	2.586	0.826	2.700	4.86
Machadodorp	16.8	25.8	19.1	1461	1443	0.01	10.42	8.900	3.938	10.113	13.878	3.372	2.264	3.700	5.56
Mahehle	14.1	21.5	16.8	1150	1150	0.00	6.05	7.600	2.285	7.930	10.216	3.131	1.349	3.700	5.58
Melmoth	12.7	18.4	14.3	1103	816	0.14	5.80	7.600	2.192	7.930	8.705	2.679	1.113	3.700	5.17
Morgenzon	9.8	21.8	12.0	1372	1015	0.14	7.21	7.600	2.726	7.930	9.165	2.756	1.384	3.700	5.40
NECF stand 11	15.0	15.0	15.8	1230	1230	0.00	12.45	8.900	4.707	10.113	14.820	3.309	1.929	3.700	5.01
NECF stand 15	17.0	23.9	18.8	1149	1149	0.00	6.04	7.600	2.283	7.930	10.214	3.131	1.348	3.700	5.43
NECF stand 18	13.0	16.0	11.8	1181	1181	0.00	2.91	6.200	1.100	5.796	6.897	2.940	0.709	2.700	4.19

Location	Age	Dq	Hq	TPH0	TPH1	Mortality	Stand volume at age 4	DBH at age 4	Stem mass at age 4	Branch and bark	Ws	Wr	Wf	Mean height	Dominant height at age 4
Nelshoogte	14.9	20.6	17.5	1111	822	0.14	5.84	7.600	2.208	7.930	8.719	2.681	1.121	3.700	5.58
NewAgatha	14.0	23.8	16.3	816	706	0.13	4.29	7.600	1.621	7.930	8.264	2.613	0.828	3.700	5.46
Ngodwana1	17.8	16.8	15.9	1400	1035	0.14	3.45	6.200	1.304	5.796	6.107	2.559	0.723	2.700	4.44
Ngodwana2	21.6	22.5	21.3	1131	1076	0.05	8.06	8.900	3.048	10.113	12.521	3.105	1.688	3.700	5.18
Piet Retief	11.6	18.1	12.3	1611	1481	0.08	7.98	8.900	3.016	10.113	12.070	3.019	1.738	2.700	4.80
Roburnia	20.6	28.1	21.8	1372	1015	0.14	7.21	7.600	2.726	7.930	9.165	2.756	1.384	3.700	5.48
Sevenoaks	14.8	22.8	16.0	1497	1405	0.06	7.87	7.600	2.975	7.930	10.235	3.046	1.648	3.700	5.12
Spitskop	13.3	23.7	17.3	1372	638	0.14	12.27	8.900	4.638	10.113	12.686	3.017	2.215	4.500	6.02
Sudwala1	18.0	28.9	20.8	1171	866	0.14	6.16	7.600	2.327	7.930	8.821	2.699	1.181	3.700	5.74
Sudwala2	8.9	13.5	10.0	1493	1400	0.06	10.65	8.900	4.024	10.113	13.257	3.215	2.196	3.700	4.91
Tweefontien	27.2	36.4	32.7	1372	1015	0.14	12.27	8.900	4.638	10.113	12.686	3.017	2.215	4.500	6.84
Uitsoek	19.3	23.3	20.3	1372	1015	0.26	7.21	7.600	2.726	7.930	7.882	2.370	1.190	3.700	5.35
Wilgeboom	11.0	22.1	15.2	1372	1015	0.26	12.27	8.900	4.638	10.113	10.910	2.595	1.905	4.500	6.19
Witklip	19.3	31.0	23.0	1372	1015	0.14	12.27	8.900	4.638	10.113	12.686	3.017	2.215	4.500	6.06
Woodbush	36.7	42.5	28.3	1372	306	0.14	9.78	8.900	3.698	10.113	11.877	2.901	1.851	3.700	4.99
Average	**1.0**	**22.4**	**16.3**	**1314.4**	**1101**	**0.10**	**7.72**	**7.85**	**2.918**	**8.386**	**10.12**	**2.90**	**1.50**	**3.63**	**5.29**

Appendix 6: Example of a single site run for 3-PGpjs version used in this study.

Run type: **SingleSite**
Site = **Wildebees**
Species = **P. elliottii**

This **Single-site** run uses the standard initialisation technique to initialise the stand with data from a biomass harvest.



Site factor block

Latitude = -31
Fertility rating = 0.4
Soil class = SL
Maximum ASW = 136
Minimum ASW = 0
Altitude **1349**

Initialisation block

Year planted = 1980
Month planted = January
Initial year = 1984
Initial month = January
End age = 13
Initial WF = 0.709
Initial WR = 2.94
Initial WS = 6.897
Initial stocking = 1181
Initial ASW = 100

Output details

Title : **Growth from initial year**
Output data :
Details sheet : Wildebees
Output frequency : m

Silvicultural events

Thinning Age	Stocking	F	R	S
8	650	0.5	0	0.5
13	400	0.3	**0**	0.3

Observed data

Age	**standVol**	**StemNo**	**Mean DBH**
1		1181	
2		1181	
3		1181	3
4		1181	4.8
5		1181	6.2
n		n	n

	Climate data	**Tmax**	**Tmin**	**Rain**	**Pan Evap**	**Solar rad**	**Rain days**	**Frost days**
1980	**January**	25.6	13.1	90.8	0.0	29.921	0.0	0.0
	Feb	25.6	13	117.8	0.0	27.605	0.0	0.0
	March	24.8	12.8	87.8	0.0	22.657	0.0	0.0
	April	23	7	11.5	0.0	20.171	0.0	0.0
	may	20.8	2	6.2	0.0	15.989	0.0	0.0
	June	17.4	-1	0	0.0	13.838	0.0	0.0
	July	18.3	-3.3	1.2	0.0	14.851	0.0	0.0
	Aug	19.8	2.5	3.7	0.0	18.518	0.0	0.0
	Sep	17.9	4.5	65.5	0.0	22.32	0.0	0.0
	oct	22.2	8.3	33	0.0	27.49	0.0	0.0
	Nov	23	10	132	0.0	29.902	0.0	0.0
	Dec	25.1	12.3	120	0.0	30.943	0.0	0.0
1981	**Jan**	24.8	13.7	210.4	0.0	27.236	0.0	0.0
	Feb	23.3	13.5	209.5	0.0	21.882	0.0	0.0
	Mar	22.4	10.6	55.1	0.0	22.518	0.0	0.0
	Apr	22.9	7.2	27.2	0.0	20.268	0.0	0.0
	May	17.9	4.5	54.6	0.0	14.933	0.0	0.0
	Jun	16.3	-0.1	17	0.0	13.7	0.0	0.0
	Jul	17.5	-0.2	0.8	0.0	14.676	0.0	0.0
	Aug	15	1.1	59.1	0.0	17.414	0.0	0.0
	Sep	18.3	3.3	6.8	0.0	23.144	0.0	0.0
	Oct	20.5	5.1	16.7	0.0	28.289	0.0	0.0
	Nov	24.3	10.5	67	0.0	30.734	0.0	0.0
	Dec	24.6	12	110.7	0.0	30.63	0.0	0.0

#Output from 3PGpjs 2.4 / 3-PG May2004. Stand initialised by pool biomasses

Stand development for Wildebees

Growth from initial year

Year & month	**Stand age**	**Stems**	**Foliage DM**	**Root DM**	**Stem DM**	**Stand volume**	**LAI**	**MAI**	**Mean DBH**
1984 - Jan	4	1181	1.13	3.053	7.549	8.70	0.36064	2.18	6.78
1984 - Feb	4.0833333	1180.99	1.27	3.23	7.98	9.27	0.41	2.27	6.93
1984 - Mar	4.1666667	1180.979	1.41	3.38	8.43	9.86	0.45	2.37	7.07
1984 - Apr	4.25	1180.969	1.51	3.45	8.78	10.34	0.48	2.43	7.18
1984 - May	4.3333333	1180.959	1.58	3.44	9.06	10.71	0.50	2.47	7.27
1984 - Jun	4.4166667	1180.949	1.59	3.32	9.23	10.93	0.51	2.48	7.32
1984 - Jul	4.5	1180.939	1.62	3.26	9.44	11.22	0.52	2.49	7.38
1984 - Aug	4.5833333	1180.929	1.70	3.30	9.76	11.66	0.54	2.54	7.48