Quantifying and modelling the effects of environmental factors on wood properties of *Eucalyptus grandis* in South Africa

by

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ABSTRACT

In the past 25 years, forest management has shifted emphasis from simply growing trees for maximum volume towards managing plantations to provide sufficient quantities of fibres with properties that better meet the requirements of the manufacturing process and the final product produced by mills. The goal of that shift was to minimise processing costs and achieve more consistent and predictable outputs from plantation forests. *Eucalyptus grandis*, the dominant hardwood species for the pulp and paper industry in South Africa, accounts for 56.4% of the total *Eucalyptus* plantation area and is planted across a wide range of site conditions.

This research aimed to quantify and model the effects of specific environmental variables on the wood quality of *Eucalyptus grandis* in the warm temperate (WT) and sub-tropical (ST) forestry regions in South Africa using non-destructive, rapid screening techniques. Furthermore, because this species lacks distinct annual boundaries that correspond to seasonal climatic changes, the change in wood properties with age usually cannot be studied with reasonable accuracy. For this reason, a study was carried out to examine the linkage between radial variation patterns in wood density and annual radial growth, in order to determine to what degree of accuracy annual ring boundaries could be detected through this method.

The warm temperate and the sub-tropical regions were each divided into nine sub-classes on the basis of three mean annual precipitation (MAP) classes (dry, moist and wet) and three soil water storage (SWS) capacities (low, medium and high) to achieve a range of water availability among blocks within each region. Compartments planted to *E. grandis* were selected from KwaZulu-Natal and Mpumalanga. Plots within the compartments were enumerated and cores (from pith to bark) were sampled at breast height from five trees per compartment. Wood density, wood anatomical characteristics, and percentages of cellulose and lignin were assessed using gamma-ray densitometry, light microscopy combined with image analysis, and near infrared (NIR) spectroscopy.

A method was developed to identify annual growth ring boundaries on wood density profiles of *E. grandis* using bark-to-pith density profiles and annual measurements of diameter at breast height (DBH) from permanent sample plot (PSP) datasets. Using the PSP data, it was possible to assess the annual pattern of stem diameter growth at a compartment level by calculating the radial increment (RI) per year and expressing that value as a percentage of the radius at the end of the increment for that year. Mean radial increment percentage (%MRI) was calculated for each year and used to predict annual RI at an individual tree level. Predicted RI values for each tree were expressed as cumulative distances from the bark end and superimposed onto their respective density profiles. Predicted RI corresponded well with latewood density peaks and these separation points were considered a reliable guide to divide the density profile into annual increments closer to the bark end and into broader age classes closer to the pith. By assessing the pattern of variation in radial density within the context of the growth history of a compartment by means of annual PSP data, it was possible to confirm that growth rings on density profiles of *E. grandis* closer to the bark-end can serve as a reliable representation of annual growth. This conclusion was used as the basis of a method to standardise the age of wood properties of trees from compartments sampled in this research that varied in age.

Radial maps illustrating pith to bark variation in wood properties, and weighted mean values, were assessed for each region in terms of responses to soil characteristics, water availability and their effects on wood quality. Compartments sampled from areas with higher MAP in the sub-tropical region typically had lower density wood with larger vessel and fibre diameters, thinner cell walls, higher cellulose percentages, lower lignin percentages and fewer vessels per unit area. Results from the warm temperate region revealed similar results with wood from areas with higher MAP having larger fibre diameters, higher cellulose percentages, lower lignin percentages and lower vessel frequencies.

Multiple linear regression and non-linear regression modelling techniques were used to develop models to predict selected basic wood properties of *E. grandis* from compartments in KwaZulu-Natal (KZN). Models were developed for individual regions, and at each MAP and SWS level. Models were validated using an independent data set and leave-one-out cross validation. In multiple regression models developed for KZN, a large proportion of the variation could not be explained in terms of the effects of the variables considered. Only a small proportion of the between site variation in wood properties were accounted for by variables related to rainfall and soil. Variation in site index was explained by MAP in KZN with a weak R^2_{adj} (0.14) and by solar radiation in the ST region with a stronger R^2_{adj} (0.53). Models developed for the estimation of density, vessel and fibre properties at 'dry' MAP had much higher R^2_{adj} (R^2_{adj} of 0.62 for density, 0.90 for vessel diameter, 0.71 for vessel frequency, 0.91 for vessel percentage and 0.67 for cell wall thickness) compared to models developed at a regional level. Site index was a better predictor of wood properties at 'dry' MAP, while at 'wet' MAP, Lange's climatic index (LCI) in combination with percentage organic carbon (OC%) and percentage clay (clay%) explained variability in wood density ($R^2_{adj} = 0.58$) and cell wall thickness ($R^2_{adj} = 0.58$).

Non-linear regression models relating bark-to-pith radial wood properties to measured rainfall revealed that vessel characteristics were more strongly influenced by rainfall compared to wood density and fibre characteristics. Vessel diameter increased with increasing rainfall and vessel percentage decreased with increasing rainfall (R^2_{adj} = 0.43 and 0.41 respectively). Varying levels of water availability had a greater effect on physiologically active cells (vessels) compared to that of the mechanical cells (fibres). Vessel diameter and vessel percentage showed the clearest pattern of response to varying levels of rainfall and a similar trend was seen at a regional level and at individual MAP and SWS levels. Models improved slightly at 'dry' MAP and at 'low' SWS. Non-linear regression models developed to predict wood density, vessel frequency, fibre diameter and cell wall thickness were weak with low R^2_{adj}.

Coefficients of determination of the models developed were generally far to low to use the equations in a predictive way. The low predictive power of the models developed is a clear indication that factors other than the independent variables considered are involved. A large proportion of the variation cannot be explained in terms of the effects of the variables considered. Large differences between trees within sites are probably the most important contributing factor towards the low predictive levels found in this research.

The objectives of this research were achieved. A method was developed to identify annual growth ring boundaries in *E. grandis*, radial maps were created which illustrated variation in wood properties with changes in water availability in the two regions assessed and empirical models were developed developed using climatic and soil characteristics to predict wood properties.

PREFACE

The experimental work described in this thesis was carried out at the Forestry and Forest Products (FFP) Research Centre under the supervision of Professor Fethi Ahmed. The FFP Research Centre is a joint venture between the Natural Resources and Environment unit of the Council for Scientific and Industrial Research (CSIR) and the University of KwaZulu-Natal (UKZN).

The supervisors of the research were:

Prof. Fethi Ahmed, School of Environmental Sciences, University of KwaZulu-Natal, South Africa

Prof. Norman W. Pammenter, School of Biological and Conservation Sciences, University of KwaZulu-Natal, South Africa

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

DECLARATION 1 - PLAGIARISM

I, Sasha Naidoo declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons’ data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
   a. Their words have been re-written but the general information attributed to them has been referenced
   b. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks, and referenced.

5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the Reference sections.

Signed

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DECLARATION 2 - PUBLICATIONS

I, Sasha Naidoo, was the main author of publications 1-6 and contributed to each publication with regards to researching and writing the content, the experimental design of the research, data collection, data analysis and discussion of the data analysed. My co-authors contributed in their supervisory capacity by providing guidance for the research conducted and proof-reading drafts of the publications.

Publication 1

Naidoo, S. and Ahmed, F. Submitted to editors in April 2009. Wood Properties of South African grown *Eucalyptus* spp. grown for pulp and paper production in South Africa. *In:* B. Bredenkamp (Ed.) *South African Forestry Handbook 5th Ed.* (*in press*)

Publication 2

Naidoo, S., Zbonák, A., Pammenter, N.W. and Ahmed, F. (2007) Assessing the effects of water availability and soil characteristics on selected wood properties of *E. grandis in* South Africa. *In: Eucalypts and Diversity: Balancing Productivity and Sustainability. Proceedings of the IUFRO Working Group 2.08.03 Conference, Durban, South Africa*. 22-26 October 2007 (ISBN: 978-0-620-40465-5)

Publication 3

Naidoo, S., Zbonák, A. and Ahmed, F. (2007) Effects of moisture availability on wood properties of South African-grown *E. grandis*. *In:* Proceeding of Abstracts, IUFRO All Division Five Conference, 29 October - 2 November 2007, Taipei, Taiwan, Pg. 322

Publication 4

Naidoo, S., Zbonák, A. and Ahmed, F. (2006) The effect of moisture availability on wood density and vessel characteristics of *Eucalyptus grandis* in the warm temperate region in South Africa. *In:* S. Kurjatko, J. Kúdela, & R. Lagana (eds) *Proceedings of the 5th International Symposium, Wood Structure and Properties '06.* September 3-6. Sliac-Sielnica, Slovakia. The Technical University in Zvolen. pp. 117– 122 (ISBN 80–968869–4–3)

Publication 5

Naidoo, S., Ahmed, F., Pammenter, N.W. and Zboňák, A. (2010) A technique to identify annual growth rings in *E. grandis* using permanent sample plot data and gamma-ray densitometry. *Southern Forests: a Journal of Forest Science* **72:3**, 191-200

Publication 6

Naidoo, S., Ahmed, F. and Pammenter, N.W. Modeling the effects of limiting environmental factors on the wood properties of *E. grandis* in the warm temperate and sub-tropical regions of South Africa. (In preparation for submission to *Southern Forests: a Journal of Forest Science*)

Signed:

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Sappi-CSIR *Eucalyptus* Co-operative). The financial assistance of the National Research Foundation (NRF) towards this research is also acknowledged.

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ARMSE	Absolute root mean square error
ANOVA	Analysis of variance
CWT	Cell wall thickness
CSIR	Council for Scientific and Industrial Research
DWAF	Department of Water Affairs and Forestry
DBH	Diameter at breast height
FD	Fibre diameter
FFP	Forestry and Forest Products
ICFR	Institute for Commercial Forestry Research
IUFRO	International Union of Forest Research Organisations
KZN	KwaZulu-Natal
LCI	Lang's Climatic Index
LD	Lumen diameter
MAP	Mean annual precipitation
MAT	Mean annual temperature
MRI	Mean radial increment
MPU	Mpumalanga
NIR	Near Infra-Red
OC%	Percentage organic carbon
PSP	Permanent sample plot
3-PG	Physiological Principles in Predicting Growth
RI	Radial increment
RBH	Radius at breast height
RMSE	Root mean square error
SI_5	Site index at reference age five
SWS	Soil water storage
SA	South Africa
SAAAC	South African Atlas of Agrohydrology and Climatology
SASRI	South African Sugar Research Institute
SAWS	South African Weather Service
SPH	Stems per hectare

ST	Sub-tropical
UKZN	University of KwaZulu-Natal
VD	Vessel diameter
VF	Vessel frequency
VP	Vessel percentage
WT	Warm temperate

CHAPTER ONE

GENERAL INTRODUCTION

Based on:

Naidoo, S. and Ahmed, F. Submitted to editors in April 2009. Wood Properties of South African-grown *Eucalyptus* spp. grown for pulp and paper production in South Africa. *In:* B. Bredenkamp (Ed.) *South African Forestry Handbook 5th Ed.* (*in press*)

1.1. Introduction

Maximising stem volume growth and yield per unit area are recognised as important objectives towards maintaining or enhancing plantation forest productivity (Landsberg and Gower, 1997). In addition to growing trees for maximum volume, forest managers also manage their plantations with the goal of producing fibres with properties that better meet to the manufacturing process and quality of the final product produced by the mills (Downes, 1997; Jacobs and Drew, 2002). Focus has shifted in the past 25 years to increasing fibre production, accelerating tree growth and reducing rotation length in order to maximise returns on investments (Bhat *et* al., 1990; Malan, 1991; Malan, 1995; Downes *et al*., 2002; Jacobs and Drew, 2002; Dyer, 2007; Christie, 2008). These objectives are achieved through site-species matching, intensive silviculture and genetic improvement. However, while these efforts have greatly increased forest growth and yield in plantation forestry, there still remain gaps in our knowledge regarding the effects of various environmental factors, silvicultural practices and the genetic make-up of trees on wood properties (Turner *et al*., 2001, Downes *et al*., 2002).

Interactions between trees, geographic location, site conditions and management actions (i.e.: the total environment of the tree) on wood properties are complex and the components are interrelated (Landsberg and Gower, 1997; Louw and Scholes, 2002). These environmental influences, however, occurs within the bounds of the genetic make-up of the individual tree. This results in difficulties in separating the influence of the individual factors on wood and fibre quality attributes (Kang *et al*., 2004). The various factors influencing wood quality must be considered together, since a simple cause-effect relationship between any two components of an interacting system will not be capable of fully explaining the variation in the wood (Downes *et al*., 2009). An improvement in our understanding of the factors that control tree growth, and the limitations of the sites on which they are planted, is required to achieve sustainable plantations (Louw, 1999). It is through a better understanding of site quality and the environmental variables affecting it, that we can better understand the quality of the *Eucalyptus* resource in South Africa (S.A.).

1.2. Eucalypts in South Africa for the pulp and paper industry

Eucalyptus is one of the most widely cultivated hardwood genera in tropical and subtropical regions of the world. Eucalypt plantations occur in South Africa over a wide range of sites of varying potential productivity. The importance of this genus can be attributed to its adaptability to a variety of climatic and edaphic conditions, fast growth, excellent stem form and branch properties, resistance to pests and diseases, and the versatility and usefulness of its wood for industrial applications (Malan, 1988; Santos *et al*., 2004, Clarke *et al*., 2008).

Plantation forestry is based predominantly on intensively managed short-to-medium rotation crops. The major plantation forestry areas in South Africa are located in the summer rainfall region (du Toit *et al*., 1999) and cover a range of soils and biophysical environments (summer rainfall areas are all characterized by a marked summer peak in precipitation and relatively dry winter months of between 10 and 30 mm rainfall per month (Herbert, 2000)). In 2006/2007, the total commercial timber plantation area in South Africa was 1 266 196 hectares. Of that total, the area planted to hardwoods was 46.5% (DWAF, 2008). Approximately 80% of the total area planted to hardwoods is managed for pulp production. *Eucalyptus* plantations compose 81% of the hardwood area while wattle and other hardwoods made up the other 19%.

Eucalypts are planted most extensively in the provinces of KwaZulu-Natal (KZN) and Mpumalanga (MPU), where 52.9% and 38.1% of *Eucalyptus* plantations occur respectively (DWAF, 2008). KwaZulu-Natal is situated along the east coast of South Africa and Mpumalanga lies in the eastern part of the country, north of KwaZulu-Natal (Figure 1.1). Historically, eucalypts grown on the subtropical Zululand Coastal Plains of KZN were for pulp and paper production and eucalypts grown on the temperate, higher altitude sites of MPU and Tzaneen were for mining timber (Swain and Gardner, 2003). However, in the early 1980s, a shift in focus from mining timber to pulp and paper production resulted in *Eucalyptus* species being grown for the pulp industry on the colder high altitude sites of MPU and the highland areas of western KZN.

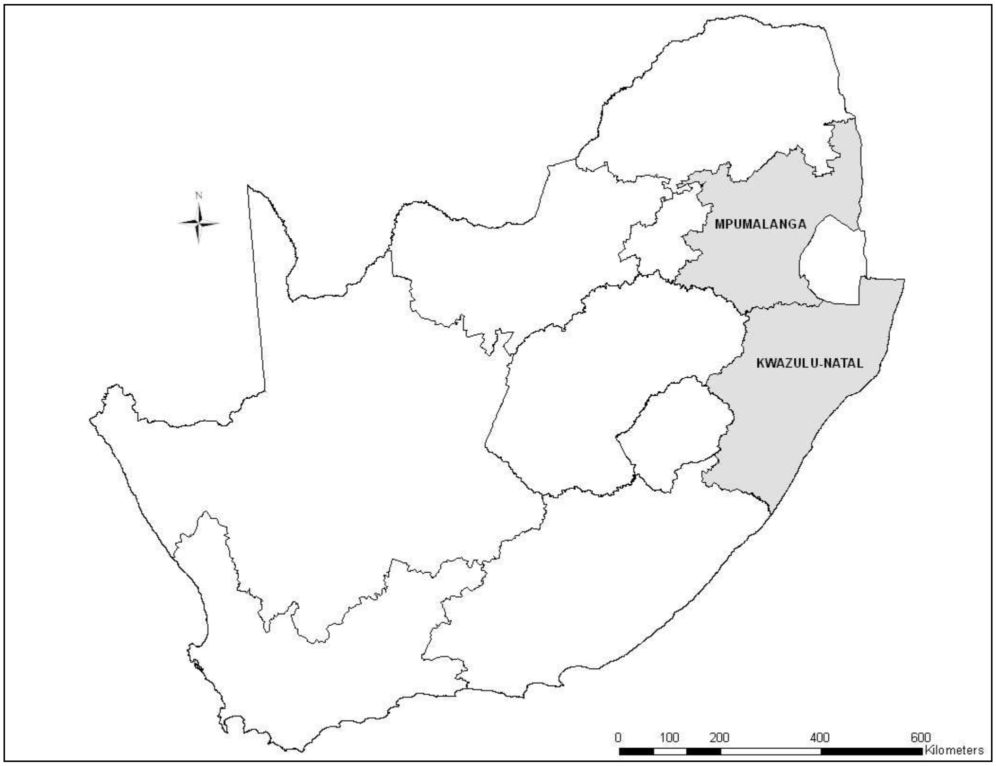

Figure 1.1. Map illustrating the location of the provinces of KwaZulu-Natal and Mpumalanga in South Africa

Five commercial species make up the majority of eucalypt plantations *viz*. *Eucalyptus grandis*, *E. nitens*, *E. smithii*, *E. macarthurii* and *E. dunnii* (Pallett and Sale, 2004). The dominant species is *Eucalyptus grandis*, which accounts for 56.4% of the total *Eucalyptus* plantation area (DWAF, 2008). Recently, the area planted to various cloned eucalypt hybrids (hybrids of *E. grandis* with either *E. urophylla* or *E. camaldulensis)* has increased significantly, particularly in Zululand (DWAF, 2008). Most cloned hybrids are *Eucalyptus grandis* based. The rotation lengths of eucalypts in South Africa vary from 6 to 12 years and the average productivity of eucalypt stands is 21 $m^{3}\cdot ha^{-1}\cdot yr^{-1}$ (ranging between 15 to 55 $m^{3}\cdot ha^{-1}\cdot yr^{-1}$) (du Toit *et al*., 1999).

1.3. Relevance of assessing the effects of environmental factors on wood properties of *Eucalyptus grandis* - previous studies in South Africa

Water and nutrient interactions are widely recognized worldwide, as key factors in determining forest productivity, and South African forests are no exception (Roberts, 1994, Louw, 1999). The areas that are both available and suitable for growing trees are limited and much of this limitation is driven by a competition for water, which is a scarce resource in what is essentially a semi-arid country (Dyer, 2007). The growth rate and health of plantations is highly dependant on soil water availability, which is often limited. At the same time, evaporative demand is high (Roberts, 1994).

Eucalyptus grandis is grown across a wide range of site conditions of varying potential productivity, with the optimum mean annual precipitation (MAP) and mean annual temperature (MAT) for *E. grandis* being above 900 mm and 16 ^{o}C respectively (Schulze, 1997, Herbert, 2000). This species is well-suited to summer-rainfall and capable of very high yields on sites well supplied with water (Herbert, 2000). *E. grandis* is highly intolerant of poor site conditions and shows substantial declines when planted on shallow soils and/or on dry sites (Boden, 1991). The productivity of many sites, in terms of wood production per unit area of land, is below their potential and tree growth rates vary widely within a relatively small geographic region (Louw, 1999).

Forest managers are becoming increasingly aware of the need to manage not only for increased yield, but also for wood quality (Turner *et al*., 2001). Although stem volume growth and yield per unit area are still regarded as important measures of plantation forest productivity, much research has been undertaken to understand how site factors (climatic, edaphic, biological) affect the quality of the wood that is produced. Worldwide, a number of studies have reported significant effects of a range of site factors on the wood property variation of various eucalypt species. These studies included research by Bamber *et al*. (1982), Bhat *et al*. (1990), February *et al*. (1995), Downes *et al*. (1999), Wimmer *et al*. (2002 a and b), Leal *et al*. (2004), Searson *et al*. (2004), Drew *et al*. (2008), Gava and Gonçalves (2008), Wimmer *et al*. (2008) and Drew *et al*. (2009).

Similarly, numerous studies have been undertaken in South Africa to understand the effect of climate, site, genetics, silviculture and age on the wood quality of *Eucalyptus grandis* resource (Taylor, 1973; duPlooy, 1980; Malan, 1991 and 1993; Malan and Hoon, 1992; Malan *et al*., 1994; Malan and Verryn, 1996; Megown *et al*., 2000; Clarke *et al*., 1999; Grzeskowiak and Turner, 2000; Sefara and Turner, 2001; Little *et al*., 2003 and Venter, 2003). These studies, summarised in Table 1.1, assessed the effects of various independent variables on the growth, wood properties and/or pulp and paper properties of South African-grown *E. grandis*. However, due to the time-consuming (and expensive) nature of the work, these studies could evaluate only relatively few stands of trees from a limited number of geographic locations and age ranges.

Climatic factors were rarely included as independent variables, and if included, factors such as age, genetics or silviculture confounded the results. In addition, density was often the only basic wood property assessed, and in studies where vessel and fibre characteristics were included in wood property assessments, the datasets were limited and the aims of those studies did not focus specifically on the effect of climatic variables on wood properties of *E. grandis*.

Taylor (1973) assessed the within-tree variation in *E. grandis* across geographic areas in South Africa and concluded that differences in growth, density and fibre length between trees and within plots were in most cases larger than differences in these characteristics between geographic areas. As such, gross environmental factors (which were not individually assessed) were considered to not have had an appreciable effect on wood properties.

Table 1.1. Summary of past studies assessing growth, wood and pulp properties of E. grandis in South Africa (N/A = not assessed)

Author(s)	**Year**	**Location**	**Growth properties assessed**	**Wood properties assessed**	**Pulp and paper properties assessed**	**Independent variables assessed (genetics, climate, site, silviculture and age)**
Taylor	1973	Eastern Cape, KwaZulu-Natal, Mpumalanga and Limpopo	Diameter and height	Density, fibre length, fibre diameter and fibre wall thickness	N/A	Geographic location
duPlooy	1980	Eastern Cape, KwaZulu-Natal, Mpumalanga and Limpopo	N/A	Density, fibre diameter, fibre length, fibre wall thickness	Cellulose and lignin content, extractives, pulp yield, rate of delignification, burst, tear and tensile strength, brightness and bulk density	Geographic location
Malan	1991	Mpumalanga	N/A	Density, fibre diameter, fibre length, fibre wall thickness, fibre volume, vessel diameter, vessel volume and vessel frequency	N/A	72 Families of *E. grandis*, growth rate within families (fast and slow growth based on DBH), distance from pith and height within tree
Malan and Hoon	1992	KwaZulu-Natal	Diameter, growth stress splits	Density, fibre length, vessel diameter and frequency	N/A	Initial spacing and thinning
Malan	1993	Eastern Cape, Mpumalanga and Limpopo	Growth stress splits, sapwood, preservative penetration	Density, fibre length, vessel diameter, vessel area and frequency	N/A	Geographic location and hybrid crosses of *E. grandis* and other eucalypt species
Malan *et al*.	1994	Mpumalanga	N/A	Density, fibre diameter, fibre length, fibre wall thickness, fibre volume, vessel diameter, vessel volume and vessel frequency	N/A	Species, hybrids and height within tree
Malan and Verryn	1996	KwaZulu-Natal and Mpumalanga	Diameter, splitting	Density, fibre length	N/A	Geographic location and hybrid crosses of *E. grandis* and other eucalypt species
Clarke *et al*.	1999	KwaZulu-Natal and Mpumalanga	Diameter, height and volume	Density	Cellulose and lignin content, pulp yield, active alkali consumption, rate of delignification	Species, altitude and temperature (mean annual temperature, mean minimum and mean maximum)
Grzeskowiak and Turner	2000	Not specified	N/A	Density, vessel diameter and frequency, and fibre diameter and fibre wall thickness	Burst, tear and tensile strength, and bulk density	Site index and height within the tree
Megown *et al*.	2000	KwaZulu-Natal	Diameter and height	Density	Screened pulp yield, active alkali consumption, extractives, burst, tear and tensile strength, brightness and bulk density	Site index, age
Sefara and Turner	2001	KwaZulu-Natal, Mpumalanga and Limpopo	N/A	Density	Pulp yield, rate of delignification, extractives, burst, tear and tensile strength, brightness and bulk density	Geographic location and age
Little *et al*.	2003	KwaZulu-Natal	Volume	Density, fibre length, fibre coarseness	Pulp yield, rate of delignification, active alkali consumption	Weeding treatments
Venter	2003	KwaZulu-Natal and Mpumalanga	Diameter and height	Density, fibre length	Screened pulp yield, active alkali consumption	Geographic location, site index, soil water retentivity, temperature, climate,

du Plooy (1980) attempted to establish a quantitative relationship between wood properties and pulp properties of *E. grandis* across geographic locations; climatic conditions were not included in the assessment of the individual wood or pulp properties or as explanatory variables in describing relationships between wood and pulp properties.

Various studies by Malan and co-workers (Malan, 1991 and 1993; Malan and Hoon, 1992; Malan *et al*., 1994; and Malan and Verryn, 1996) assessed a range of wood properties which included density, and vessel and fibre characteristics. These studies focused on differences between and within trees in wood properties as a result of geographic location, silviculture and/or genetic influences. Malan and Verryn (1996) did include the effect of environmental factors in their research which investigated the effect of genotype-by-environment interaction on wood properties of *E. grandis* and *E. grandis* hybrids. Unfortunately, the trees were only four-years old at the time of assessment and basic density and fibre length were the only wood properties included in the study.

The effect of climate on growth, wood density and pulp properties of nine eucalypt species at two contrasting sites were assessed by Clarke *et al.* (1999). Significant differences were found between the sites for many of the assessed properties, but most of the variation occurred between and within species. Density was the only basic wood property assessed.

The Forestry and Forest Products Research Centre (FFP) of the Council for Scientific and Industrial Research (CSIR) and the University of KwaZulu-Natal have been actively involved in collaborative research with two of the major commercial forestry companies in South Africa *viz*. Sappi Forests and Mondi South Africa to evaluate the effects of site quality and various environmental factors on wood and pulp properties of *Eucalyptus* spp. This collaboration was called the Mondi-Sappi-CSIR Eucalypt Co-operative. Studies on *E. grandis* by Grzeskowiak and Turner (2000), Megown *et al*. (2000), Sefara and Turner

(2001) and Venter (2003) on *E. grandis* (Table 1.1) were among the outputs of this co-operative.

Stand age, environmental factors, and stand growth rates were identified as having a significant effect on the properties of fibres in the eucalypt resource. Megown *et al*. (2000) and Sefara and Turner (2001) assessed the impact of site index[1] and age on density and pulp properties whilst Grzeskowiak and Turner (2000) assessed the impact of site index and age on density, vessel and fibre characteristics of *E. grandis*. A study by Venter (2003) included the effects of climatic and soil factors on density and pulping properties of *E. grandis* across geographic locations in South Africa. However, in this study, basic wood density and fibre length were the only basic wood properties assessed and other fibre properties and vessel properties were not included.

Outcomes from the Mondi-Sappi-CSIR Eucalypt co-operative have illustrated the impact of site quality-related parameters, in particular site index. Site index explained a large proportion of the variation measured in wood properties important to the pulping process (Turner *et al.*, 2001). However, site index, which is a composite expression of the effects of individual and interacting site variables on tree growth and wood properties, did not explain all of the variation. There was scope for further investigation into individual factors driving variation in wood quality of the South African eucalypt resource (Turner *et al.*, 2001).

Very little work has been done locally on the effect of individual environmental factors on wood properties and wood quality of South-African-grown eucalypt species (Table 1.1) and many conclusions can only be drawn by inference. The mechanism by which environmental variables affect wood properties remains unclear, and so far the models developed to predict variation on the basis of these variables are not sufficiently accurate because of insufficient validation and replication. It is therefore necessary to research the effects of

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[1] Site index (SI) is a widely used indicator of site quality. SI is defined as the mean height of dominant trees in an even-aged stand of trees at a specific base age (McLeod and Running, 1987)

environmental factors on wood quality of *Eucalyptus grandis* planted in South Africa to understand the range in wood quality and identify trends in response to these factors.

While many of the studies discussed thus far have reported on the wide variation in wood properties of *E. grandis* grown in different areas of South Africa these studies usually only compared the weighted mean wood properties or plotted wood properties against relative distance from the pith since it was not possible to compare wood properties at specific ages of growth. The reason for this is because *Eucalyptus grandis*, like many other tropical eucalypts, does not have well defined growth ring boundaries due to a lack of strong seasonal climatic variation making it difficult to study the change in wood properties with age (Malan, 2005; Downes and Drew, 2008; Downes *et al*., 2009). Therefore a technique was needed to identify annual growth rings in *E. grandis.*

1.4. Aims and objectives of research

There were two aims to this research. The frst was to quantify and model the effects of specific environmental factors and their interactions on the wood quality of *E. grandis* in the warm temperate and sub-tropical forestry regions in South Africa. *E. grandis* was chosen for this research since it accounts for 56.4% of the total *Eucalyptus* plantation area (DWAF, 2008) and most cloned eucalypts hybrids are based on this species. The second aim was to develop a technique to identify annual growth ring boundaries in this species from radial wood profiles.

The objectives of the research were to:

i. Develop an appropriate experimental design which will define regions which represent a wide range of sites and environmental conditions under which *E. grandis* is planted
ii. Develop a technique to identify annual growth rings in *E. grandis* more accurately

iii. Quantify and evaluate selected basic wood properties of *E. grandis*, important to the pulp and paper industry, from trees grown in compartments[2] of varying levels of water availability,

iv. Develop models to predict selected basic wood properties of *E. grandis* grown at varying levels of water availability and explain observations made in objective iii.

The objectives of this research are discussed briefly below to highlight the relevance of the research, the applicability of each experimental approach used and the significance of each outcome.

i. Develop an appropriate experimental design (Chapter three)

To achieve the objectives of this research, an appropriate experimental design was needed which captured the wide range of sites and environmental conditions under which *E. grandis* is planted. In the past, such a design would be severely limited by the expense of intensive sampling and laboratory work. However, the use of rapid screening tools to characterize basic wood properties from pith to bark in this research made it possible to sample a larger number and wider variety of sites (compared to previous studies) both time- and cost-efficiently. The rapid screening tools used were light microscopy combined with image analysis, gamma-ray densitometry and near infra-red (NIR) spectroscopy.

The use of a site classification system developed by the Institute for Commercial Forestry Research (ICFR) (Smith *et al*., 2005) was considered as a basis for the experimental design to define two unique forestry regions. These regions differed from each other in terms of mean annual temperature (MAT) (warm temperate (WT) - 16.1-19°C and sub-tropical (ST) - 19.1-22°C) and each

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[2] A compartment is a permanent, geographically recognizable unit of forest land (FAO, 1998). A commercial plantation is made up of compartments or stands (blocks) of trees where the trees of one compartment are all usually the same species/ clone and age, and are planted at a fixed spacing (DWAF, 2010)

region was divided into sub-classes representing varying levels of water availability among blocks within each region.

ii. Develop a technique to identify annual growth rings in *E. grandis* (Chapter four)

The difficulty in separating radial wood property data of many eucalypt species into annual increments is of particular concern to the forestry industry where growth rate is typically expressed in terms of mean annual increment and research has been conducted on the effect of site, genotype or silvicultural treatment on annual ring width of various *Eucalyptus* species. This has resulted in a range of methods being used for examining radial variation in wood properties. However, the method used to divide the radius have marked effects on the trends reported (Downes and Drew, 2008), and there is a need to develop a technique to assess annual growth ring boundaries more accurately.

Eucalyptus grandis is an example of a species that does not have well defined growth rings (Malan, 2005, Zboňák *et al*., 2007). The light and dark bands visible on the cross-section of the wood of *E. grandis* do not always correspond with the growing season. Numerous studies have reported on the wide variation in wood properties of this species grown in different areas of South Africa (Taylor, 1973, Malan, 1991; Malan and Hoon, 1992; Grzeskowiak and Turner, 2000; Malan, 2005; Zboňák, 2006; Zboňák *et al*., 2007). However, these studies compared only the weighted mean wood properties or plotted wood properties against relative distance from the pith since growth rings in this species did not necessarily equate to annual rings.

In Chapter four, a technique is described which has been developed to identify annual growth ring boundaries of *E. grandis* in more accurate terms. It was envisaged that a more reliable identification of annual growth ring boundaries would allow for more reliable comparative studies, especially for comparing the wood properties of trees of different ages, as was the case in this research.

iii. Quantify and assess selected basic wood properties of *E. grandis* from compartments grown at varying levels of water availability (Chapter five)

A quantitative description of how basic wood properties change within the environments in which *E. grandis* is planted will contribute to better understanding the characteristics of this resource.

Rapid screening tools were used to measure wood properties of *E. grandis* in this research. Sites with varying levels of water availability were selected. Combinations of mean annual precipitation (MAP) and estimated soil water storage (SWS) were used to select sites with varying levels of water availability. The approach used in this research involved obtaining core samples taken at breast height. Analyses of strips cut from the cores included microscopy and image analysis, gamma-ray densitometry and near infra-red spectroscopy. Relationships among selected wood properties (*viz*. density, vessel and fibre characteristics) with water availability and soil characteristics were examined.

iv. Develop empirical models to predict selected basic wood properties of *E. grandis* grown at varying levels of water availability (Chapter six)

Empirical models which relate wood properties to the environmental factors assessed in this research will be the outputs of this chapter. Multiple linear regression models were developed using climatic and soil characteristics to predict wood properties. In addition, linear and non-linear regression models were developed using bark-to-pith radial wood properties (averaged at 10% intervals) and rainfall during the total growth period of each compartment.

Descriptive models are fundamental in forecasting wood and pulp quality to guide policy making and future research (Downes *et al*., 2009). If strong relationships with environmental factors and wood properties are found, then wood properties which can be easily measured using rapid screening tools can then become powerful predictors of pulp and paper parameters of critical importance to the pulp and paper industry.

1.5. Outline of thesis

The thesis is comprised of seven chapters. A paper entitled ‘Wood Properties of SA grown *Eucalyptus* spp. grown for pulp and paper production in SA’ was submitted for inclusion in the South African Forestry Handbook (5th Edition) in the section ‘Timber utilization’. Sub-sections of the above paper were included in this chapter and Chapter two (Review of wood properties and factors affecting wood properties) of this thesis. Thereafter results related to each objective of this research are discussed in four separate chapters. A summary of results and recommendations for future research is presented in the final chapter.

Chapter one (the current chapter) outlines the background to this research, the need for this research and a summary of previous studies on *E. grandis* in South Africa, the main objectives of the research conducted and the relevance of the outcomes of this research to the forestry industry.

Chapter two provides a background on basic wood properties and factors affecting wood quality of the eucalypt resource. Wood quality is addressed in terms of commercially important wood and fibre properties of *Eucalyptus* species and their role in obtaining good quality pulp and paper. Techniques utilized for the rapid assessment of wood properties are discussed.

Chapter three addresses the first objective of this research and outlines the approach in developing an appropriate experimental design to meet the specific aim of this research. The methods used to select, sample and enumerate compartments and techniques used to measure wood and soil properties are described. Sources of climatic data are provided.

Chapters four, five and six address each of the remaining objectives of this research. Each chapter is introduced and concluded, and links with subsequent chapters. Areas of overlap exist with regards to the sampling strategy and measurement of wood and soil properties. Chapter four was prepared in a paper/ article format and submitted to a peer-reviewed journal, and was presented in the form of a poster at the Joint IAWA, IAWS and IUFRO[3] conference in 2010. Chapter five is based on results from two peer-reviewed conference proceedings which were presented at IUFRO conferences in 2006 and 2007. An article based on selected results from Chapter six is currently in preparation for submission to *Southern Forests: a Journal of Forest Science.*

Chapter seven consists of a summary of the research presented. This chapter provides recommendations with regards to future work that can be conducted in this area of research.

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[3] International Association of Wood Anatomists (IAWA), International Academy of Wood Science (IAWS) and International Union of Forest Research Organisations (IUFRO)

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CHAPTER TWO

REVIEW OF THE WOOD PROPERTIES OF *EUCALYPTUS* SPP. AND THE FACTORS AFFECTING THEM

Based on:

Naidoo, S. and Ahmed, F. Submitted to editors in April 2009 Wood Properties of South African-grown *Eucalyptus* spp. grown for pulp and paper production in South Africa. *In:* B. Bredenkamp (Ed.) *South African Forestry Handbook 5th Ed.* (*in press*)

2.1. Wood quality for the pulp and paper industry

In any industry, the quality of raw material needs to be evaluated and related to the end product. The term wood quality means different things to different users. A pulp manufacturer may consider wood density, fibre dimensions and chemical content as key wood properties while a manufacturer of solid wood products may, for example, consider the proportion of compression wood or the presence of density, spiral grain, shrinkage and permeability in wood as important quality factors that affect wood performance (Punches, 2004). For this reason, it is important to identify what is meant by the term ‘quality’ in terms of the end user to assess its potential impact on the value of a product. A sound knowledge of the characteristics of the resource and an understanding of its value to the end-user will enable the identification of the appropriate material for specific processes. This translates into an overall reduction of costs as a result of optimal use of the raw material.

Wood quality in the pulp and paper industry starts with the fibre where the value and productivity of a pulp-wood plantation is determined by stem wood volume, wood density and pulp yield (Sands, 1995). The product of these components measures fibre production which relates to the yield of pulp produced per hectare of land (Clarke, 1999). Fibre dimensions, fibre distributions, strength properties and chemical composition are determined by properties of the raw fibres in wood and are modified by processes employed during pulp preparation and paper manufacture. Pulp quality ranges from the physical properties and chemical composition of the pulp to the physical properties of resulting paper (Sands, 1995). Therefore, in the pulp and paper industry, it is essential to understand how wood properties affect product quality to assess and improve raw material and energy efficiencies in the pulp mill.

2.1.1. Variation in basic wood properties

Wood, the raw material of the forest, is the product of the plant’s ability to convert sunlight, water, carbon and a variety of nutrients into this complex tissue. Wood formation is a complex process initiated in the cambium. The vascular cambium is a thin layer of meristematic tissue from which secondary growth occurs in roots and stems, producing xylem (woody tissue) on the inner side of the cambium and secondary phloem on the outer side (inner bark) (Plomion *et al*., 2001). The vascular cambium is the source of both the growth of secondary xylem and secondary phloem tissues and is located between these two tissues in the stem. The cambium plays an important role in the diametral growth of roots and shoots, and is particularly significant in respect to the characteristics of wood that is produced (Plomion *et al*., 2001). The cambium surrounding the woody stem produces wood with a range of properties at any given point in time.

Wood, which is the secondary xylem, is manufactured by the succession of five major steps *viz*. cell division, cell expansion (elongation and radial enlargement), cell wall thickening (involving cellulose, hemicellulose, cell wall proteins, and lignin biosynthesis and deposition), programmed cell death, and heartwood formation (Plomion *et al*., 2001). Hardwood xylem mother cells differentiate into three cell types. These are fibres, parenchyma and vessel cells. Hardwood anatomy is more complex than conifers and has very short and large diameter vessel elements, fibres, longitudinal parenchyma and rays with differing types of cells (Zobel and van Buijtenen, 1989).

Large variation in wood properties exists among species and genera, between trees of the same species (even among trees growing within one uniform site) and within trees (Taylor, 1973; Zobel and van Buijtenen, 1989; Malan, 1991; Downes *et al*., 1997; Clarke *et al*., 1999; Malan, 2000b; Drew *et al*., 2001; Drew and Pammenter, 2007; Naidoo *et al*., 2007). There exists as much variability in wood characteristics within a single tree as there is among trees growing on the same site and between trees that are grown on different sites (Taylor, 1973; da Silva Perez and Fauchon, 2003). Variability in wood is due to the heterogeneity of the cell types that make up the different woods and the structure of individual cells. Variation also exists in juvenile wood, from pith to bark, particularly in the early years of cambial activity (Plomion *et al*., 2001), making juvenile wood an important quality factor since its properties are very different and more variable compared to mature wood. Trees used for pulp and paper production are usually young when harvested (rotation age between 6-12 years (du Toit *et al*., 1999)), which means that the pulp and paper industry uses a resource which is quite variable.

Eucalypt plantations are extremely variable in nature and the largest single quality constraint in existing commercial industry is the variation itself (Turner, 2001). Variations in wood quality have both technical and economical implications. Irrespective of the wood property, increased uniformity is valuable, as uniformity can be translated into greater efficiency and better control at all stages of the manufacturing process (Malan, 2000b). Wood that is more uniform can be more efficiently produced into a specific product because it is more predictable. The plantation resource needs to be understood and managed to minimize the impact of these variations on wood quality (Turner, 2001). If the underlying causes of variation are understood, variation in wood properties can be better managed and even exploited (Clarke *et al*., 2003).

Individual plants, through the structures of cells, tissues and organs, with their spatial relations and physiological states, bring a wealth of information regarding their life history and their environment (Wimmer *et al*, 2002b). Wood anatomy indicates that growth and development of trees are dynamic processes. Aspects of wood anatomy are commonly observed, through the use of various microscopes, in two and three dimensions but in reality, also has a fourth dimension – time (Wimmer *et al.*, 2002b). This temporality is evident in structures and patterns on the cross-sections of trees. The most visible change in anatomy regulated by the environment and mediated by plant growth regulators is the change in cell size. Variation patterns within trees, among trees within species, and among species needs to be understood for the efficient production and utilization of wood (Clarke and Wessels, 1995; Downes and Drew, 2008).

Wood properties that show marked within-tree variation are density, fibre diameter, fibre length, fibre wall thickness, vessel diameter and vessel frequency (the number of vessels per unit area measured) (Malan, 1991; Downes *et al*., 1997; Naidoo *et al*., 2007). Variation in basic wood properties of young *E. grandis* is adequately described by studying wood density, fibre length and vessel properties such as size and frequency (Malan, 1991). Wood density and fibre length accounted for more than 60% of the variation in wood properties confirming the usefulness of these variables as indices for wood quality.

2.1.2. Wood density

The wood density of a stem can be described as a gross measurement of its internal anatomy; it is not a single wood property but represents a combination of characteristics. Wood density is determined largely by fibre wall thickness as well as the proportions of thick and thin-walled cells that are present (Taylor, 1973; Haygreen and Bowyer, 1989, Malan, 2000b). However, density does not automatically correlate with fibre cell wall dimensions as density also measures vessels and parenchyma, which have thinner walls and wider lumens and hence reduce density (Sandercock *et al*., 1995).

Wood density varies greatly within and between trees. Radially, wood density increases from pith to bark (as the cambium matures). Longitudinally, trends in variation differ among studies due to the sampling strategy and treatments used leading to conflicting results (Downes *et al*., 1997). However, these authors offered an alternative explanation for the conflicting results in variation in density. It is possible that the magnitude of the treatment effect is relatively small compared to the natural variation that exists which leads to difficulty in establishing consistent trends of longitudinal variation in density.

In mature *E. grandis*, density increases rapidly from pith towards the bark, especially in the zone of juvenile wood (Taylor, 1973; Malan, 1988) but in young fast growing trees, such steep gradients do not exist. Density starts to level off from about the age of 15 years, depending on the rate of growth (Malan, 2000b). The slower the growth, the steeper the gradient. On a good quality site, the air-dry wood density of *E. grandis* at breast height ranges between 400 kg.m^{-3} (close to the pith) to approximately 750 kg.m^{-3} in the outer layers of a 30-year old tree (Malan, 2000b). Logically, faster growth rate over a shorter period can yield the same amount of growth as slower growth over a longer period. However, the differing growth rates are expected to result in different wood properties (Malan, 2000b).

Marked differences, however, do exist between early and latewood zones making the wood extremely variable within trees (Malan and Arbuthnot, 1995). In areas of fast growth, such as South Africa, juvenile wood is important since it constitutes a large proportion of the stem and is a major source of within tree-variability (Malan, 2005). Variation in density along the stem is less consistent than that in the radial direction. Density within trees decreases with increasing height between 1.5 and 4.5 m above ground level and thereafter increases (Poynton, 1979; Malan, 1991). Similarly, Bhat *et al*. (1990) found that density in *E. grandis* declined from stump level to 25% of tree height and then gradually increased towards the top in a curvilinear manner.

Density is an important wood property since higher density improves yield per hectare, assists in maximising transport efficiencies and leads to improved digester productivity in chemical pulping (Turner, 2001). There are, however, limits to acceptable densities for different processes and products. The preferred range for wood density in pulp and paper industry is between 400 and 600 kg/m^3 (Downes *et al*., 1997). In *E. grandis*, the density of wood is strongly related to the cross-sectional morphology of fibres (Taylor 1973). Density relates particularly well to fibre wall thickness and this applies strongly to eucalypts (Haygreen and Bowyer, 1989; Taylor, 1973). Due to the strong relationships that exist between wood density and cross-sectional fibre dimensions, breeding for wood uniformity to a density of approximately 500 g.cm^{-3} could lead to a considerable improvement in the quality of timber meant for pulp and paper production (Arbuthnot, 1991). *E. grandis* growing on good sites in S.A. usually produces wood of higher density and better uniformity across the radius than when grown on poor sites (Malan, 1993).

2.1.3. Fibre properties

Pulp consists of fibres and each fibre has its own properties as a building element. Paper should be regarded as an engineered product thus the optimal use of fibre is of great economic importance (Karlsson, 2006). The most important fibre properties for pulp and paper manufacture are fibre length, fibre diameter and fibre wall thickness. *Eucalyptus* spp. are ideal for this purpose since their fibres are short, slender and thin-walled. Collapsibility ratio is a ratio of cross sectional thickness of the fibre wall to the lumen diameter. This ratio provides an indication of the collapsibility of the fibre which impacts on paper properties. Young *E. grandis* usually has thin fibre walls and very collapsible fibres (Clarke, 1999). These properties result in desirable pulp properties which make them suitable for fine paper production. *Eucalyptus* fibres delignify with ease and produce high yield pulps, which lead to their ability to produce superior quality paper with high opacity and a smooth printing surface (Karlsson, 2006; Clarke *et al.*, 2008).

Variations in fibre wall thickness from tree to tree and within individual trees are similar to the patterns of variation in density as a result of the strong relationship between fibre wall thickness and wood density (Bhat *et al*., 1990, Naidoo *et al*., 2007, Zboňák *et al*., 2007). Wall thickness of fibres can vary greatly within a species where trees can have the same cell wall thickness but larger diameter cells. Trees with smaller cells can have a higher density due to the smaller lumens (Zobel and van Buijtenen, 1989). The fractional wall volume and wall thickness of fibres increases rapidly with age as a result of the combined effect of an increase in fibre diameter and a decrease in lumen size (Malan, 1991). This probably accounts for most of the radial variation in wood density. Fibre length, diameter and wall thickness increase rapidly with increasing distance from the pith, leveling off after about 8 to 15 years (Bhat *et al*., 1990). Fibre length varies from about 700-900 µm close to the pith reaching a maximum of 1000-1200 µm at a distance of 100-150 mm from the pith (Malan, 2000b).

Fibre lengths and their length distribution, and vessel and ray sizes of *E. grandis* were less affected by the degree of suppression which resulted from changes in stand density (Malan and Hoon, 1992). These authors expected other fibre morphological properties to be affected to some degree by suppression due to the good relationship that exists between wood density and fibre properties, i.e.: the less the tree is suppressed, the higher the density and the thicker the walls of fibres.

2.1.4. Vessel properties

For many hardwoods, vessel elements are a major problem in paper-making. Ideally, when hardwood trees are grown specifically as a raw material for pulp and paper, vessels should be few and small and easy to separate from the fibre material (Lundqvist, 2002). Often, wide, long and abundant vessel elements have a major negative effect on paper properties (Zobel and van Buijtenen, 1989). In pulp and paper manufacture, the relative proportions of rays and vessels are important because these have a significant effect on wood density, pulp yield and paper quality.

Increased vessel volume may have an adverse effect on surface quality as a result of vessel picking. Vessel picking is a phenomenon that occurs when cells that form vessels flatten when paper is formed (because their shape is not conducive to intra-element bonds) (Haygreen and Bowyer, 1989). Since vessels are not fibrous, they are only held loosely on the paper surface. Consequently, these cells tend to lift up causing surface roughness known as ‘picking’ (Haygreen and Bowyer, 1989).

In *E. grandis*, vessels are diffuse porous and exclusively solitary. They are arranged in a conspicuous oblique arrangement on the cross-section, are fairly large and are clearly visible by means of a 10x magnifying glass (Malan, 2000b). In general, vessel diameter increases with increasing distance from the pith while vessel frequency declines (Taylor, 1973; Malan, 1991). Vessel diameter and vessel frequency vary significantly between fast- and slow-growing *E. grandis*, with faster growing trees having larger vessels and lower vessel frequency (Bamber *et al*., 1982; Malan, 1991; Downes *et al*., 1997; Raymond *et al*., 2000). There is no significant variation in vessel diameter or vessel frequency with height. Vessel diameter of *E. grandis* ranges between 74 and 205 µm and vessel volume between 9 and 21% (Taylor, 1973).

2.1.5. Summary of wood density, fibre and vessel dimensions of *E. grandis*

Wood density, and fibre and vessel characteristics of *E. grandis* grown in S.A. for pulp and paper production are summarized in Table 2.1 to show variation in wood properties within this species.

Table 2.1. Wood density, and fibre and vessel dimensions of young *E. grandis* used for pulp production in South Africa (n/s = not stated) (blank cells in table = wood properties were not measured)

Source	**Age (years)**	**Density (kg.m^{-3})**	**Fibre diameter (µm)**	**Fibre lumen diameter (µm)**	**Fibre wall thickness (µm)**	**Vessel diameter (µm)**	**Vessel frequency (no.mm^{-2})**	**Vessel %**
Zbonak *et al.* (2007)	7.3	450	13.4	8.2	2.62	101.7	13.6	12.1
Zbonak *et al.* (2007)	7.3	449	13.2	8.3	2.47	106.4	12.4	11.7
Retief and Stanger (2007)	6	349						
Zbonak (2006)	n/s		14.2	8.6	2.6	112.9	10.2	11.2
Malan *et al*. (1994)	n/s	374	14.5	9.0		118	10	12
Malan (1988)	8.5	408				119.3	8.3	12.1

2.1.6. Wood chemical properties

Wood is composed of cellulose, hemicellulose, lignin and extractives. It is the variation in the relative amounts of these substances that give rise to the chemical variation in wood. Typical ranges of wood chemical properties of eucalypts are provided in Table 2.2.

Table 2.2. Ranges of wood chemical properties of eucalypts (Clarke and Wessels, 1995)

Cellulose	**Hemicellulose**	**Lignin**	**Extractives**
48-55%	17-22%	20-24%	5-10%

The main component of the cell wall of trees is cellulose. The principal source of fibre-to-fibre bonding in paper is the attraction between cellulose molecules to different fibre surfaces (Karlsson, 2006). Hemicellulose, another major component in wood fibre, promotes the development of fibre-to-fibre bonding through its influence on fibres to take up water during processing and their direct participation in bonding (Karlsson, 2006). In hardwoods, the predominant hemicelluloses are xylans (*O*-acetyl-4-*O*-methylglucuronoxylans) and glucomannans are present in lower amounts (Pereira *et al*., 2003).

Lignin is often described as the 'glue' that holds the cellulose and hemicellulose together and it provides rigidity to the cells. Hardwoods have a complex lignin made up of syringyl (S) and guaiacyl (G) units and *p*-hydroxyphenyl (H) units (Pereira *et al*., 2003).

Wood is converted to fibres through a pulping process which can be chemical, semi-chemical, or mechanical. Mechanical pulping liberates the fibres from the wood through mechanical means, however, since the lignin is retained in the pulp, papers produced from mechanical pulps have a tendency to yellow on exposure so these pulps are better suited to short-lifetime papers. With chemical pulping, lignin is degraded, dissolved and largely removes so that mostly cellulose and some hemicelluloses are left behind (Karlsson, 2006).

Extractives are also present in wood and this component provides an indication of the amount of impurities that need to be removed from the wood. Extractives can be dissolved by neutral solvents such as water, alcohol, acetone, benzene, and ether (Wenger, 1984). Examples of extractives include tannins, polyphenolics, fats, essential oils, resins, gums and starches. High extractive content lowers pulp yield, impacts on the brightness of unbleached pulp and increases chemical demand of pulping and bleaching chemicals (Little *et al*., 2003).

2.1.7. Paper properties and their relationship with wood properties

Extensive research has been conducted to identify exploitable relationships between wood and paper properties (Horn, 1978; du Plooy, 1980; Malan *et al*., 1994; Wimmer *et al*., 2002b; Grzeskowiak and Turner, 2000; Wimmer *et al*., 2008). If relationships exist, it would be valuable to industry to use the variability in raw wood to reduce costs and optimize product quality to meet market demand (Wimmer *et al*., 2002b; Downes and Drew, 2008, Downes *et al*., 2009a).

Pulp strength is usually described in terms of handsheet strength properties. Fibres in handsheets are non-orientated therefore handsheets can provide a good proxy for pulp properties. Handsheet properties of importance include bulk, burst, tear and tensile index. Physical properties of paper made from hardwood pulp fibres are strongly dependant on fibre characteristics (Horn, 1978, Karlsson, 2006).

Wood density, fibre length and cell wall thickness are the driving factors in the relationship between basic wood properties and the strength properties of paper. The wood density of eucalypt pulp wood is widely regarded as possibly one of the most influential factors controlling the strength and several other characteristics of the paper sheet (duPlooy, 1980; Malan, 1991; Malan *et al*., 1994; Malan and Arbuthnot, 1995). Wood density is the strongest predictor for handsheet properties and relates negatively with tensile, tear, and burst indices (du Plooy, 1980; Zobel and van Buijtenen, 1989; Malan *et al*., 1994).

Wood with thick cell walls tend to produce paper with poor printing surface and poor burst strength, Thick-walled cells do not bend easily and do not collapse upon pulping, which inhibits chemical bonding (Zobel and van Buijtenen, 1989). Thinner-walled cells collapse upon pulping, bond well together chemically, and produce a smoother paper surface. Paper quality and strength are negatively impacted by decreased fibre length, while a decline in wood density reduces pulp yield (Malan 1988).

Tear strength is related to fibre strength, fibre length and cell wall thickness. Tensile strength is determined by both fibre strength and bond strength. Burst strength and bulk density have a strong inverse relationship with wood density and features related to wood density (Malan *et al*., 1994). The ability of cells to collapse or flatten increases the inter-fibre bonding and bulk density, which depends strongly on cell wall thickness which in turn is strongly related to density (Malan and Arbuthnot, 1995).

Malan (1988) found that genetic selection for increased growth rate may result in a decrease in wood density and fibre length. Both these properties are widely regarded as very important indices of wood quality; any changes to them may have important effects on the various avenues of timber utilization. Paper quality and strength are negatively impacted upon with decreased fibre length; while a decline in wood density reduces timber strength, behaviour of wood during drying, pulp yield and various other properties of wood (Malan 1988).

Chemical constituents such as the relative composition of hemicelluloses in the wood (mannose, xylose, galactose, glucose and arabinose) can also play a role in contributing to the strength properties of pulp. The extent of hydrogen bonding between fibres (which influences strength) is a function of the physical characteristics of the fibres and the reactivity of the chemical constituents of the cell walls (Turner, 2001).

2.2. Effects of environmental factors on tree physiology and wood properties

The environment to which a tree is exposed is an integrated complex of climatic and topographical factors as well as a number of soil-related and biological factors (Landsberg and Gower, 1997; Louw and Scholes, 2002). The environmental influence, however, occurs within the bounds of the genetic make-up of the individual tree. Studies conducted on *E. grandis* and other eucalypt species are discussed in the sections that follow with reference to the effects of environmental factors on tree physiology, wood properties and wood quality.

2.2.1. Environmental factors – rainfall, temperature and soil factors

Climate has an important influence on plant growth and is useful in predicting where plants grow. The two primary drivers of growth response are water and energy. The underlying assumption is that growth is directly related to absorbed radiant energy, and that the efficiency of energy utilization is directly affected by plant water status (Landsberg and Gower, 1997). This interaction is also influenced by soil type, depth, nutrients, acidity and texture, which influence water retention and water availability, and effective rooting depth of the soil.

Worldwide, water and nutrient interactions are widely recognised as key factors in determining forest productivity (Louw, 1999). South African forests are no exception, where the growth rate and health of plantations is highly dependent on variation of soil water availability. Soil water availability is one of the main factors influencing commercial tree growth in South Africa, and is often limiting as evaporative demand is high (Roberts, 1994). Of importance to the forestry industry is not soil water levels *per se*, but the impact of these levels on tree growth (Roberts, 1994).

Soil water availability is determined by rainfall and its distribution, soil water holding capacity and evapotranspiration. Geological and soil conditions also directly affect the amount of water available for tree growth. A mean annual rainfall of 800 mm, for example, may be less effective than 600 mm under different soil and climatic circumstances (Theron, 2000). The capacity of soil to store water is known to be strongly correlated to site productivity (Louw, 1999). Trees require a minimum soil depth (or effective depth) for roots to develop without limit to their extent of development to facilitate water and nutrient uptake and to maintain a healthy above ground ‘factory’ (Ellis, 1996). In a review of site growth studies, Louw (1999) showed significant correlations between variables affecting available water capacity (effective rooting depth, soil texture and organic carbon) and growth.

The major plantation forestry areas in South Africa are located in the summer rainfall region (du Toit *et al*., 1999) and cover a range of soils and biophysical environments. The productivity of many of the sites is below their potential in terms of tree growth, however, and growth rates vary widely within a relatively small geographic region. Summer rainfall areas are all characterized by a marked peak in precipitation with relatively dry months of between 10-30 mm rainfall per month (Herbert, 2000). Mean annual precipitation (MAP) can thus be used as a means of comparison between areas and the requirements of trees, as seasonal distribution is broadly similar. Schulze (1997) reported that the optimum MAP and mean annual temperature (MAT) for *E. grandis* were ≥ 900 mm and $\geq 16\ ^{o}C$ respectively. Site-species matching to the temperature of the environment is an important issue, even in areas with mean annual rainfall exceeding 800 mm and where exotic hardwoods would be expected to grow well from a temperature perspective (Schulze, 1997). Temperature tolerances of species need to be considered together with rainfall to ensure sustained yields and minimum stand failure which affects long-term profitability.

2.2.2. Effect of environmental factors on tree physiology

Forest production depends on trees capturing resources from the environment and utilising these resources to fix atmospheric CO_2. Furthermore, wood production depends on the pattern of biomass partitioning. Environmental factors can vary from periodic and/or predictable changes in temperature, precipitation and anthropogenic stress factors to occasional episodic events such as fire or storms. The impact of a change in environment can seldom be related directly to a single measurable factor in the total complex; subtle interactions usually exist between environmental factors. Therefore it is useful to know how trees respond to various individual contributing factors that result from varying environmental conditions. Plant physiology is the study of the way in which plants grow and develop, which is fundamentally determined by the biological processes that occur within the organism and deals with plant function (Salisbury and Ross, 1985). There is a need to understand weather-by-climate interactions fully at the level of whole tree physiology to fully understand the effect of weather on cambial activity and therefore stem increment and wood properties (Downes *et al*., 1999).

The pattern of response of trees to change is recorded in their wood structure across the stem radius. The variation of wood properties over time is the net result of a complex web of interactions, and the pattern of this variation is a function of genotype x environment interactions on the whole tree as they impact on factors that are responsible for control of cambial growth (Downes *et al*., 2002, Downes and Drew, 2008). The genetic potential of a species sets its potential for growth, and environmental constraints limit the expression of that potential (Wimmer *et al*., 2002a). Understanding the pattern of growth will enable researchers to date particular features within an annual ring and relate properties to changes in the environment (Wimmer *et al*., 2002b, Downes *et al*., 2009a).

Favourable environmental conditions lead to higher growth of *Eucalyptus* plantations by increasing both the supply of resources, and the efficiency of resource use. Environmental conditions influence the proportion of plant production that is partitioned underground. Productivity in forests is usually defined as the increase in above-ground dry matter per unit time. For any given stand of trees, light use-efficiency decreases as productivity becomes limited by environmental and site variables (Whitehead and Beadle, 2004).

Various limiting factors affect tree growth and the release of one limitation (e.g. temperature) will result in a shift in growth rates (i.e.: greater stem production and radial increase in stems) up to the point where growth is again affected by another limiting factor such as soil water availability (Downes *et al*., 1999).

Photosynthetic rates are limited by water and nutrient stress. Favourable environmental conditions may reduce belowground partitioning from near 50% of gross primary production (GPP) to 30% of GPP (Binkley *et al*., 2004). A leaf with an adequate supply of water can fix more CO_2 per unit of light intercepted than a water-stressed leaf with closed stomata. Therefore, when the supply of a limiting resource is increased, logically, the efficiency of use of other resources should increase.

E. grandis has been planted successfully on a variety of soils, and is quite accommodating of various edaphic conditions. Growth is best on deep loams and clay loams derived from igneous rocks such as dolerite and granite, however, siliceous soils overlying sandstone or quartzite, or marine soils yield satisfactory growth (Poynton, 1979). Good soil depth is usually reflected in superior vigour and resistance to drought. However, *E. grandis* sometimes fails on sites which become waterlogged during the rainy season, and may suffer from drought on shallow soils during dry spells. In areas of low rainfall, soil depth is usually more limiting than soil nutrient status; however, in well watered localities, the latter becomes more limiting (Poynton, 1979).

E. grandis has been planted more extensively than any other eucalypt in Natal and Zululand (now known as KwaZulu-Natal) as this species is capable of rapid growth in these areas due to the deep, moist soils from the coastal belt to the foothills of the Drakensberg (Poynton, 1979). Noble *et al.* (1991) studied the interactions of site with *E. grandis* on the Zululand coastal plain. Of the soil factors considered, soil organic carbon (OC) content of the topsoil was the major soil component best related to the performance of trees on the sandy-textured soils. These authors found the soil OC content on soils with thriving trees was almost double that of poorly performing stands and a highly significant linear correlation was found between this parameter and site index based on height. Athough the range in OC was not wide (0.05-0.5%), OC was speculated to have a major influence on general fertility and physical condition of a site.

The soils of the Zululand coastal plain are of a predominantly sandy nature (clay < 13%) and have low levels of soil organic carbon (Noble *et al.*, 1991). The sandy nature of these soils suggest that their water holding capacity is low and that soil moisture may be lost rapidly after a rainfall event. These inherent characteristics limit the cation exchange capacity (CEC) and nutrient supplying ability and capacity of these soils. Higher exchangeable levels of Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} were found on better performing stands suggesting that a general lack of basic cations could have resulted in lower growth in the poorly performing stands of *E. grandis* that were investigated (Noble *et al.*, 1991).

Drought is often a major limiting factor in South African commercial forestry and drought events occur frequently enough to be considered likely within the life of any stand (Theron, 2000). The period of severe drought during 1992-1993 that affected the eastern regions of Africa, and particularly South Africa, had a devastating effect on the survival and growth of trees in forestry plantations. Eucalypts suffered heavily during this period, approximately 9 500 ha of *E. grandis* died, and 1.5 million cubic metres of wood production was lost (Darrow, 1994). Tree mortality resulting from this drought was more severe on shallow soils than deep soil (Darrow, 1994).

Numerous yield declines in second rotations have been reported for *E. grandis*, and this could be a result of insufficient soil water once initial soil resources have been utilised. *E. grandis* is highly intolerant of adverse conditions, and shows substantial declines when planted on shallow soils and/or on dry sites (Boden, 1991). This author found an inverse proportional relationship between soil water status and tree vigour (expressed in terms of mean annual increment, (MAI)); the soil under large trees was consistently and substantially drier than under small trees. Periods of slow growth of *E. grandis* were associated with low levels of soil water. Similarly, the onset of periods of faster growth coincided with periods of increased soil water (Boden, 1991).

A study was conducted by the ICFR attempting to relate growth curves for *E. grandis* to moisture supply (Roberts, 1994). A minimum of 300 mm of annual rainfall, at any site, is lost due to interception storage (i.e.: when the first drops of rainfall are intercepted by leaves and vegetation), this proportion of rainfall does not contribute to moisture availability, and was regarded as the lower limit of rainfall. According to Roberts (1994), the upper limit of rainfall was a limit above which additional rainfall on a site would be superfluous for growth. Therefore, the maximum amount of rainfall that would be effective for tree growth would be between the lower and upper limits defined for each site on an annual basis. Estimated effective rainfall in any year also included soil water storage capacity (which is related to soil type and depth). Total available water in any year is consequently made up of effective rainfall and additional storage (if required and if available) (Roberts, 1994).

Stem growth per unit rainfall (water use efficiency ($WUE_{(stem/rain)}$)) will be influenced by the quantity of rain that percolates into the soil and contributes to available soil water, and losses and gains can occur (Dye, 2000). Losses in rain water available to the trees may occur through rainfall interception by plant canopies and the litter layer and by surface runoff and drainage out of the rooting zone (both vertically and horizontally). The depth of the rooting zone is an important determinant of the quantity of rainfall accessible to trees. Gains can occur through carry-over of surplus water from the previous year and access by tree roots to groundwater or lateral inflow of soil water from upslope areas (Dye, 2000).

Dye (1996) conducted a study on *E. grandis* subjected to soil drying to determine the relationship between transpiration rate and soil water availability. Plastic sheeting was used to prevent soil water recharge and thereby allow the roots in the soil to induce a progressive depletion of soil water. Measurements of pre-dawn xylem pressure potential (XPP), leaf area index, growth and sap flow rates revealed that the prevention of soil water recharge resulted in only moderate drought stress (Dye, 1996). Height and volume growth increments of the four-year old experimental trees declined relative to the growth increments of trees growing outside the study site. A marked reduction in the final height growth (but not volume growth) was measured in both the four- and ten- year old study trees. An increase in daily sap flow and pre-dawn XPP after the soil water deficit was relieved halfway during the study period implied that the soil water deficits were sufficient to cause some physiological responses in the trees, although the minimum predawn XPP of -1.1 MPa indicates that the stress was not severe (Dye, 1996). The failure of the trees to respond to the imposed soil water deficit can be attributed to the ability of the trees to abstract soil water to a depth of at least 8 m (Dye, 1996). Deep drilling revealed that live roots reached 28 m below the surface. It was concluded that water was possibly recharged by infiltration along old root channels.

Relationships between hydraulic characteristics and growth efficiency of closely related *Eucalyptus* clones growing in plantations on mesic and xeric sites were assessed by Vander Willigen and Pammenter (1998). It was found that growth was influenced more by site than by clone; and that growth and hydraulic characteristics were more closely related to water availability than to genetic makeup. Since trees grown on the xeric sites did not show an increased conducting capacity, they were more susceptible to water stress through lower xylem water potentials (which were lower due to low soil water availability) and reduced transpiration by decreased stomatal conductance, at higher water potentials than at the mesic site, which in turn could lead to reduced carbon assimilation (Vander Willigen and Pammenter, 1998).

Dye (2000) investigated the relationship between rainfall and *Eucalyptus* stem growth and found that for a given rainfall amount, large differences in stem growth occurred at different sites. It was suggested that observed differences in stem growth per unit of rainfall ($\text{WUE}_{\text{(stem/rain)}}$) are caused primarily by differences in carbon allocation patterns brought about by differences in the frequency and intensity of physiological stress. There were intrinsic differences in maximum $\text{WUE}_{\text{(stem/rain)}}$ attainable at each site investigated. Maximum values were achieved in years with high rainfall when the incidence of soil water deficits would be minimal. Markedly higher temperature at one of the sites studied was probably a significant factor causing high WUE $_{\text{(stem/rain)}}$ and early canopy development at that site (Dye, 2000).

In a study attempting to quantify the effect of genotype-by-environmental interaction (GEI) on clones and hybrid clones of *E. grandis*, mean annual rainfall (MAP) was identified as the main environmental factor responsible for volume production (on a species level, however, some interaction, on an individual clone basis, with other environmental variables was found (Pierce and Verryn, 2000). These authors found no significant correlations between growth and the soil factors recorded. This was explained by the fact that all of the sites chosen were considered as ideal *E. grandis* growing sites, in terms of high, well distributed rainfall, a range of temperatures ideal for *E. grandis*, and no shallow soils (Pierce and Verryn, 2000).

2.2.3. Effect of environmental factors on wood properties

Wood properties are determined by environmental factors, silvicultural practices, genetic factors, age and position in the tree stem. Pith-to-bark variation in wood properties is a function of changing environmental and physiological factors. A close relationship between wood properties and growth rate is therefore expected (Downes *et al*., 2009a), but, these relationships are complex and vary widely (Zobel and van Buijtenen, 1989; Sandercock *et al*., 1995; Downes *et al*., 1997). Factors that cause variation in the different types of cells produced by trees are usually interactive, so there is rarely a single factor that controls variation. By assessing wood property variation within the context of its growth history, it will be possible to gain insight into cause and effect relationships between factors that drive wood variability (Downes *et al*., 2009a).

A large volume of literature exists which discusses the influence of environmental factors on various wood properties. Various studies undertaken to understand the effect of environmental factors on the wood properties of

Eucalyptus grandis and various other eucalypt spp. include Bamber *et al*. (1982), Malan (1991), Malan and Hoon (1992), February *et al*. (1995), Clarke *et al*. (1999), Downes *et al*. (1999), Downes *et al*. (2000), Megown *et al.* (2000), Wiemann and Williamson (2002), Wimmer *et al*. (2002a and 2002b), Leal *et al*. (2004), Searson *et al*. (2004), Thomas *et al.* (2004), Drew and Pammenter (2006), Gava and Gonçalves (2008), Wimmer *et al*. (2008), Drew *et al*. (2008), Drew *et al*. (2009a and 2009b). These studies assess the effects of various independent variables on basic wood properties such as vessel and fibre characteristics and wood density, however, a variety of experimental approaches and results have resulted in interpretations being just as diverse (Zobel and van Buijtenen, 1989; Sandercock *et al*., 1995; Downes *et al*., 1997; Downes and Drew, 2008).

Clarke *et al*. (1999) compared growth and wood properties of eucalypts at two sites that differed in terms of temperature and found that while *E. grandis* yielded the lowest wood density of all the eucalypts studied at both sites, all species had higher densities at the colder site. This was probably a result of higher levels of extractives. Megown *et al.* (2000) found recognisable trends towards decreasing density with an increase in site index, density at breast height was strongly correlated with weighted mean tree density (R = 0.97).

Downes *et al*. (1999) used electronic dendrometers as a means of assessing changes in stem radius and relating changes in the environment to stem growth and wood production of *E. globulus* and *E. nitens*. To a large extent, rainfall was the limiting environmental variable, but the determining factors varied between species and throughout the growing season. When irrigation was adequate, i.e.: no growth limitations were present due to shortage of soil water, the shrinkage experienced by trees during the day, in summer, exceeded the night-time growth. Often, no net growth is experienced over a 24 hour period in summer, even when water is available (Downes *et al.*, 2000). Slower growth leads to an increase in wood density, so the pattern of growth over the year is more important than the width of the annual ring. Similarly, in a study which compared patterns of daily stem size variation in eucalypt clones, Drew *et al*. (2009b) concluded that discrete rainfall events, through the release of drought stress, were the drivers of short-term growth responses. It is important to understand such growth responses because this intermittant growth can be expected to have an important effect on wood properties (Downes *et al*., 2000; Downes and Drew, 2008).

Wimmer *et al*. (2002a) found an obvious relationship between wood density of *E. globulus* and soil water deficits with density decreasing in response to water stress releases. The density decrease was accompanied by acceleration in daily increment. Wimmer *et al*. (2002b) reported a slowing down of cambial growth and a consequent increase in density in *E. nitens* as a result of increasing soil water deficit. This increase in density was explained by a reduction in vessel size and an increase in fibre wall thickness. Searson *et al*. (2004) found significant increases in wood density of water-limited *E. grandis* seedlings. Higher increases in density were initially found but this was due to extractive compounds embedded in the cell wall matrix. Similar relationships between water availability and the wood density and fibre diameter of *E. globulus* were reported by Drew *et al*. (2009a), where wood density increased and radial fibre diameter decreased in response to reduced water availability. A study by Wimmer *et al*. (2008) reported that site quality had an inverse effect on wood density with poorer quality sites having higher wood density. Fibre length and pulp yield increased with increasing site quality.

For many genera and species, vessel element diameter and length decrease while vessel frequency increases with decreasing water availability (Carlquist, 1975; Bamber *et al*., 1982; Malan, 1991; February *et al*., 1995, Leal *et al*., 2004, Drew and Pammenter, 2006). There are two ways in which a tree may increase transport efficiency, one is by producing more cross-sectional xylem and the other is by changing anatomical features that affect conductivity such as vessel diameter, length and frequency. One of the most important of these variables in angiosperm wood is probably vessel diameter, since hydraulic conductivity is proportional to the vessel radius raised to the 4th power (Zimmerman, 1983). This means that even a slight increase in vessel radius is equivalent to an enormous increase in ability to transport sap. Species on dry sites need narrow, shorter vessel elements to avoid embolizing and require more vessels per unit area to provide the needed water transport, since narrow vessels provide exponentially less flow than wide vessels (Zimmerman, 1983). Leal *et al*. (2004), in a study on *E. globulus*, also reported that low water availability was related to more frequent and smaller vessels. Similar findings for various eucalypt species were reported by February *et al*. (1995), Searson *et al*. (2004), Drew and Pammenter (2006), Drew *et al*. (2009a).

Significant differences in vessel diameter and vessel frequency were found between fast and slow-growing *E. grandis*, with faster growing trees having larger vessels and lower vessel frequency (Malan, 1991). Drew *et al*., (2009a) reported similar results for *E. globulus*. Bamber *et al*. (1982) found that vessel size and frequency decreased and ray volume increased with fast growth, and density and fibre dimensions were unaffected. It is important to note, however, that the study material was 2.5 years old. Fast growth appeared to have an effect on physiologically active cells but not the mechanical cells, i.e.: the fibres (Bamber *et al*., 1982).

February *et al*. (1995) attempted to predict water use efficiency in *Eucalyptus* species and found that vessel diameter and vessel element length of *E. grandis* and *E. grandis* x *E. camaldulensis* increased significantly with increased water availability and vessel frequency was not correlated with available water. Water availability had a significant influence on stem diameter and transverse sectional stem area. Results for *E. grandis* and *E. grandis* x *E. camaldulensis* showed significant correlations between water consumed and vessel diameter, and it was suggested that both these eucalypts have plasticity in vessel morphology that allowed them to optimise use of plant-available water (February *et al*., 1995). Findings by these authors were contrary to expectations by Wilkes (1988) where variations in wood properties were related to a specific factor in the environment such as available water.

Mean vessel lumen area of *E. grandis* was significantly reduced by water limitation but this was balanced by an increase in vessel frequency in water-limited plants, resulting in no difference in the proportion of stem area allocated to vessels (Searson *et al*., 2004). Conduit efficiency values were lower in water-limited plants suggesting that there was a cost in terms of stem hydraulic conductivity for decreasing vessel lumen area. The conclusion was that periods of drought longer than one month are required to increase wood density in eucalypts, and the consequence of increased wood density would result in diminished capacity to supply water to leaves.

Drew and Pammenter (2006) assessed short-term variation in vessel size and frequency in two *Eucalyptus* clones at sites which differed in water availability and reported that trees grown on the drier site had smaller vessels and a higher vessel frequency compared to trees on the wetter site. These authors found a significant inverse relationship between vessel size and frequency.

Gava and Gonçalves (2008) reported on the effect of soil attributes on the wood quality of *Eucalyptus grandis*. These authors found that wood productivity and quality were affected by physical attributes of soil, mainly clay content (which is related to the amount of available water). Tree growth was directly associated with soil type and textural classes. Wood density did not change at different soil types, however, the total lignin content decreased as clay content increased (until approximately 350-400 $g.kg^{-1}$ clay) (Gava and Gonçalves, 2008).

Temperature is considered to be an important factor influencing wood density. Temperature is thought to influence wood density through its influence on growth. Tree growth is stimulated by increasing temperatures resulting in a relatively larger proportion of carbon allocated to the stem (Creber and Chaloner, 1984). Positive relationships between wood density and temperature were reported in field grown trees in response to seasonal variation in growth environment during a growing season (Thomas *et al.*, 2004) or changes in the environment due to latitudinal or elevation changes. However, it was not possible to definitively relate changes in wood density to changes in temperature alone since variations in factors such as leaf-air vapour pressure difference, and possibly rainfall and length of growing season, often occur in association with changes in temperature.

Roderick and Berry (2001) proposed that the mechanism by which temperature affected wood density is via its impact on the viscosity of water. The argument proposed that at higher temperatures, when the viscosity of water is lower, smaller or fewer vessels would be required to transport water to leaves. Research by Thomas *et al.* (2004) supported the model of Roderick and Berry (2001) showing that wood density of *E. camaldulensis* increased with increasing temperature and hydraulic conductivity per unit wood area decreased.

Stand density (i.e. number of stems per hectare) affects tree growth and wood quality. Initial stand density has pronounced effects on growth and yield of short-rotation fast-growing eucalypts (Smith *et al.*, 2005). Accelerated growth increases production per unit area and also reduces the age at which the trees can be harvested (Malan, 2000a). Spacing and thinning practices, which are aimed at achieving maximum volume growth, usually do not have adverse effects on wood properties. The control of stand density, either through silvicultural practices, such as initial spacing or thinning or combinations of the two, strongly influences both tree growth and wood formation (Malan and Hoon, 1992). Under conditions of similar nutrient and water availability, individual trees of widely spaced and/or thinned stock will grow faster than trees which are grown closer together, i.e.: tree and stand growth efficiency is increased (Whitehead and Beadle, 2004).

Thinning has significant effects on wood formation because of its impact on crown development and rate of growth. Rapid early growth will result in the size of the juvenile core being larger, resulting in lower density wood with shorter fibres, higher longitudinal shrinkage upon drying and higher lignin content (Malan and Hoon, 1992). The density of suppressed trees increases rapidly with increasing distance from the pith, showing no tendency to level off towards the bark. Trees growing more freely, however, reach maximum density levels fairly early in life resulting in a stem with a larger proportion of mature wood of relatively uniform density (Malan and Hoon, 1992).

2.3. Non-destructive techniques for evaluating wood properties

In the past, wood quality evaluation was costly, time consuming and often limited in its usefulness due to the inherent variability in wood (Downes *et al*. 2009). Research, in terms of wood quality, has evolved to a large degree and much work has focused on developing techniques and equipment to help minimize the cost and time needed for the evaluation of wood characteristics (Downes *et al*., 1997; Turner, 2001; Zboňák and Bush, 2006; Downes *et al*., 2009a). These tools that have been developed have assisted in providing a means of integrating plantation wood quality with specific product characteristics with the goal of minimized process costs and obtaining more consistent predictable outputs from the mill.

These technologies require the use of non-destructive sampling of standing trees, typically a core (12 mm diameter) taken at breast height. Technologies currently being utilized in South Africa to characterize wood samples from pith to bark are light microscopy combined with image analysis, gamma ray densitometry and near infra-red (NIR) spectroscopy.

Light microscopy combined with image analysis is a useful technique that enables the quantification of some wood properties from images obtained from sections of wood. Anatomical characteristics that can be measured include: vessel diameter, vessel frequency (the number of vessels per unit area), vessel percentage (percentage area occupied by vessels), fibre diameter, fibre lumen diameter, cell wall thickness and cell wall area.

Gamma-ray densitometry is a tool used to measure wood density by passing an incident beam of gamma rays from a suitable radiation source through a collimator onto the wood specimen. Part of the radiation is absorbed by the wood and the photons that pass through unchanged are counted by a detector, and subsequently, this value is used to calculate wood density (Laufenberg, 1986; Davis *et al*., 1993).

Near infra-red spectroscopy had shown great potential in the forest industry as a tool to enable the rapid assessment of various wood and pulp characteristics (Sefara *et al*., 2001; Schimleck *et al*., 1997; Zboňák and Bush, 2006; Poke and Raymond, 2006; Downes *et al*., 2009b; Tyson *et al*., 2009). The advantages of this technology are minimal sample preparation time, rapid acquisition time and a non-destructive spectral acquisition (Zboňák and Bush, 2006). The NIR technique involves the measurement of a range of samples using classical methods (such as pulping and wet chemistry). Using these measurements, calibration models can be developed and the NIR spectra can be related to wood properties of interest e.g. percentage cellulose and lignin or pulp yield.

The use of non-destructive sampling techniques combined with image analysis, gamma-ray densitometry and near infra-red spectroscopy has largely been responsible for enhancing our current understanding of the eucalypt resource grown for pulp and paper production in South Africa. Efforts to improve and refine these techniques will go a long way in deepening our understanding of variation in wood properties of *Eucalyptus* species leading to better resource optimisation and higher returns for the pulp and paper industry in South Africa. Linking forest technology, high wood production and comparative cost advantages are integral in supporting the continual growth of industrial wood plantations in the global forest products market. The outcomes and application of forest research has made an important contribution to increasing the eucalypt wood supply in South Africa (Morris, 2008).

The field of non-destructive testing and non-destructive evaluation is constantly evolving. Forestry remains a technology-based industry and will become more reliant on technology in the future, both in the raw material and processing sectors, and as such, will depend on an appropriate knowledge base generated through research (Dyer, 2007). The assessment of the quality of raw wood materials has become a crucial issue in the operational value chain as a result of increasing economic pressure on the forestry and wood processing industry to maximize extracted value from the resource (Brashaw *et al*., 2009).

2.4. Summary

This chapter provides a background on basic wood properties and factors influencing wood quality of the eucalypt resource. Eucalypt wood quality was reviewed in terms of commercially important wood properties and their role in obtaining good quality pulp and paper. Previous research, which assessed variation in wood properties and the effects of environmental factors on tree physiology and wood properties, were summarised to gain a better understanding into the complex interactions between the eucalypt resource and the environments in which it is planted. Many studies reported significant effects of a range of site factors on the wood property variation of various eucalypt species, but despite the long history of research, there are still gaps in our knowledge. A brief background on non-destructive assessment techniques used to assess wood properties in this research was also discussed.

In Chapter one of this thesis, a summary of previous studies specifically on the *E. grandis* resource in South Africa was discussed to highlight the need for this research. It was concluded that there was scope for further investigation into individual factors driving variation in wood quality of the South African eucalypt resource since the mechanism by which environmental variables affect wood properties remained unclear and models developed to predict variation on the basis of these variables were not sufficiently robust due to insufficient validation and replication.

The aim of this research was to quantify and model the effects of environmental variables on the wood quality of *E. grandis* in the warm temperate and sub-tropical forestry regions in South Africa. The experimental design to address the aims of this research requires sampling a range of sites and measuring a number of wood properties, an approach which in the past has been severely limited by the expense of intensive sampling and laboratory work. The use of rapid screening tools to characterize basic wood properties from pith to bark made it possible to work with a wide variety of sites and wood properties both time- and cost-efficiently. The rapid screening tools used were light microscopy combined with image analysis, gamma-ray densitometry and near infra-red (NIR) spectroscopy.

The next chapter includes a more detailed description of the rapid screening tools used to characterize wood samples from bark-to-pith and describes the approach used in developing an experimental design, methods used to sample and measure trees and soil properties, and obtain climatic data.

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CHAPTER THREE

EXPERIMENTAL APPROACH

3.1. Introduction

This chapter outlines the approach used in developing an appropriate experimental design to achieve the specific objectives of this research. The methods used to sample trees and enumerate stands of trees within compartments, and the methods used to measure wood and soil properties are described. The approach used to obtain climatic data is discussed.

3.2. Experimental design

3.2.1. Defining regions for sampling strategy

In South Africa, *Eucalyptus* trees are grown in plantations along the eastern seaboard of the country between latitudes 23^{o}S and 32^{o}S across a wide range of site conditions of varying potential productivity (Pallett and Sale, 2004). These areas experience summer rainfall which is characterized by a marked summer peak followed by relatively dry winter months of between 10 and 30 mm rainfall per month (Herbert, 2000). Eucalypts are planted extensively in KwaZulu-Natal (KZN) and Mpumalanga (MPU), where 52.9% and 38.1% of *Eucalyptus* plantations occur respectively (DWAF, 2008).

The dominant *Eucalyptus* species grown is *Eucalyptus grandis*, which accounts for 56.4% of the total *Eucalyptus* plantation area in South Africa (DWAF, 2008). While the area planted to eucalypt hybrids (hybrids of *E. grandis* with either *E. urophylla* or *E. camaldulensis)* has increased significantly, particularly in Zululand, *E. grandis* is still a commercially important species (DWAF, 2008).

Since one of the main objectives of this research was to describe the variation in wood properties of *E. grandis* in the plantation forestry regions in South Africa, an experimental design which considered a wide range of environmental conditions under which *E. grandis* is planted was needed. In the past, such a design would be severely limited by the expense of intensive sampling and laboratory work. However, the use of non-destructive rapid screening techniques to evaluate wood properties made it possible to research a wide variety of sites both time- and cost-efficiently. (Non-destructive rapid screening techniques are discussed in Section 3.6).

Initially, four commercially significant forestry economic zones were considered *viz.* KwaZulu-Natal Midlands, Zululand (Coastal KwaZulu-Natal), Mpumalanga North and Mpumalanga South, since eucalypts are planted most extensively in these regions (DWAF, 2008). Forestry economic zones in South Africa are delineated based on administrative (provincial) boundaries, physical (climate, soil), silvicultural (timber species), economic and historic considerations (DWAF, 2008). These forestry zones lie within the timber belt of southern Africa which is diverse in its soils, topography and climate (Herbert, 1993).

However, this method of defining forestry regions was considered to be somewhat arbitrary since the definition of region was based mainly on areas in which *E. grandis* is historically grown. While previous research has shown that rainfall and temperature do vary within and among these forestry zones, a more structured approach was needed to address the specific questions posed in this research regarding the effect of environmental factors on wood properties.

For this reason, an alternative approach of defining regions based on a site classification system developed by the Institute for Commercial Forestry Research (ICFR) was considered (Smith *et al*., 2005). While forest economic zones form the first level of this classification system, they are coupled with climatic and geological factors in the subsequent levels of the classification system. Levels two, three and four are based on mean annual temperature (MAT), mean annual precipitation (MAP) and geology (specifically soil water storage (SWS)) respectively. These levels of the classification system were of relevance to this research.

In the ICFR classification system, forestry growing areas are classified into three broad-level macro zones based on MAT – cool temperate (CT) (< 16^{o}C), warm temperate (WT) (16.1-19^{o}C) and sub-tropical (ST) (> 19.1^{o}C) zones

(Smith *et al*., 2005). Each of the three macro zones is further subdivided into three MAP and MAT classes. MAT is subdivided into increments of 1^{o}C. For each temperature range, the MAP thresholds (corresponding to dry, moist and wet categories) change since evapo-transpiration rates vary with temperature (Table 3.1). MAP thresholds therefore increase with increasing temperature for each category. (There is a degree of overlap in MAP between MAT categories).

Table 3.1. Categories of MAT and MAP within each macro zone as defined by the ICFR forestry site classification for the summer rainfall region of South Africa (Modified from Smith *et al*., 2005)

CLIMATE ZONE									
Cool temperate									
Site class	CT1	CT2	CT3	CT4	CT5	CT6	CT7	CT8	CT9
MAT (^{o}C)	10 - 14			14 - 15			15 - 16		
MAP (mm)	< 700	700 - 800	> 800	< 800	800 - 900	> 900	< 825	825 - 925	> 925
	Dry	Moist	Wet	Dry	Moist	Wet	Dry	Moist	Wet
Warm temperate									
Site class	WT1	WT2	WT3	WT4	WT5	WT6	WT7	WT8	WT9
MAT (^{o}C)	16 - 17			17 - 18			18 - 19		
MAP (mm)	< 850	850 - 950	> 950	< 875	875 - 975	> 975	< 900	900 - 1000	> 1000
	Dry	Moist	Wet	Dry	Moist	Wet	Dry	Moist	Wet
Sub-tropical									
Site class	ST1	ST2	ST3	ST4	ST5	ST6	ST7	ST8	ST9
MAT (^{o}C)	19 - 20			20 - 21			21 - 22		
MAP (mm)	< 925	925 - 1025	> 1025	< 950	950 - 1050	> 1050	< 975	975 - 1075	> 1075
	Dry	Moist	Wet	Dry	Moist	Wet	Dry	Moist	Wet

Soil water storage (SWS) formed part of the last level of this classification system, which considered geological groupings in terms of soil properties. SWS is expressed in millimeters (mm) as an estimated value for total available water (TAW) that combines the available water capacity[4] (which is the amount of water per unit depth in mm.m^{-1}) and the soil depth (m) (Smith *et al*., 2005; White, 2006). A conceptual structure of the ICFR forestry site classification system based on climate and soil water storage is illustrated in Figure 3.1.

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[4] Available water capacity is the amount of water a soil can store that is nominally available for use by plants. It is the water held between field capacity and permanent wilting point (White, 2006).

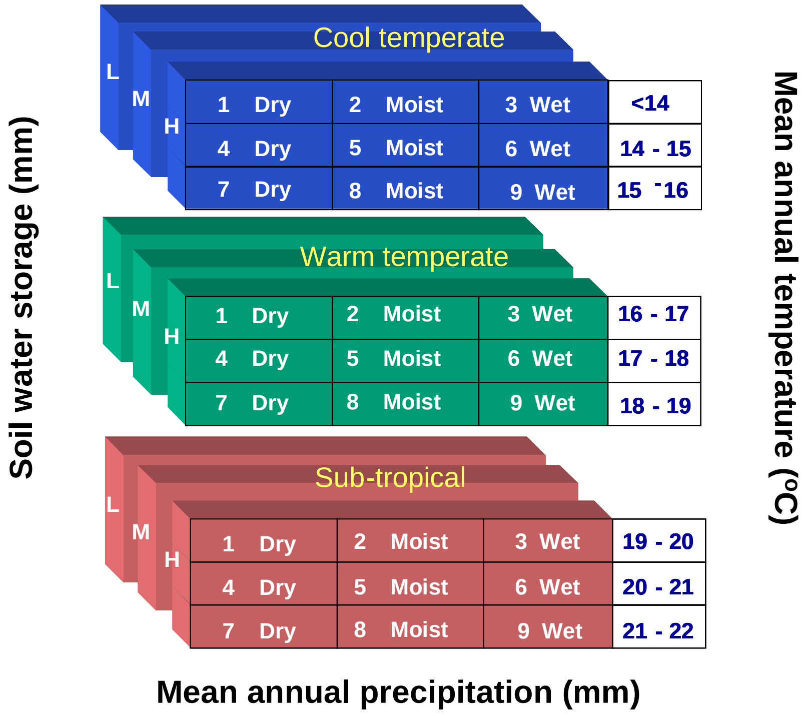

Figure 3.1. Conceptual structure of the forestry site classification system based on climate (MAT (°C) and MAP (mm)) and soil water storage (mm). For the soil water storage categories, L = low, M = moderate and H = high (C.W. Smith, Pers. Comm.[5])

The cool temperate macro zone was not considered in this research since the optimum MAT for growing *E. grandis* is ≥ 16 °C (Schulze, 1997). While this species is occasionally planted in areas within the cold temperate macro zone, the number of suitable compartments available for sampling was not sufficient. Also, if sampled, compartments would not be representative of the typical areas in which this species is planted.

The warm temperate and sub-tropical macro zones from the ICFR site classification system were selected to serve as a basis for the experimental design to define two unique regions which differed from each other in terms of MAT (warm temperate (16.1-19°C) and sub-tropical (19.1-22°C). A map of KwaZulu-Natal and Mpumalanga illustrating both macro zones is provided in

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Figure 3.2. It is acknowledged that a limitation of using MAT is that it integrates diurnal, monthly and seasonal patterns of minimum and maximum temperature. However, in this research, MAT was only used as a good first approximation to describe broad differences between two macro zones.

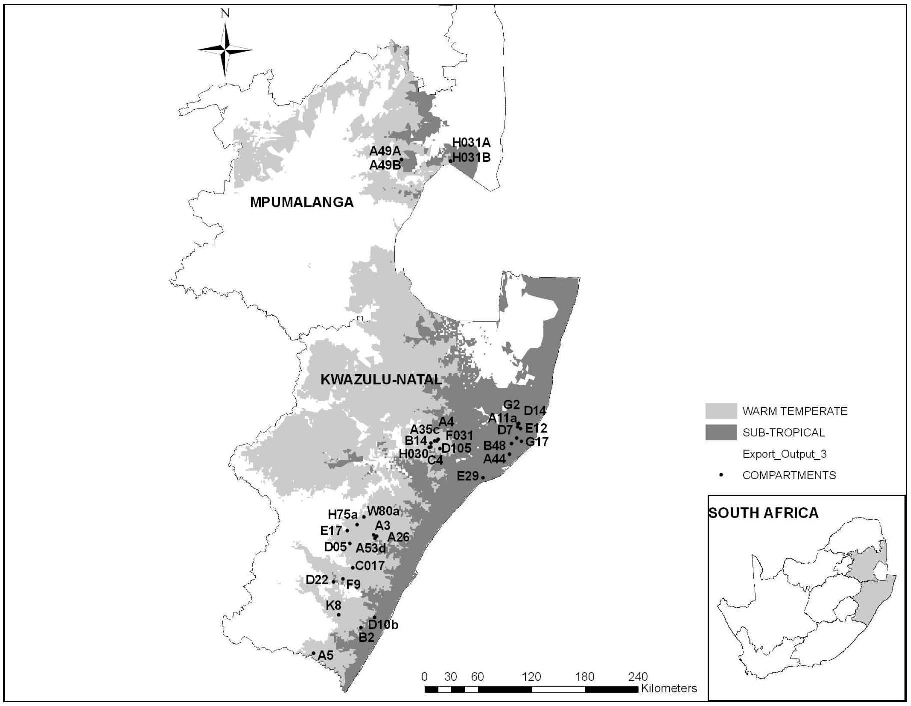

Figure 3.2. Map of KwaZulu-Natal and Mpumalanga illustrating the warm temperate and sub-tropical macro zones

Since seasonal rainfall distribution is similar in the summer rainfall areas in a broad sense, mean annual precipitation (MAP) may be used as a basis for comparisons between areas and the requirements of trees (Herbert, 2000). The warm temperate and the sub-tropical macro zones were divided into nine MAP (dry, moist and wet) x SWS (low, medium and high) combinations to achieve varying levels of water availability among blocks within each macro zone. This was done as an alternative to sub-dividing each macro zone into three MAT and MAP classes as in the ICFR classification system (Table 3.1 and Figure 3.1).

In this research, MAT was not used as a factor to define blocks within each macro zone. Since the criteria used to define the sub-divisions within each macro zone in this research differed from the criteria used in the ICFR classification system, the term ‘region’ will be used instead of the term ‘macro zone’ when referring to either the warm temperate or sub-tropical macro zones (as defined in this research) from this point forward.

In both regions, ‘new’ thresholds for dry, moist and wet values for MAP were calculated using the average of the threshold values that corresponded to the average temperature range for each macro zone in the ICFR system. This was done to eliminate overlap that existed among the MAP classes which were initially associated with individual sub-divided MAT classes within a macro zone (in the ICFR classification system) (Table 3.1). The three levels of SWS took into account the variability in the range of soil forms that were present within and among regions.

3.2.2. Estimates of MAT, MAP and SWS

The South African Atlas of Agrohydrology and Climatology (SAAAC) (Schulze, 1997) was used to extract approximate MAT and MAP values for the *E. grandis* resource in South Africa. According to Schulze (1997), the objectives of the SAAAC are to map climatic parameters (important to agrohydrology and agroclimatology) at a regional level, and apply this information to resource planning in the fields of water and agriculture. The values provided for climatic variables are ‘approximate’ because the author of the SAAAC recommends that values at specific points should be viewed in relative rather than absolute terms. The reason for this is that while considerable spatial detail is provided in the atlas, values at specific points were derived by regression analysis or other simulation models resulting in a smoothing of local effects and dampening of outlier values (Schulze, 1997). Spatial data in the atlas was created at a 1 min x 1 min of a degree grid size (i.e.: 1’x 1’ latitude by longitude grid size).

Estimates of total available water (TAW) for the low, moderate and high SWS ranges were obtained from two shapefiles[6] provided by the ICFR (C. Smith, Pers. Comm.[7]). The first shapefile provided estimates of TAW for the areas found in the ‘dry’ MAP class and the second shapefile provided estimates of TAW for areas within the ‘moist’ and ‘wet’ MAP classes.

The reason for having two sets of estimates of TAW depending on rainfall experienced, summarized in Smith *et al*. (2005), is that climate has an effect on geological groupings and soil properties. For a given lithology[8], a single natural body of importance occurs in afforested areas[9] (Turner, 2000 *in* Smith *et al*., 2005), but this is not always true of a geological zone as a whole. Soil forming processes are different in drier climates compared to wetter climates resulting in different natural soil bodies occurring within the same lithology (Smith *et al*., 2005). Since most afforestation occurs in moister climatic regions, soil bodies are fairly homogenous in these regions. However, in some cases, several soil bodies were identified for a particular geological zone. In the summer rainfall region where plantation forests occur, 23 geological zones relating to key lithologies were documented (Smith *et al*., 2005). These authors presented the relationships between geological zones and soil properties for soils in the dry climatic zones and the moist/wet climatic zones. Soil textural and horizon depth data were derived from a large number of soil data points from various studies referred to in Smith *et al*. (2005). This information was contained in the two shapefiles, provided by the ICFR, with the estimates of TAW for the ‘dry’ MAP class and the ‘moist’ and ‘wet’ MAP class. ESRI® ArcMap™ version 8.3 was used to extract data for MAT, MAP and SWS.

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[6] A shapefile is a vector data storage format for storing the location, shape, and attributes of geographic features (ESRI, 2006)

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[8] “A lithology refers to the mineralogical composition and texture of rocks as parent materials of soil and weathered material” (Smith *et al*., 2005)

[9] Land previously used for other purposes that have been converted into forest plantations

3.2.3. Selection of compartments for sampling

Lists of commercial compartments planted to *E. grandis* were provided by both Mondi South Africa and Sappi Forests. Using the centroid (longitude and latitude) co-ordinates of each compartment listed, MAT, MAP and SWS values were extracted using the SAAAC and TAW shapefiles from the ICFR. (Note: In this research, only one plot of trees (10 m radius) was sampled per compartment, so the term ‘compartment’ will be used instead of ‘plot’ or ‘stand’ throughout the thesis).

It is well known that tree age, environmental factors, and growth rate have significant effects on the properties of wood in the eucalypt resource (Taylor, 1973; Malan, 1988; Malan, 1991; Megown *et al.*, 2000; Clarke *et al*., 1999; Searson *et al*., 2004). However, the mechanism by which the combination of these factors affects wood properties is unclear. Therefore, prior to selecting compartments (replicates) to populate the experimental design based on the three environmental factors (*viz*. MAT, MAP and SWS), other factors also needed to be considered and, where possible, kept within a narrow range to minimise sources of variation when relating wood quality to ‘site’. These factors included stand density (or stems per hectare (SPH)), compartment age, genetic background, and events such as diseases or fire.

Availability of water and nutrients is affected by stand density. The higher the stand density, the greater the competition for the resources by trees in plantations. Stand density is usually variable among compartments across the *E. grandis* resource, and compartments reflecting good silviculture have a stand density of >1300 SPH (C. Smith, Pers. Comm.[10]). Schönau and Coetzee (1989) suggested that initial stand density should approach but not exceed 2000 SPH on high site productivities and should be lower but not less than 1200 SPH on lower productivities (at the time of planting). This information was used as a guide when selecting compartments within a range of SPH.

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Wood properties vary with tree age and much research has involved assessing the effects of site and age on wood properties. Initially, when considering the design for this research, it was intended to assess compartments of a similar physiological age, between 6-8 years (approximately rotation age) therefore no explicit ‘age’ factor was included in the experimental design. However, ‘on the ground’ not enough compartments planted to *E. grandis* between ages 6 and 8 years were available for sampling that fit into the experimental design. For this reason, older compartments were also considered. It was acknowledged that the inclusion of older compartments would be another source of variation in wood properties. The methods used to minimise this additional variaton are discussed in Chapters 4 and 5.

With regards to genetic variation, it was acknowledged that genetic variation does exist between seedling and clonal material of *E. grandis*. In addition, there are different provenances of *E. grandis* and variation also exists between genetic material used by the forestry companies (Sappi Forests and Mondi South Africa). However, reliable records detailing these differences among companies, provenances, seedlings and clonal material were not always made or were available. The inclusion of genetic variation as a variable when selecting compartments was therefore not possible.

After taking the above factors into account, first rotation compartments (i.e. the trees were propagated from seeds or cuttings but not coppice[11]) were selected. Coppiced material was not included since growth rates and wood properties of coppiced stems were thought to differ from parent stem. This was later supported in a study by Zboňák *et al.* (2007) where it was found that the fibre diameter and fibre lumen diameter were larger in the coppiced stems and wood density was lower.

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[11] The term ‘coppice’ refers to stems that have grown from harvested tree stumps or from the base of a damaged stem. Coppiced trees use the same root system developed from the original planted trees

This initial selection of compartments were further sorted based on SPH (ranging between 1100-1750) and compartment age (6-12 years). Older compartments were considered if they had permanent sample plots (PSPs) or research plots within them which added value to this research in terms of temporal growth data (annual measurements of growth such as diameter at breast height). The inclusion of age is a confounding variable in this research and the use of PSP data are discussed in greater detail in Chapter 4.

Compartments that were chosen were grouped within blocks of the experimental design in terms of region (MAT), MAP (dry, moist and wet) and SWS (low, medium and high) with the intention of capturing the variability in climatic and soil conditions in each region. Tables 3.2a and 3.2b provide the threshold ranges for dry, moist and wet MAP and low, medium and high SWS in the sub-tropical and warm temperate regions respectively, and the distribution of sampled compartments in the experimental matrices. Since evaporation rates vary with temperature, the thresholds for dry, moist and wet values of MAP varied between the two regions (Smith *et al*., 2005).

Table 3.2a and 3.2b. Experimental design for the sub-tropical region (3.2a) and warm temperate region (3.2b) with threshold ranges for MAP and SWS. Compartment names and position of compartments in the design are shown in each block

3.2a SUB-TROPICAL

MAP (mm)	**DRY**	**MOIST**	**WET**
SWS (mm)	**700-950 mm**	**951-1050 mm**	**1051-3500 mm**
LOW (72-151 mm)	B2	D10b	H031a
	A49a		H031b
	A49b		
MEDIUM (152-230 mm)			
HIGH (231-309 mm)	E12	A11a	B48
	G2	A44	G17
	D14	D7	E29

3.2b WARM TEMPERATE

MAP (mm)	**DRY**	**MOIST**	**WET**
SWS (mm)	**600-875 mm**	**876-975 mm**	**976-3500 mm**
LOW (72-151 mm)	B14	F9	H75a
	K8	C017	W80a
	A5		D22
MEDIUM (152-230 mm)		A3	A53d
		A26	C4
		D05	D105
HIGH (231-309 mm)		A4	A35c
		F031	E17
			H030

The experimental matrices were incomplete as a result of compartments not being found for all blocks as defined by the selection criteria outlined in the experimental design, i.e. within specific MAT, MAP and SWS combinations. Available compartments either were not within the required age range, or were coppiced, or in some instances, *E. grandis* was simply not grown in some areas. Compartments were not found for all the medium SWS blocks in the subtropical region, and the dry x medium and dry x high blocks in the warm temperate region.

3.3. Sampling strategy

Three compartments were sampled per block in the experimental design (in most blocks in the design). Two discs[12] or two pith to bark cores were sampled at breast height (1.3 m above ground) from the north-facing side of five trees per compartment (trees selected based on diameter at breast height and represented one large, three medium and one small tree). One core/disc was used for wood density evaluation and near infra-red (NIR) spectroscopy, and the other for measurements of vessel and fibre characteristics.

3.4. Enumeration of compartments – Calculation of site index and number of stems per hectare

The quality of a site can be described by site index, an indicator of the growth rate of trees in a compartment. Site indices were derived by calculating the mean height of the tallest 20% of the trees in each stand using a reference age of five years (Bredenkamp, 1993). Five years is considered a useful reference age for hardwoods (Pallett, 2005). A sample plot (10 m in radius) was randomly selected within each compartment and enumerated by measuring diameter at breast height (DBH) and total tree height using a Vertex III for all trees that were within the enumeration plot.

Site index at a reference age five (SI_5) was calculated using Modified Schumacher-difference form (Coetzee, 1994 *in* Pienaar and Kotze, 1998) (Equation 3.1).

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[12] Trees were destructively sampled during sampling events when the corer was not available. A pith to bark wedge was cut from each breast height disc

$$SI_5 = \beta_3 * HD_1 * \exp[\beta_1 (AGE_1 - AGE_2) + \beta_2 (1/AGE_1 - 1/AGE_2)]$$

Equation 3.1

Where: β_1, β_2 and β_3 = parameter estimates

AGE_1 and AGE_2 = compartment age at sampling and at reference age five, respectively

HD_1 = average dominant height of the measured 20% tallest trees

The number of stems per hectare (SPH) (at time of sampling) was calculated using Equation 3.2.

$$SPH = (1/\text{area of plot}) * \text{number of stems in plot}$$

Equation 3.2

Where: area of plot = 314 m^2 (for a 10 m radius enumeration plot)

3.5. Description of compartments

The location and description of compartments in terms of MAT, MAP, SWS, age, site index at a base age five years (SI_5), and number of stems per ha (SPH) are provided in Tables 3.3 and 3.4 for the sub-tropical and warm temperate regions, respectively. Trees sampled in the sub-tropical region (Table 3.3) ranged between ~8 and 13 years of age and SI_5 ranged between 15 and 25. The total number of stems per hectare (SPH) was in the range of 980–1 470 at the time of sampling (and enumeration). Compartments from the warm temperate region (Table 3.4) also had a broad range of ages (5.6–13 yrs), site indices (17-28) and stems per hectare (1 050-1 752).

Table 3.3. Compartment names, location (longitude and latitude in degrees and minutes), age of compartments, and description of site characteristics in the sub-tropical region

Compartment code	Longitude	Latitude	MAT (°C)	MAP (mm)	SWS (mm)	MAP level	SWS level	Age (years)	SI$_5$	Stems per ha.
A49A	30° 52'	-25° 40'	19	809	111	dry	low	10.0	17.0	1019
A49B	30° 52'	-25° 40'	19	809	111	dry	low	10.0	15.3	1115
B2	30° 23'	-30° 25'	19	867	136	dry	low	9.3	19.8	1210
D10b	30° 33'	-30° 19'	19	999	136	moist	low	12.9	20.4	1178
H031A	31° 25'	-25° 42'	19	1517	136	wet	low	12.1	19.5	1338
H031B	31° 25'	-25° 42'	19	1517	136	wet	low	12.1	19.5	1338
D14	32° 13'	-28° 21'	21	908	257	dry	high	8.3	16.5	1465
E12	32° 12'	-28° 23'	21	862	257	dry	high	9.2	18.3	987
G2	32° 12'	-28° 21'	21	917	257	dry	high	9.6	17.9	1083
A11a	32° 14'	-28° 24'	21	989	257	moist	high	9.4	22.4	1178
A44	32° 8'	-28° 33'	21	1008	257	moist	high	9.0	22.6	1019
D7	32° 11'	-28° 30'	21	985	257	moist	high	10.1	19.0	1338
B48	32° 6'	-28° 40'	21	1118	257	wet	high	8.6	24.5	1178
E29	31° 48'	-28° 54'	21	1467	257	wet	high	8.7	22.5	1115
G17	32° 14'	-28° 32'	21	1130	257	wet	high	8.9	24.2	1242

Table 3.4. Compartment names, location (longitude and latitude in degrees and minutes), age of compartments, and description of site characteristics in the warm temperate region

Compartment code	Longitude	Latitude	MAT (°C)	MAP (mm)	SWS (mm)	MAP level	SWS level	Age (years)	SI$_5$	Stems per ha.
A5	29° 50'	-30° 41'	17	811	91	dry	low	9.8	17.7	1369
B14	31° 12'	-28° 33'	17	866	100	dry	low	9.8	21.8	1752
K8	30° 08'	-30° 17'	17	792	100	dry	low	10.5	21.1	1465
C017	30° 18'	-29° 49'	16	974	136	moist	low	11.7	20.3	1465
F9	30° 11'	-29° 55'	17	927	136	moist	low	10.9	27.9	1242
D22	30° 04'	-29° 57'	17	1079	136	wet	low	11.2	20.4	1338
H75a	30° 21'	-29° 23'	18	1106	136	wet	low	10.3	24.3	1369
W80a	30° 26'	-29° 18'	17	1071	136	wet	low	11.0	23.2	1274
A26	30° 34'	-29° 30'	17	961	187	moist	medium	12.5	21.7	1083
A3	30° 32'	-29° 29'	17	880	187	moist	medium	11.9	19.7	1274
D05	30° 16'	-29° 34'	16	919	160	moist	medium	7.5	19.6	1624
A53d	30° 33'	-29° 31'	18	1051	187	wet	medium	5.6	22.5	1306
C4	31° 12'	-28° 35'	17	996	187	wet	medium	7.4	21.9	1401
D105	31° 18'	-28° 36'	17	1020	187	wet	medium	8.0	20.1	1561
A4	31° 16'	-28° 32'	17	948	309	moist	high	9.9	17.2	1401
F031	31° 17'	-28° 31'	17	901	260	moist	high	7.6	19.5	1146
A35c	31° 15'	-28° 32'	16	980	309	wet	high	10.8	21.8	1433
E17	30° 14'	-29° 26'	16	1067	257	wet	high	12.6	19.8	1401
H030	31° 11'	-28° 36'	17	995	309	wet	high	7.4	20.2	1497

3.6. Measurements of wood properties using non-destructive assessment techniques

In the past, wood quality evaluation was costly, time consuming, and often limited in its usefulness due to the inherent variability in wood. In recent decades, much research has focused on developing techniques and equipment to help minimize the cost and time needed for the evaluation of wood characteristics (Downes *et al*., 1997; Turner, 2001; Baijnath, 2003; Turner *et al*., 2005; Zboňák, 2006, Zboňák and Bush, 2006; Downes *et al*., 2009). Outcomes from these authors have contributed to the development of non-destructive sampling techniques combined with image analysis, gamma-ray densitometry and near infra-red spectroscopy.

These technologies required only non-destructive sampling of standing trees, typically a core (12 mm diameter) taken at breast height. Studies examining density variation in trees (Downes *et al.*, 1997; Zboňák, 2002; Baijnath, 2003) have shown that cores sampled at breast height are reliable representations of whole-tree characteristics since variation at breast height is no greater than elsewhere. For the purposes of this research, sampling at breast height was sufficient.

3.6.1. Wood density

Gamma-ray densitometry is a tool used to measure wood density by passing an incident beam of gamma rays from a suitable radiation source through a collimator onto the wood specimen. Part of the radiation is absorbed by the wood and the photons that pass through unchanged are counted by a detector. The difference between the intensity of radiation in air and the intensity of radiation after passing through the sample is used to calculate wood density (Laufenberg, 1986; Davis *et al*., 1993). The equations used to calculate density were described in Malan and Marais (1991) (Equations 3.3, 3.4 and 3.5).

Lambert’s equation (Equation 3.3) expresses the relationship between the count rates and density.

$$\frac{I}{I_o} = e^{-\mu t}$$ *Equation 3.3*

where: I = intensity of radiation after passing through the sample (counts.second^{-1})

I_o = intensity of radiation through air (reading through zero sample thickness) (counts.second^{-1})

μ = linear attenuation coefficient (cm^{-1})

t = thickness of sample (cm)

The linear attenuation coefficient (μ) depends on the density and mass attenuation coefficient of the material (Equation 3.4):

$$\mu = \mu' D$$ *Equation 3.4*

where: μ' = mass attenuation coefficient (cm^2.g^{-1})

D = density (g.cm^{-3}).

By replacing μ in equation (3.3) with $\mu' D$, taking logarithms and rearranging, the following equation for calculating density is obtained (Baijnath, 2003):

$$\frac{\ln I_o - \ln I}{\mu' t} = D$$ *Equation 3.5*

where: ln = natural log

μ' = material property depending on the chemical composition of the specimen material (wood in this case).

The mass attenuation coefficient of wood was assumed to be constant (Malan and Marais, 1991). The values of t, I and I_o are determined at each sample location within the density scan.

Prior to measuring density, core samples or 2 cm thick radial blocks obtained from discs sampled at breast height were stored at 23ºC and 50% relative humidity to achieve an equilibrium moisture content of approximately 10%. Radial strips of uniform thickness were cut along the radius using a twin-blade saw. The strip dimensions were 12 mm in along the grain, 2.5 mm in the tangential direction and length was determined by the radius of the core/disc (Figure 3.3).

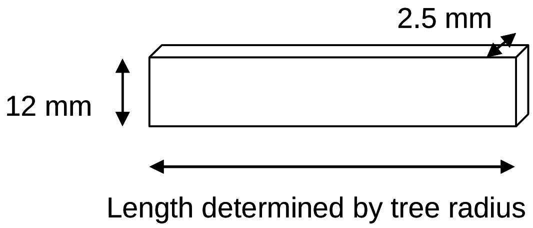

Figure 3.3. Dimensions of a solid wood strip of uniform thickness cut with a twin-blade saw

Radial strips were scanned from bark to pith at consecutive 0.5 mm intervals, using a gamma-ray densitometer with a Fe^{55} radiation source to determine the density profile. Use of a gamma-ray densitometer is considered to be an accurate and reliable technique for determining the density of wood (Malan and Marais, 1991). This measurement of density is commonly referred to as air-dry density and is strongly correlated with basic density[13] (Zboňák, 2002). Since extractives were not removed prior to scanning, this density is “un-extracted” air-dried wood density (Zboňák, 2006).

3.6.2. Vessel and fibre characteristics

Light microscopy combined with image analysis is a useful technique that enables the quantification of specific wood properties from images obtained from sections of wood. Radial strips, 2.5 mm thick, were obtained from the cores or discs taken at breast height samples. Strips were softened by soaking in water. Thereafter, the strips were sectioned in the transverse plane with a sledge microtome to obtain 20-25 µm thick sections. Sections were mounted in

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[13] Basic density is usually evaluated using the water displacement method using the TAPPI standard method T 258 om-94 (TAPPI, 1996)

ethanol on a glass slide, covered with a cover-slip, and examined using a Leica fluorescent microscope. Anatomical measurements were performed every 0.5 mm for vessel measurements and every alternate 0.5 mm for fibre measurements, from bark to pith using an image analysis system (Leica QWin, version 2.8). An algorithm, developed using the image analysis software, enabled the automatic separation of vessels from the fibres and parenchyma in each image acquired. An example of vessel cells, fibre cells and radial and axial parenchyma cells are illustrated in Figure 3.4.

Anatomical characteristics that were assessed in this research included:

- Fibre diameter (FD) (µm)
- Fibre lumen diameter (LD) (µm)
- Fibre/cell wall thickness (CWT) (µm)
- Vessel diameter (VD) (µm)
- Vessel frequency (VF) (the number of vessel elements per unit area of wood) (no.mm^{-2})
- Vessel percentage (VP) (the area occupied by vessels; %)

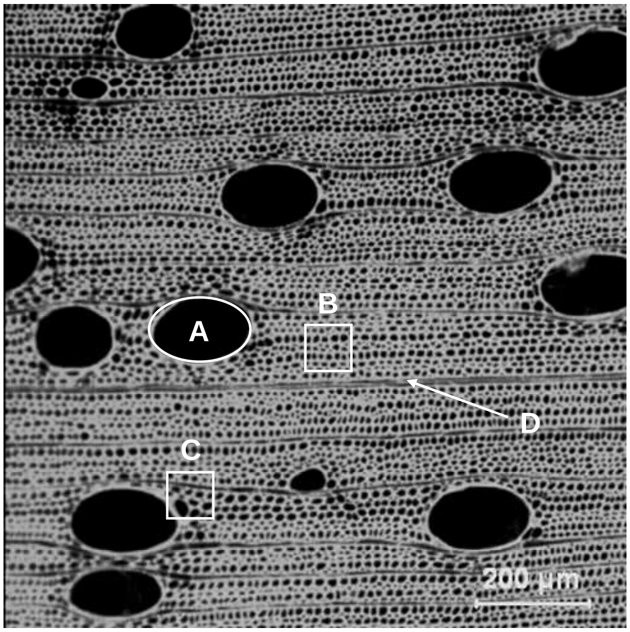

Figure 3.4. Transverse section of *E. grandis* xylem illustrating the different cell types. A – Vessel cell; B – Fibre cells; C – Axial parenchyma cells; D – Radial parenchyma cells

3.6.3. Predicted wood chemical properties (using near infrared spectroscopy)

Near infra-red spectroscopy (NIR) had shown great potential in the forest industry as a tool to enable the rapid assessment of various wood and pulp characteristics (e.g. pulp yield, cellulose and lignin contents) (Sefara *et al*., 2001; Schimleck *et al*., 1997; Zboňák and Bush, 2006; Downes *et al*., 2009). The advantages of this technology are minimal sample preparation time, rapid acquisition time and a non-destructive spectral acquisition (Zboňák and Bush, 2006). The NIR technique involves the measurement of wood and pulp properties for a range of samples in a laboratory. Using these measurements, calibration models can be developed by relating the NIR spectra to basic and chemical wood properties.

NIR reflectance spectra were acquired for radial strips (the same as those used for density measurements) over the 1 100-2 250 nm wavelengths using an XDS NIR spectrometer. NIR reflectance spectra were obtained at consecutive 5 mm intervals from bark to pith using a fibre optic probe of diameter 4.5 mm oriented at a right angle to the sample surface. Thirty-two scans were obtained from each scanning location and averaged into a single spectrum. Background corrections were conducted at 30-minute intervals using a reference ceramic sample (Zboňák and Bush, 2007).

Cellulose and lignin models, from a multi-species calibration model outlined in a report by Zboňák (2006), were applied to the NIR spectra collected for each strip to obtain radial variation in predicted percentage cellulose and lignin.

3.7. Soil analyses

Soil samples for each compartment were taken from two sampling points within the enumeration plot (10 m radius). One of the sampling points was in the centre of the plot, while the other was at a random location within the plot. A soil auger was used to obtain two samples of the topsoil from each sampling point at depths of 0-100 mm and 100-200 mm. (The topsoil is usually regarded as the soil contained in the top 300 mm of the soil (0-300 mm)). The soil properties were averaged at each sampling depth and for each compartment to contribute to the overall description of the compartments.

Measurements of organic carbon and particle size distribution were undertaken. Organic carbon (%) was determined using the Walkley-Black method as described in Walkley (1946). The Walkley-Black method is based on oxidation of organic matter by $K_2Cr_2O_7$ with H_2SO_4 heat of dilution (Mikhailova, 2003).

The relative proportions of sand, silt and clay (particle size distribution) were assessed according to the hydrometer method outlined in Gee and Bauder (1986). This method of estimating particle size is based on the dispersion of soil aggregates using a sodium hexametaphosphate solution and silt and clay fractions were measured with a pipette by a sedimentation procedure based on Stokes' Law (Gee and Bauder, 1986). The sand fraction was separated into fine, medium and coarse classes by dry sieving.

3.8. Sources of climatic data

It was envisioned at the outset of this research that each compartment sampled would have a set of climatic variables associated with it. Values for MAT and MAP were obtained from the South African Atlas of Agrohydrology and Climatology (SAAAC) (Schulze, 1997). Sim-A-Tree (3-PG) (Sim-A-Tree (3-PG), 2005) was used to identify weather stations close to compartments and the South African Weather Service (SAWS) (SAWS, 2007) and the South African Sugar Research Institute (SASRI) (SASRI, 2007) were contacted to update weather records, where possible for weather stations selected.

3.8.1. SAAAC

The SAAAC was discussed in detail earlier in this chapter in Section 3.2.2. Long term mean values (~50 year period between the years 1950 and 2000) for MAT and MAP were extracted for compartments planted to *E. grandis* and were used for the initial grouping of compartments within the experimental design. Mean monthly values for minimum and maximum temperature and solar radiation were extracted using the SAAAC for all sampled compartments.

3.8.2. Sim-A-Tree (3-PG)

Sim-A-Tree (3-PG) (version 1.2) is a computer model that simulates the month-by-month growth and water use of plantation forests in South Africa. This program is a version of the original 3-PG model (Landsberg and Waring, 1997) (the acronym '3-PG' stands for **P**hysiological **P**rinciples in **P**redicting **G**rowth). Sim-A-Tree (3-PG) was developed, in a joint venture between the CSIR, ICFR, and the School of Biosciences Engineering and Environmental Hydrology, UKZN, specifically for application of the 3-PG model in South Africa. This program allows for the selection of weather data and soils input data. Thereafter, using parameter sets contained within the program, growth and water use simulations can be made for *Eucalyptus grandis* (short rotation), *Pinus patula*, *Pinus elliottii* and *Acacia mearnsi*.

For the purposes of this research, Sim-A-Tree (3-PG) was required for the selection of weather stations close to sampled compartments. The database of weather stations included a total of 5 386 rainfall stations and 765 temperature stations. The measurement period for a large majority of these weather stations was between the years 1950 and 2000.

Using the longitude and latitude co-ordinates of each sampled compartment, Sim-a-Tree (3-PG) was used to identify weather stations within a 10 km radius of each compartment to obtain measures of rainfall and temperature data (where available) during the time the trees were grown (up to the year 2000). Unfortunately, some compartments did not have weather stations close to them and weather stations within a 20 km radius were considered.

Initially, the use of interpolation techniques (such as Kriging or Spline interpolation procedures) was considered to estimate climatic data for compartments which did not have weather stations near them (within ~10 km radius). These data were intended for the prediction of rainfall values at the location of each compartment as opposed to using only nearby stations. However, after exploratory analysis of climatic data, it was found that rainfall prediction surfaces could be created for only the sub-tropical region and a small part of the warm temperate region (based on the compartments sampled and stations selected). The data set for climatic data would remain incomplete and additional error would be introduced with the creation of predicted rainfall surfaces. Since part of the initial aim of this research was to relate wood properties to measured climatic data, it was concluded that it was beyond the scope of the current research to pursue the option of creating prediction surfaces to generate rainfall or temperature data for compartments which did not have updated nearby weather stations.

Monthly rainfall was therefore the only measured climatic variable used in this research. Since reliable, updated measured temperature data was not available for the majority of the compartments sampled, only long term means for temperature variables (extracted from the SAAAC) were used.

3.8.3. SAWS and SASRI

The period of climatic data required from weather stations was between January 1992 and December 2007 since those dates covered the time period between the time of planting until the time of sampling for all compartments assessed. However, weather records in Sim-A-Tree 3-PG ended in the year 2000. Additional weather records were required to supplement the records obtained from Sim-A-Tree (3-PG) database.

The names, locations and corresponding codes of weather stations selected were submitted to the SAWS and updated weather records were requested for the time period between 2000 and 2007. Unfortunately, many of the SAWS stations had closed down or had not been monitored regularly since the year 2000 (or earlier in some cases). Where possible, records from weather stations managed by SASRI were used to supplement the weather records.

3.9. Data representation

3.9.1. Radial Maps

To allow for comparisons among trees of varying diameters, measurements for pith to bark profiles were averaged at 10% intervals and wood property values were expressed as percentages of the total pith-bark radius (after data was adjusted for age, discussed further in Chapter 5). Disc maps were constructed to illustrate the radial distribution of wood properties among the varying levels of water availability. The maps enabled easy visualization of the radial variability and differences between compartments in response to the different combinations of MAP and SWS. These maps were constructed and compared for each level of water availability (experimental block) in the sub-tropical and warm temperate regions. The diameter of each map was scaled down and represents the actual mean tree diameter per block (in the experimental design).

3.9.2. Weighted means

Weighted mean values were calculated for each wood property for each radial strip using Equation 3.6. The reason a weighted value was used was because a tree stem has more ‘outer’ than ‘inner’ wood (Zboňák, 2002).

$$WM = \frac{\sum_{i=1}^{n}(x_i a_i)}{\sum_{i=1}^{n} a_i} \qquad \text{Equation 3.6}$$

where: WM = *w*eighted mean of the wood property measured

x_i = the wood property value of the i^{th} radial interval

a = the area of the i^{th} radial interval in the disc,

n = the number of observations

These results were used to assess the effects of the environmental variables on wood properties.

3.9.3. Statistical analyses

Results in Chapters 4-6 were analysed using univariate analysis of variance using the General Linear Models procedure and Bivariate Correlations procedure conducted in SPSS, Version 15 (SPSS, 2006). The ‘Duncan's multiple range test’ is a test that ranks group means and computes a range value. This test was conducted on main effects and interactions between wood properties and environmental variables to assess whether values differed significantly at a 95% confidence level. Pearson's correlation coefficient was used to assess linear relationships, if any, between variables. The statistical approach used to develop models relating wood properties to environmental factors is discussed in detail in Chapter 6.

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CHAPTER FOUR

A TECHNIQUE TO IDENTIFY ANNUAL GROWTH RINGS IN *E. GRANDIS* USING ANNUAL MEASUREMENTS OF DIAMETER AT BREAST HEIGHT AND GAMMA RAY DENSITOMETRY

Based on:

Naidoo, S., Ahmed, F., Pammenter, N.W. and Zboňák, A. (2010) A technique to identify annual growth rings in *E. grandis* using permanent sample plot data and gamma-ray densitometry. *Southern Forests: a Journal of Forest Science* **72:3**, 191-200

and

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[14] International Association of Wood Anatomists (IAWA), International Academy of Wood Science (IAWS) and International Union of Forest Research Organisations (IUFRO)

Abstract

Many eucalypt species do not show distinct growth rings because cambial activity does not show a strong response to seasonal variation in climate. *Eucalyptus grandis*, one of the most important commercial hardwood species in South Africa, is one such example. The light and dark bands visible on the cross-section of the wood of *E. grandis* do not always correspond with the growing season which makes it difficult to study the change in wood property values with age in more exact terms. A method was developed to separate growth rings using bark-to-pith wood density profiles of *E. grandis* and relating with annual growth obtained from measurements of diameter at breast height (DBH) from permanent sample plot (PSP) data. Using the PSP data, it was possible to assess the annual pattern of stem diameter growth at a compartment level by calculating the radial increment (RI) per year and expressing that value as a percentage of the radius at the end of the increment for that year. Mean radial increment percentage (%MRI) was calculated for each year and used to predict annual RI at an individual tree level. Predicted RI values for each tree were expressed as cumulative distances from the bark end and superimposed onto their respective density profiles. Predicted RI corresponded well with latewood density peaks and these separation points were considered a reliable guide to divide the density profile into annual increments closer to the bark end and into broader age classes closer to the pith. By assessing the pattern of variation in radial density within the context of the growth history of a compartment by means of annual PSP data, it was possible to confirm that growth rings on density profiles of *E. grandis* closer to the bark-end can serve as a reliable representation of annual growth.

KEYWORDS

Growth rings; annual rings; *Eucalyptus grandis*; gamma-ray densitometry, density; diameter at breast height

4.1. Introduction

Many eucalypt species do not have distinct annual growth rings because cambial activity does not respond strongly to seasonal variation in climate (Bhattacharyya *et al*., 1992; Sandercock *et al*., 1995; Downes *et al*., 2002; Lanner, 2002). There is no actual period of dormancy and growth occurs throughout the year when environmental conditions are favourable. Often, when growth rings are present, it is only through our knowledge of when the trees were planted that we can tell that the ring structure is not annual (Downes *et al*., 2002). As such, measurement of variation is made difficult in a number of eucalypts since it is difficult to study the change in wood properties with age (Malan, 2005; Downes and Drew, 2007; Downes *et al*., 2009).

This is of particular consequence to the forestry industry where growth rates are typically expressed in terms of mean annual increment. Research is conducted on the effect of site, genotype or silvicultural treatment on various *Eucalyptus* species. This has resulted in a range of methods being used for examining radial variation. Some of these methods involve sub-dividing the radius into equal portions and calculating mean wood properties for each fraction, sub-sampling at specific points along the radius, or dividing the radius into discrete lengths (Downes *et al*., 1997). The method used to divide the radius can have marked effects on the trends reported (Downes and Drew, 2007).

Eucalyptus grandis, one of the most important commercial hardwood species in South Africa, is one such example of a eucalypt species that does not have well defined growth rings (Malan, 2005; Zboňák *et al*., 2007). The light and dark bands visible on the cross-section of the wood of *E. grandis* do not always correspond with the growing season and therefore provides little information on the timing of their formation. Numerous studies have reported on the wide variation in wood properties of this species grown in different areas of South Africa (Taylor, 1973, Malan, 1991; Malan and Hoon, 1992; Grzeskowiak and Turner, 2000; Malan, 2005; Naidoo *et al*., 2007; Zboňák *et al*., 2007). However, these studies usually only compare the weighted-mean wood properties or plotted wood properties against relative distance from the pith since it is not possible to compare wood properties at specific ages of growth.

Given the limitations associated with existing methods, a technique was needed to enhance our understanding of characteristics of growth rings of *E. grandis* in South Africa for use in studies when comparing stands of trees that vary in age and/ or time of planting, and to assess the value that additional years of growth could add to the weighted mean wood property of the tree (or stand of trees). In addition, the ability to separate growth rings would benefit studies, such as those conducted on *E. grandis* mentioned above, on the effects of environmental factors or silviculture on wood properties at specific ages of growth.

The research described in this paper was primarily undertaken as part of a broader study in which radial wood anatomical properties of *E. grandis* grown in the warm temperate and sub-tropical regions of South Africa were compared. The aim of that research was to explore the effects of environmental variables on wood properties of trees within a comparable age range between 6-8 years (approximately rotation age for eucalypts in the pulp industry); for this reason, no explicit “age” factor was included in the experimental design. However, the number of plots within the 6-8 year age range was not sufficient to populate the experimental design in terms of meeting the specific requirements of that study. Therefore older material was also included in the sampling strategy, with tree age ranging between 6 and 13 years. This, however, resulted in the inclusion of the effect of age as a confounding variable when assessing the effect of environmental variables on wood properties. It was therefore necessary to able to identify and separate growth rings of *E. grandis* into annual rings in order standardize the age of material compared within each region by using only portions of the wood property profile that represented age eight and below for analysis, thereby reducing the effect of age on the wood properties assessed.

To achieve this, continuous diameter measurement data was required for tree ring estimation (Clark *et al*., 2007) to assess how quickly the trees grew in their initial years. As a tree gets older, it approaches a steady state of growth and growth rings that are produced become narrower in their growth intervals. This declining trend in tree-ring width with age is due to the geometric restriction associated with adding growth increments to a circumference of increasing diameter (Brookhouse and Brack, 2008), i.e. the cross-sectional area of the growth ring may be the same as that of the previous year, however, since that area is spread over a larger circumference, the growth ring width is narrower.

Wood density is a key wood property for understanding growth rates of trees since changes in wood density of growing wood occurs throughout tree development as the tree gets older and larger and in response to changes in the environment. Typically, lower density wood is formed during the first months of the growing season with an increase in density later in the season; which means that a growth ring consists of low density earlywood and high density latewood. The wood property selected to test a technique to separate growth rings was wood density.

This paper describes and evaluates the technique developed to identify annual growth rings in *E. grandis* using a combination of annual measurements of diameter at breast height (DBH) from permanent sample plots (PSP) and radial wood density profiles. The method used to calculate mean radial increment at a compartment level and predict radial increment at an individual tree level is provided. Thereafter, the approach used to relate predicted radial increments to bark-to-pith wood density profiles from trees sampled from within the PSP is described.

4.2. Experimental approach

4.2.1. Research sites and data collection

Data was obtained from three *E. grandis* permanent sample plots (compartments A26, E17 and K8) (seedling material) managed by Sappi Forests in KwaZulu-Natal, South Africa. Records of diameter at breast height (DBH) measured on an annual basis for all trees within the sample plots was provided by Sappi Forests. Records of monthly rainfall were obtained from the South African Weather Service (SAWS) for weather stations situated near each PSP (within a 10 km radius).

Since compartment A26 had the most annual PSP measurements of the three PSPs assessed, this compartment is used to test the usefulness of the technique developed to use DBH values to calculate mean radial increment percentage (%MRI) at a compartment level, predict radial increment (RI) values at an individual tree level and the use of these predicted values to indicate growth rings using the peaks in the density profiles. Compartments E17 and K8 were used to test the validity of this method to separate growth rings on density profiles into annual increments. The location, measurement history and sampling history of the PSPs are provided in Table 4.1

Table 4.1. Location of PSPs, measurement and sampling history

PSP name	Longitude	Latitude	Altitude (m)	Date planted	First date measured	Last date measured	Date sampled	Age when sampled	Number of annual measurements
A26	30^o 34'	-29^o 30'	933	Feb-93	Aug-95	Jun-05	Jul-05	12.5	11
E17	30^o 14'	-29^o 26'	1090	Nov-92	Jul-00	Jun-05	Jun-05	12.5	6
K8	30^o 08'	-30^o 17'	963	Sep-95	Aug-00	Jul-05	Feb-06	10.5	6

4.2.2. Measurement of wood density

One pith to bark 12 mm increment core was sampled at breast height (1.3 m above ground), using a petrol-motorized drill, from the north-facing side of five trees within each PSP. Core samples were stored at 23ºC and 50% relative humidity to achieve an equilibrium moisture content of about 10%. Solid wood radial strips of uniform thickness were cut along the radius of the core using an electric twin-blade saw. The radial strip dimensions were 12 mm in the longitudinal direction, 2.5 mm in the tangential direction and length was determined by the radius of the tree. Radial strips were scanned at consecutive 0.5 mm intervals, from bark to pith, using a gamma-ray densitometer with a Fe^{55} radiation source to determine the density profile. The data acquisition system was fully computer controlled and the sample holder had a stepper motor drive which allowed for fixed 0.5 mm incremental movement of the sample.

4.2.3. Calculation of radial increment – compartment A26

DBH measurements were taken annually from 1995 – 2005 (data provided by Sappi Forests). From that set of measurements, trees within the PSP were excluded if DBH values were missing for any of the years of measurement, if trees were forked, dead or suppressed (i.e. DBH under 10 cm at the final PSP measurement). DBH measurements were divided by two to obtain measurements of the radius at breast height (RBH) for each year since the wood samples used for density measurements extended from pith to bark. Given that cores were not sampled from bark to bark, it was not possible to estimate the relative position of the pith from each side of the tree. As such, for the purposes of this research, an assumption was made that radial growth was symmetric and that there was no eccentricity of the stems. This assumption was made for simplicity; the authors do acknowledge that growth in eucalypts can be asymmetric.

The radial increment was defined as the difference in radius between annual RBH measurements. Radial increments were calculated from the bark end towards the pith (i.e. the final PSP measurement till the first measurement). It was considered more accurate to begin calculations from a known point of reference which was the DBH at the time of sampling and calculate values towards the pith. This approach was considered more reliable compared to trying to estimate the exact centre of the pith where the degree of error was considered to be higher as core samples were taken from bark to pith and not bark-to-bark. The rate of radial growth among individual trees within a compartment often varies and is dependant on site, climatic conditions, genetics and the age of the tree. From the data assessed, it was observed that smaller trees usually had smaller annual radial increments while larger trees had larger radial increments.

It was assumed that trees growing within the same stand would exhibit similar growth patterns across the radius, but the rate of growth for individual trees would differ. To take into account the varying radii of the trees at each age of growth, RI was calculated for each year of measurement and expressed as a percentage of the radius at the end of the increment for that year (%RI). All %RI values were calculated from the final PSP measurement (i.e. closest to the bark end), working inward towards the pith. The first radial increment between year_X and year $_{X\text{-}1}$ is used as an example (Equation 4.1).

$$\%RI = RI_{x-1} / R_x \times 100 \qquad \textit{Equation 4.1}$$

where:

x = final year of measurement (closer to the bark end)

R_x = radius at year x (mm)

RI_{x-1} = radial increment (mm) between years x and x-1

Observations from individual trees were combined for each year and averaged to provide a mean assessment of annual growth over the period of measurement. %MRI was calculated by dividing the sum of the %RI values each year by the number of trees measured. Seventy percent of the trees in the PSP (n= 23) were used to calculate the %MRI, thereafter the %MRI values were applied to the remaining 30% of the trees (n=10) from the PSP to predict annual radial increments.

4.2.4. Predicting radial increment – compartment A26

The %MRI for each year was used to predict the annual RBH for ten trees, which comprised of five trees which were randomly chosen from the PSP data set and the five trees that were sampled for the study (these ten trees (30%) were excluded from the initial calculation of %MRI). The RBH at the time of sampling (and final PSP measurement) was used as the starting point of reference for the prediction of RBH. The predicted radial increment was defined as the difference in the radius at breast height between each predicted RBH value; equations 4.2 and 4.3 are examples of how this was calculated for the first two measurements.

$$\text{Predicted } RBH_{x-1} = RBH_x - (RBH_x \times (\%MRI_{x-1} / 100)) \qquad \text{Equation 4.2}$$

$$\text{Predicted } RBH_{x-2} = RBH_{x-1} - (RBH_{x-1} \times (\%MRI_{x-2} / 100)) \qquad \text{Equation 4.3}$$

….and so on….

where:

x = final year of measurement (bark end of sample)

RBH_x = radius at year x (mm)

$\%MRI_{x-1}$ = % mean radial increment for the PSP between year x and x-1(mm)

4.2.5. Relating predicted radial increments to density profiles

Density profiles (from bark to pith) were constructed for each of the trees sampled in PSPs A26, E17 and K8. Three trees, representing one small tree and two medium-to-large trees, were selected from each of the PSPs to illustrate the separation of growth rings into annual increments using the predicted radial increments. The predicted RI values (mm) were expressed as cumulative distances from the bark end of the radial strip. The cumulative radial increment was a sum of the predicted radial increment values where RI_{x-1} was the first RI value closest to the bark end. The cumulative values for each tree were superimposed onto their respective density profiles with the first RI value located on the first latewood peak of the density profile. It was not possible to allocate a threshold value of density to delineate between earlywood and latewood zones due to marked differences in density between these zones in *E. grandis*; this makes the wood extremely variable within trees of this species (Malan and Arbuthnot, 1995).

It is important to note that PSP diameter measurements were taken ‘over-bark’ and bark thickness was not measured at any point in the compartments’ growth history. It was observed during sampling that bark thickness varied considerably among trees within the same compartment. By using %MRI to describe the average annual growth over each period of measurement in the PSP, this incorporated changes in bark thickness with age and consequently standardized the effect of varying tree size at a compartment level.

At an individual tree-level, however, bark thickness was still a confounding factor which was not quantified. In each density profile, ‘over-bark’ predicted RI (using a compartment level %MRI) was superimposed onto an axis representing ‘under-bark’ density (at an individual tree level). It was therefore necessary to align the first RI value with a reference starting point that corresponded to the period of measurement in which the first RI was calculated. The reference starting point selected was at the position of the maximum density value of the first latewood peak. This point of reference would vary among compartments depending on the season (or month) of sampling and season (or month) of final measurement (i.e. winter or summer). It was assumed that the first complete latewood peak would correspond to the first RI measurement.

This assumption was based on the observation that the annual increase in RBH (and therefore RI) after age eight was relatively smaller compared to when the trees were younger (Figure 4.1). It was therefore expected that this smaller and less variable increase in RI would be reflected on the density profiles closer to the bark end. Subsequently, RI values for each tree were shifted by the same value either to the left (outwards from the pith) or right (inward towards the pith) of the profile depending on the season in which the tree was sampled and last measured.

4.3. Results and discussion

4.3.1. Comparison and prediction of annual radial increment – compartment A26

The overall trend in radial growth over time was assessed by comparing measured RBH at the various ages of the five trees sampled in compartment A26 (Figure 4.1). The increase in RBH with age varied among trees of different sizes. Smaller trees had smaller annual radial increments while larger trees had larger radial increments, and the five trees did show a similar pattern of variation over the total period of growth assessed for the PSP.

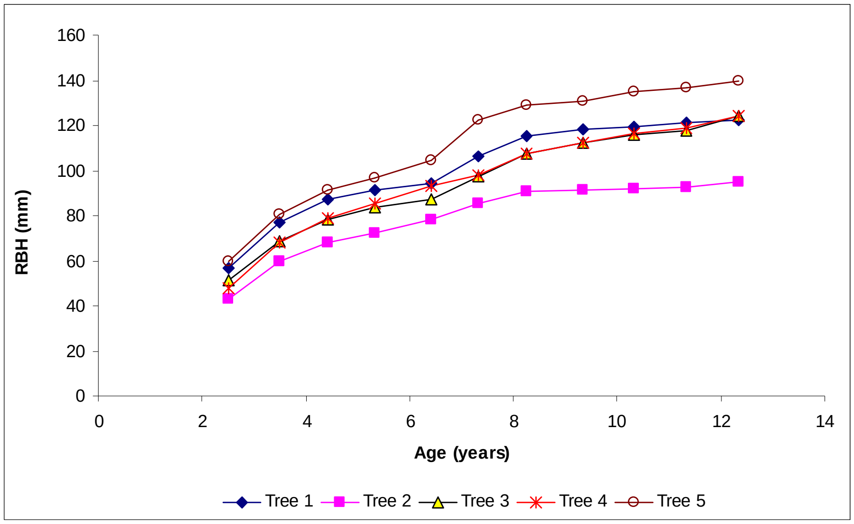


Figure 4.1 Increase in radius at breast height (RBH) with increasing age for the five trees sampled in compartment A26. There is a change in RBH following a fire in a section of the compartment which occurred when trees were between 5-6 years old

An increase in RBH was recorded following ages 5 and 6 probably as a result of a forest fire which occurred in 1998. The increase in RBH after that point is more marked in the larger trees 1, 3 and 5. It is important to note that the fire affected only a section of the PSP which resulted in swollen trees with abnormal DBH. However, the trees selected for sampling did not show any visible signs of fire damage and had a relatively uniform circumference. Evidence of the effect of the fire on diameter growth is reflected in the data for most trees measured in the PSP. It is likely that the increase in diameter growth within the PSP in the year following the fire was a result of the higher amount of nitrogen available to the trees as a result of the topsoil and litter being burnt during the fire.

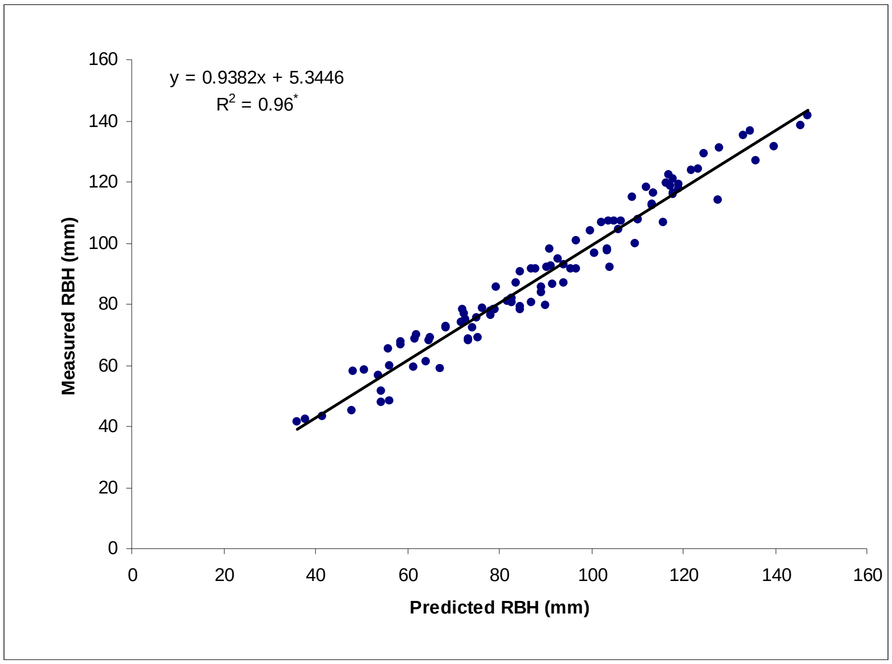


Figure 4.2. Relationship between predicted and measured RI (compartment A26). Coefficient of determination (R^2) and significance of correlation (^{NS} P>0.05; * 0.01<P<0.05) are shown.

Table 4.2. Results from paired sample t-tests comparing measured and predicted RI for each year of measurement. Significance of t-test for each year (*P < 0.05) is shown.

Results of paired samples test				
YEAR	**Mean (of paired differences)**	**Std dev.**	**Std error**	**p**
All years	-0.18	2.25	0.23	0.42
2004	-0.03	2.54	0.80	0.97
2003	-0.11	0.83	0.26	0.69
2002	0.96	1.36	0.43	0.05
2001	0.23	1.36	0.45	0.62
2000	-0.88	2.54	0.80	0.30
1999	-0.95	4.79	1.51	0.55
1998	-0.05	1.87	0.59	0.94
1997	-0.76	1.24	0.39	0.08
1996	0.66	0.93	0.30	0.05
1995	-0.85	2.17	0.69	0.25

The accuracy of the method used to predict RI was tested by comparing measured RI with predicted RI (for all years measured) for the 10 trees that were not included when calculating the %MRI for the compartment (Figure 4.2). An R^2 of 0.83 was obtained.

A paired samples t-test was used to test the hypothesis that there were no differences between the measured and predicted RI in each year of measurement (Table 4.2). No significant differences were found between the measured and predicted RI for any of the years measured.

4.3.2. Relating predicted radial increment to density profiles

Density profiles (from bark to pith) for three trees from compartments A26, E17 and K8 are illustrated in Figures 4.3a-c, 4.5a-c and 4.6a-c respectively. In each figure, predicted RIs (expressed as cumulative values from bark to pith) correspond well with latewood density peaks and were used as separation points which served as a reliable guide to divide the density profile into annual increments. These separation points, however, did not always lie directly on top of each latewood peak. This was a result of using %MRI at a compartment level (which represented a range of varying tree sizes) to predict RI at an individual tree level. These separation points were used as a guideline to separate growth rings into annual increments (as shown by the dotted lines). Separation points for annual increments were defined by the location of the maximum densities that defined the beginning and end of a growth ring on the x-axis (i.e. distance from bark (mm)).

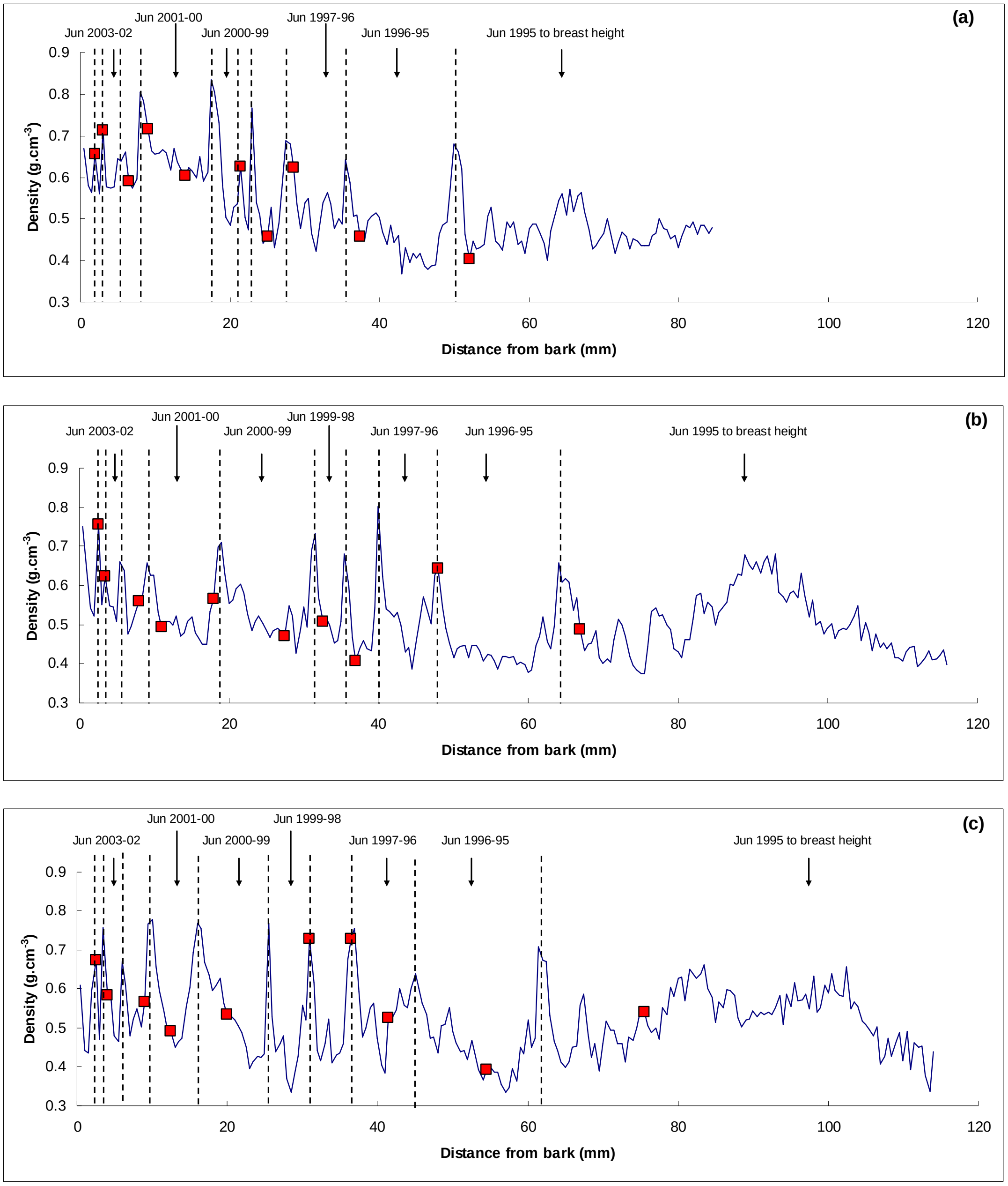
The wood of *E. grandis* is extremely variable (Malan and Arbuthnot, 1995) and the maximum densities from the latewood peaks used to separate annual rings varied within a profile and among profiles within the same compartment. Density also fluctuated within growth rings and the maximum densities for each growth ring varied within the profile (from bark to pith) and among trees. However, variation in density within an annual growth ring did not exceed the maximum densities of the latewood peaks that served as ring boundaries between annual rings. Results for compartments A26, E17 and K8 are presented and discussed in the sections that follow.

4.3.2.1. Density profiles – compartment A26

The final DBH measurement for trees in A26 was in June 2005, after which trees were sampled in July the same year. Most measurements of DBH for this compartment were made around June each year. This period corresponds to the winter season in South Africa, typically experienced between May and August when temperature and rainfall are lower.

At the bark end on each density profile (Figure 4.3a-c) the highest density value represented the first part of the latewood peak for density for the year 2005 (year x = final year of measurement (Equation 4.1)) since the compartment was sampled in June 2005 during winter. It was expected that subsequent predicted RI points would be situated on the latewood peaks of the wood formed earlier when separating growth rings, since measurements of DBH were made during June each year.

Between age eight and twelve years (PSP measurement period between June 2001 – June 2005), the latewood peaks appeared less variable in their growth intervals and the distance between maximum values of the latewood peaks corresponded well with the smaller increase in RI during those measurement periods. Similarly, below age eight (before June 2001), the distance between the maximum values representing latewood peaks was more variable. Fluctuation in density between growth rings within annual increments of the profile was seen, especially in areas of the profile representing wood formed before age eight.



Figures 4.3 a-c. Density profiles of three trees sampled from compartment A26 and corresponding predicted RI (as indicated by the solid squares) which serve as a guideline for separation points selected for each year of growth (as indicated by vertical dotted lines)

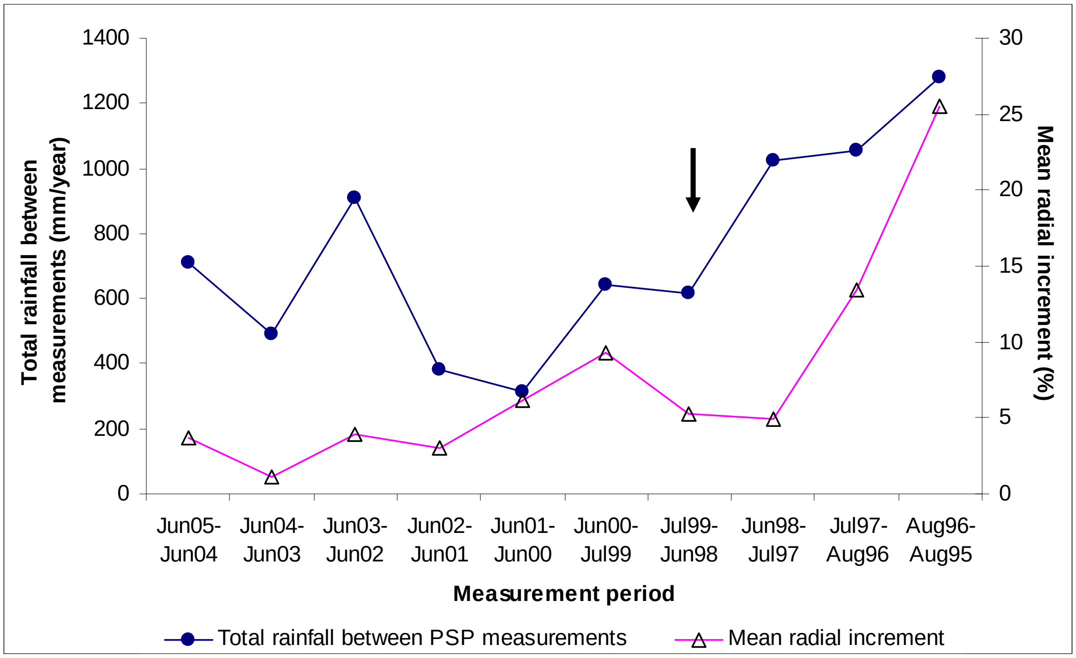


Figure 4.4. Mean radial increment (%) for compartment A26 in relation to the rainfall experienced between the measurement periods. The arrow indicates the period between 1998 and 1999. A fire was experienced between these two measurement periods.

A forest fire was reported during the measurement interval between June 1998 and June 1999. Rainfall was also lower during this interval compared with the previous year (Figure 4.4). In the year following the fire, in the interval between June 1999 and June 2000, wider growth rings are present (Figure 4.3a-c), whereas the rainfall during this time period did not increase and this corresponds well with the increased growth reflected in the %MRI for this compartment during this interval (Figures 4.1 and 4.4). The larger ring width and fluctuation in density (smaller latewood peaks) within the annual ring, are thought to have formed as a result of accelerated growth in response to the effect of the fire on site conditions.

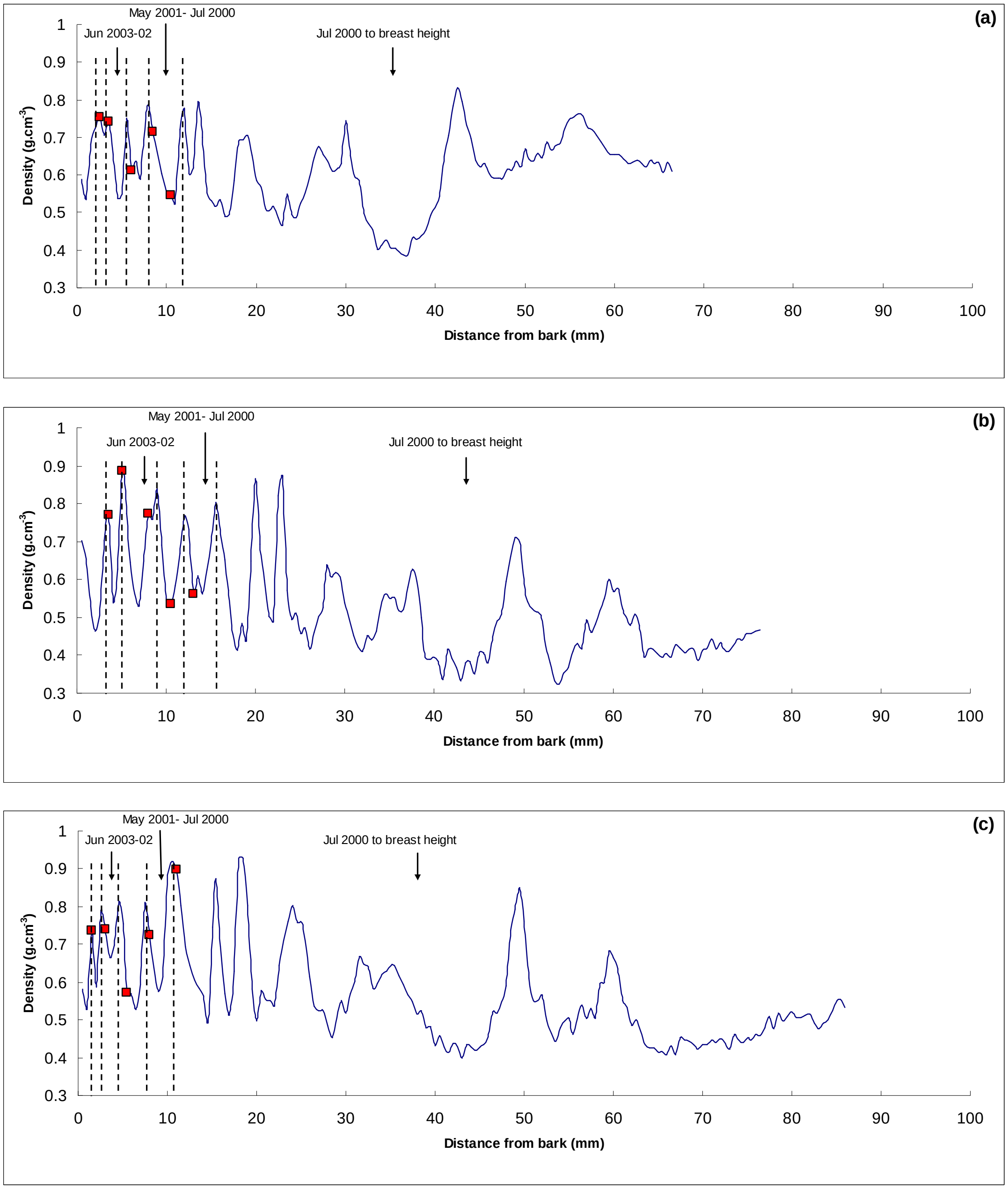
Cambial growth has been reported to show better correlations with environmental conditions at an earlier date, even from the previous year, because of the lag effect introduced by indirect action of physiological and morphological factors on current cambial growth (Fritts, 1976; Oberhuber *et al*., 1998 and Downes *et al*., 1999). The effects of changing environmental conditions on tree growth can persist over a period of time because of soil moisture carry-over, induced changes in root growth, canopy size, food supply and competition from other trees (Yoo and Wright, 2000).

4.3.2.2. Density profiles – compartments E17 and K8

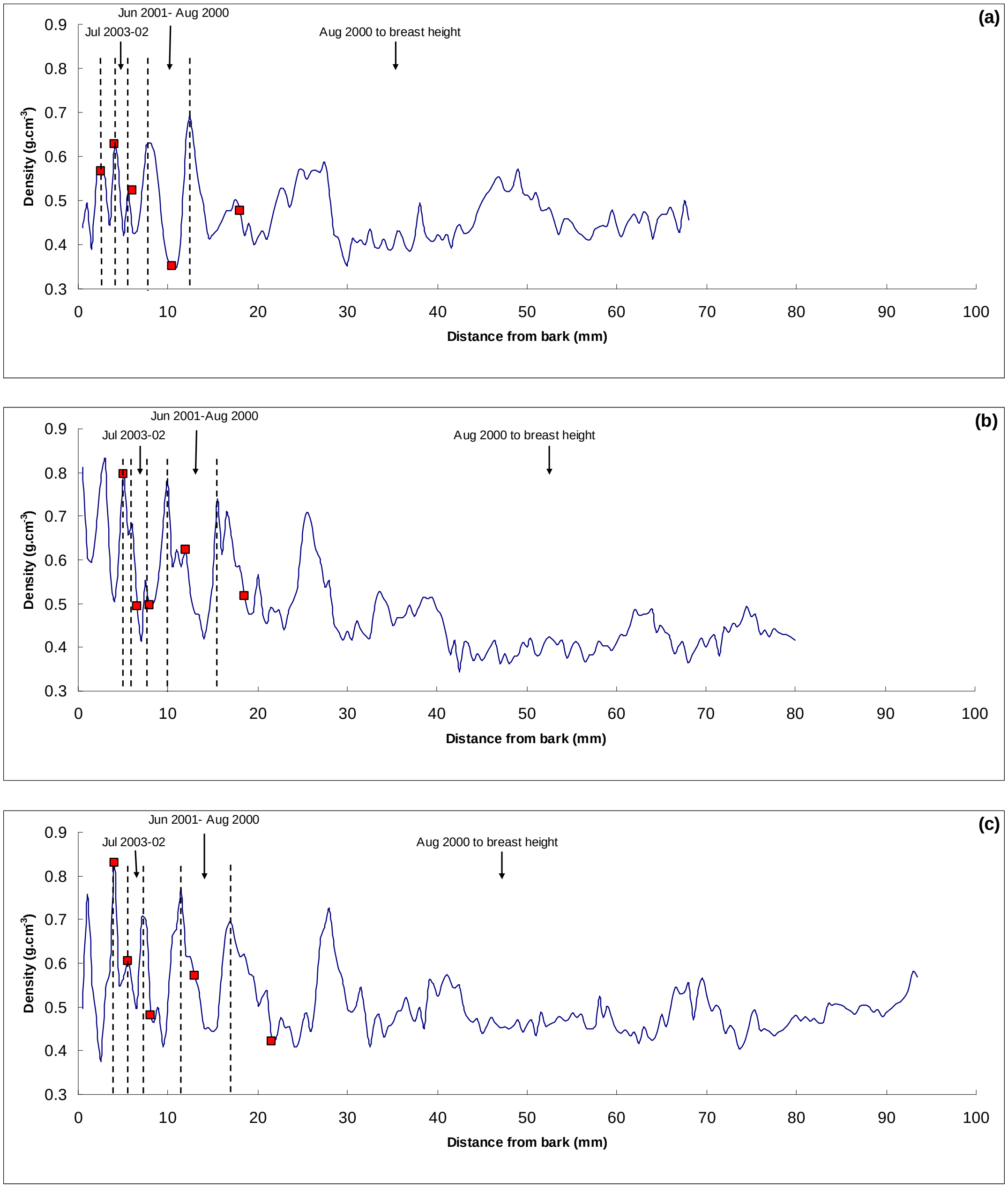
The data sets for compartments E17 and K8 were limited since only six measurements were made for each compartment. Measurements for compartment E17 commenced at approximately age seven and a half years, while initial PSP measurements for compartment K8 commenced at age five. It was not possible to assess how quickly trees in these two compartments grew in their initial years. However, using the limited data available, predicted RI values were calculated from the measured DBH data and provided a reliable guideline to separate a series of growth rings for trees in these compartments into annual increments. This was particularly so when the trees were older and growth rings on the density profiles were narrower and less variable in their intervals (Figures 4.5a-c and 4.6a-c).

Compartment E17 was sampled in June 2005 and the last PSP measurement was made at the time of sampling. Density profiles for this compartment show a pattern of regular seasonal variation and the distance between growth rings show little variation (Figure 4.5a-c) and matched well with the %MRI calculated for this PSP (Figure 4.7). Between ages seven and a half and twelve and a half years, the annual RI was on average 2.5% of the previous year's growth (Figure 4.7). The high density value at the bark end corresponded to the beginning of the latewood peak of June 2005; therefore the next latewood peak represented the latewood peak for June 2004. Subsequent RIs guided the separation of the four growth rings that followed.

Compartment K8 was sampled in February 2006, and the final PSP measurement was completed in July 2005 (Figure 4.6a-c). It was assumed that the first complete latewood peak for density profiles in Figure 4.6a-c corresponded to the latewood peak for June 2005, therefore the second complete latewood peak corresponded to June 2004 and the first predicted RI. It is important to note, however, that this compartment was planted in an area characterized by low mean annual rainfall (< 800 mm y^{-1}) (Schulze, 1997, Figure 4.8).



Figures 4.5. a-c. Density profiles of three trees sampled from compartment E17 and corresponding predicted RI (as indicated by the solid squares) which serve as a guideline for separation points selected for each year of growth (as indicated by vertical dotted lines)



Figures 4.6 a-c Density profiles of three trees sampled from compartment K8 and corresponding predicted RI (as indicated by the solid squares) which serve as a guideline for separation points selected for each year of growth (as indicated by vertical dotted lines)

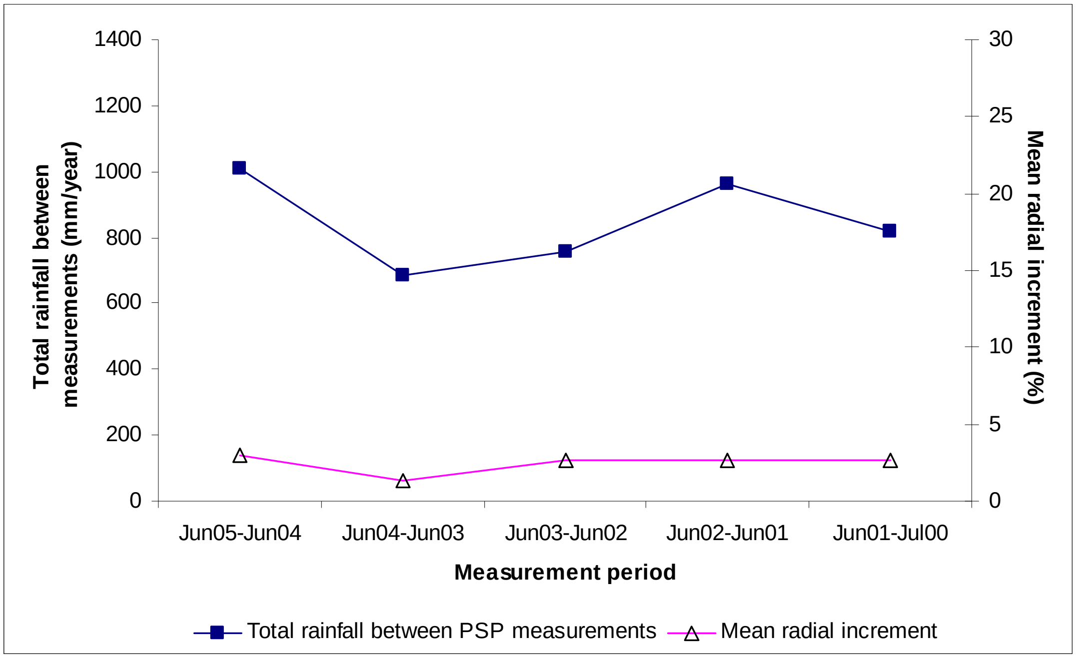


Figure 4.7. Mean radial increment (%) for compartment E17 in relation to the rainfall experienced between the measurement periods.

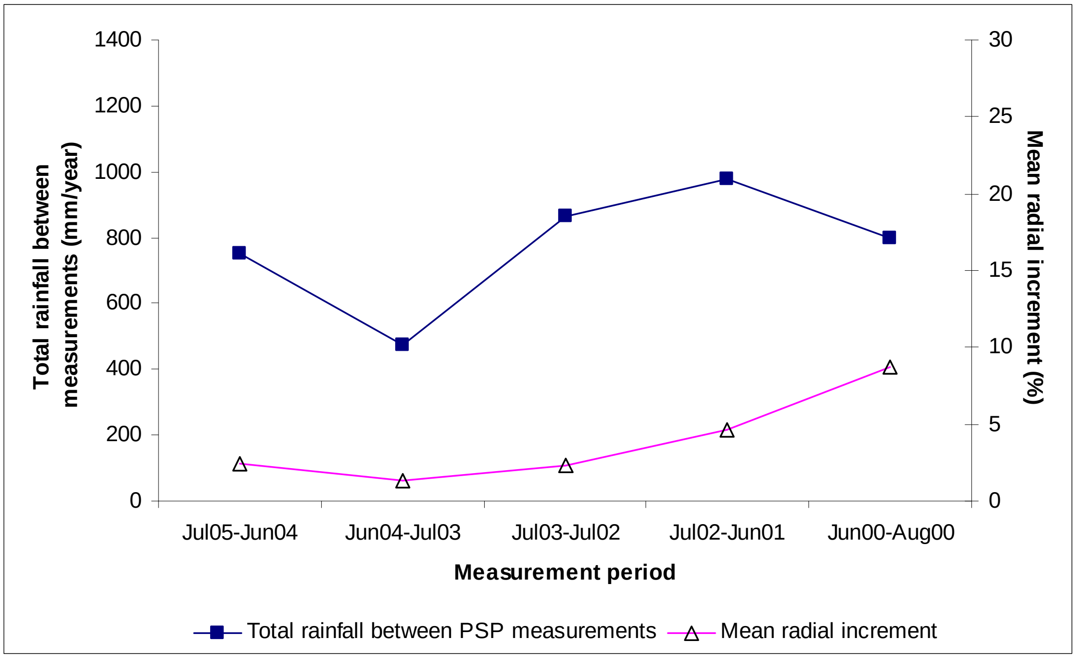


Figure 4.8. Mean radial increment (%) for compartment K8 in relation to the rainfall experienced between the measurement periods.

It was difficult to determine the position of the latewood peaks for each year of measurement since density profiles varied among trees in this compartment. For example, during the interval between measurements in 2003 and 2004, the total rainfall experienced was less than 500 mm, and the %MRI calculated for that measurement period was low (1.4%).The predicted radial increments for that measurement period were 1.3, 1.1 and 1.5 mm in Figures 4.6a, 4.6b, and 4.6c respectively. In Figure 4.6b, the latewood peak for that measurement period appears incomplete and in Figure 4.6c, the latewood peak is much smaller compared to the adjacent peaks for that density profile. However, since trees can go a year or more without producing a visible ring during times of stress, it was thought that the smaller, less defined growth rings in Figures 4.6b and 4.6c corresponded to the smaller increment during that particular measurement period.

4.4. Conclusion

A method was developed to identify growth rings from wood density profiles of *E. grandis* verified by annual measurements of DBH from PSP datasets. MRI was calculated at a compartment level, expressed as a percentage, and used to predict RI at an individual tree level. Predicted RI values (mm) for each tree were expressed as cumulative distances from the bark end and superimposed onto their respective density profiles to identify annual growth ring boundaries on the density profiles into annual rings (or annual increments). Predicted RI corresponded well with latewood density peaks, and although the separation points (i.e.: growth ring boundaries) did not always lie directly on the maximum value of each latewood peak, these separation points were considered a reliable guide to divide the density profile into annual increments.

A limitation of this method used to separate growth rings using annual PSP measurements is that predicted RIs for individual trees do not take into account instances when ‘zero’ increase in radial increment was recorded in trees measured (i.e. no measureable change in DBH (or RBH) between measurement events). It was usually only in smaller trees where measured RI was equal to zero. However, at a compartment level, other trees (of varying sizes) in the PSP also reflected smaller RIs, and this was captured in the %MRI for that period of measurement. In addition, if density profiles for smaller trees did not show distinct growth rings, this method could not be used.

By relating the pattern of variation in density within the context of the growth history of a compartment by means of annual measurements of DBH from PSPs, it was possible to verify the estimation of annual growth ring boundaries on density profiles of *E. grandis*, especially closer to the bark-end. While the younger material did not follow a seasonal pattern, after approximately eight years of age, growth rings on density profiles of this species did appear to follow a stronger seasonal pattern and represented annual growth increments.

PSP data used in this research reflected growth in compartments of *E. grandis* planted in the warm temperate region of South Africa. The mean annual temperature (MAT) in this region is ranges between 16-19^{o}C, and compartments used in this research varied with regards to mean annual precipitation (MAP) but not in terms of MAT. Assessments of wood properties of *E. grandis* sampled in the warm temperate and sub-tropical regions of South Africa showed that wood properties are significantly different between these two regions (Naidoo *et al*., 2007). It was thought that the response of wood properties to water availability in the sub-tropical region could be amplified by higher temperatures characteristic of this region.

Future work could include assessing whether this method can be applied to PSPs of *E. grandis* from the sub-tropical region where MAT is higher (between 19-21^{o}C). It was not possible to test this method in the current research due to the limited PSP data set available for compartments which were sampled in this region.

It was concluded that growth rings indicated by density profiles of *E. grandis*, closer to the bark-end, would serve as a reliable representation of annual growth. The above information was used as a means of standardizing the age of wood properties assessed in Chapter 5. Compartment age ranged from six to thirteen years (reasons for this wide range in age are discussed in Chapter 3, section 3.2.3) and PSP data were not available for most compartments assessed.

A separation point (which was a density peak in the latewood zone of ring eight) was identified by working backwards from the bark-end of the density profile, using the age of the tree and the density profile as a guide. Wood formed after age eight was 'removed' from subsequent analyses. The remaining sections of the density profile therefore represented wood that was formed when the trees were younger (approximately eight years and below).

The density profiles thus served as 'templates' and the separation points identified using the density profiles were also used on bark-to-pith profiles for vessel and fibre properties. Portions of the vessel and fibre profiles representing wood older than eight years of age (between the bark end and the separation point) were also 'removed'. Weighted mean wood properties were then re-calculated for each tree and compartment. This enabled the comparison of wood formed during the first eight years of growth. The effect of age on wood properties was thereby minimised as a confounding variable in the assessment of the effect of water availability on wood properties. This method of standardizing the age of wood properties is described further and evaluated in the following chapter (Chapter 5, section 5.2.5).

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CHAPTER FIVE

ASSESSMENT OF WOOD PROPERTIES OF *EUCALYPTUS GRANDIS* GROWN AT VARYING LEVELS OF WATER AVAILABILITY IN THE SUB-TROPICAL AND WARM TEMPERATE REGIONS OF SOUTH AFRICA

Based on results presented at three international conferences

Naidoo, S., Zbonák, A., Pammenter, N.W. and Ahmed, F. (2007) Assessing the effects of water availability and soil characteristics on selected wood properties of *E. grandis* in South Africa. *In: Eucalypts and Diversity: Balancing Productivity and Sustainability. Proceedings of the IUFRO*[15] *Working Group 2.08.03 Conference, Durban, South Africa*. 22-26 October 2007 (ISBN: 978-0-620-40465-5)

and

Naidoo, S., Zbonák, A. and Ahmed, F. (2007) Effects of moisture availability on wood properties of South African-grown *E. grandis*. *In:* Proceeding of Abstracts, IUFRO All Division Five Conference, 29 Oct. - 2 Nov, Taipei, Taiwan, Pg. 322

and

Naidoo, S., Zbonak, A. and Ahmed, F. (2006) The effect of moisture availability on wood density and vessel characteristics of *Eucalyptus grandis* in the warm temperate region in South Africa. *In:* S. Kurjatko, J. Kúdela, & R. Lagana (eds) *Proceedings of the 5th International Symposium, Wood Structure and Properties ’06.* September 3-6. Sliac-Sielnica, Slovakia. The Technical University in Zvolen. pp. 117– 122 (ISBN 80–968869–4–3)

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[15] International Union of Forest Research Organizations (IUFRO)

Abstract

The productivity of *Eucalyptus grandis*, planted extensively in South Africa, is highly dependant on soil water availability, among other factors. However, soil water availability is often limited and evaporative demand is high, resulting in reduced productivity and significant changes in wood properties. This research explored the use of rapid screening tools to characterize the properties of wood in compartments of *Eucalyptus grandis* grown in the sub-tropical and warm temperate regions of South Africa.

Gamma-ray densitometry, image analysis techniques and NIR-spectroscopy were used to assess wood density, vessel and fibre characteristics, and NIR predicted percentage cellulose and lignin of breast-height disc or core samples from trees in compartments representing varying levels of water availability. Combinations of mean annual precipitation (MAP) and estimated soil water storage (SWS) were used to achieve varying levels of water availability among blocks within each region. Radial maps illustrating pith to bark variation in wood properties and weighted mean values of material approximately eight years of age are discussed for each region in terms of responses to soil characteristics and water availability.

In the sub-tropical region, higher levels of MAP resulted in lower density wood with larger vessel and fibre diameters, thinner cell walls, lower vessel frequencies, higher NIR-predicted cellulose content and lower NIR-predicted lignin. The patterns of response of wood properties to varying MAP in the warm temperate region were similar to that of the sub-tropical region, however, results were often less clear. The response of wood properties to water availability in the sub-tropical region was thought to have been amplified by higher temperatures.

Key words: *Eucalyptus grandis*, water availability, soil organic carbon, wood properties

5.1. Introduction

Water and nutrient interactions are widely recognized, worldwide, as key factors in determining forest productivity and South African forests are no exception as the growth rate and health of plantations is highly dependant on soil water availability which varies considerably (Louw, 1999). Soil water availability is often limited and evaporative demand is high (Roberts, 1994). The productivity among many sites is variable within a relatively small geographic region and is below their potential in terms of wood production per unit area of land.

In South Africa, *E. grandis* is grown across a wide range of site conditions of varying potential productivities, with the optimum mean annual precipitation (MAP) and mean annual temperature (MAT) for *E. grandis* being ≥ 900 mm and ≥ 16 °C respectively (Schulze, 1997). *E. grandis* is highly intolerant of adverse conditions, and shows substantial declines below the potential of the species when planted on shallow soils and/or on dry sites (Boden, 1991). Various authors have illustrated significant effects of the environment on wood properties of *E. grandis* (Taylor, 1973; Boden, 1991; February *et al*., 1995; Clarke *et al*., 1999; Pierce and Verryn, 2000; Searson *et al*., 2004; Gava and Gonçalves, 2008). However, the mechanism by which environmental factors affect wood properties is still unclear.

The objective of this chapter was to characterize the wood properties of compartments planted to *Eucalyptus grandis* grown in the sub-tropical and warm temperate regions of South Africa to assess how selected basic wood properties were influenced by varying levels of water availability. Wood density, vessel and fibre characteristics and percentage cellulose and lignin were assessed using gamma-ray densitometry, light microscopy combined with image analysis, and near infrared (NIR) spectroscopy respectively.

Radial maps illustrating pith to bark variation in wood properties and weighted mean values of material were assessed for each region in terms of responses to soil characteristics and water availability, and their effects on wood quality. In addition, the method used to standardize the age of wood properties are described and evaluated.

5.2. Experimental approach

The experimental approach is described in detail in Chapter three. For ease of reference when discussing results presented in the current chapter, relevant sections have been summarized from Chapter 3 and included in this section. In addition, the approach used to standardize the age of wood properties, from trees assessed in this research, is described.

5.2.1. Compartments selected for sampling

The threshold ranges for dry, moist and wet MAP and low, medium and high SWS and the distribution of sampled compartments in the sub-tropical and warm temperate regions are provided in Tables 5.1a and 5.1b respectively (from Chapter 3, section 3.2).

Table 5.1 a and b. Experimental design for the sub-tropical region (5.1a) and warm temperate region (5.1b) with ranges for MAP and SWS, Compartment names and position of compartments in the design are shown in each block (MAP x SWS combination[16])

1(a) SUB-TROPICAL

MAP (mm)	**DRY**	**MOIST**	**WET**
SWS (mm)	**700-950 mm**	**951-1050 mm**	**1051-3500 mm**
LOW (72-151 mm)	B2	D10b	H031a
	A49a		H031b
	A49b		
MEDIUM (152-230 mm)			
HIGH (231-309 mm)	E12	A11a	B48
	G2	A44	G17
	D14	D7	E29

1(b) WARM TEMPERATE

MAP (mm)	**DRY**	**MOIST**	**WET**
SWS (mm)	**600-875 mm**	**876-975 mm**	**976-3500 mm**
LOW (72-151 mm)	B14	F9	H75a
	K8	C017	W80a
	A5		D22
MEDIUM (152-230 mm)		A3	A53d
		A26	C4
		D05	D105
HIGH (231-309 mm)		A4	A35c
		F031	E17
			H030

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[16] The term ‘block’ will be used to refer to individual MAP x SWS combinations in the experimental design. Wood properties were averaged for all trees and compartments within each block.

5.2.2. Measurements of climatic and soil characteristics

5.2.2.1. Estimates of MAT, MAP and SWS

The South African Atlas of Agrohydrology and Climatology (SAAAC) (Schulze, 1997) was used to extract approximate MAT and MAP values for the *E. grandis* resource in South Africa. Estimates of total available water (TAW) for the low, moderate and high SWS ranges were provided by the ICFR (C. Smith, Pers. Comm.[17]) (Chapter 3, section 3.2.2).

5.2.2.2. Rainfall data

Sim-A-Tree (3-PG) was used to identify weather stations close to sampled compartments (Sim-A-Tree (3-PG), 2005) and the South African Weather Service (SAWS) and the South African Sugar Research Institute (SASRI) were contacted for updated weather records for weather stations selected (SASRI, 2007; SAWS, 2007) (Chapter 3, section 3.8). Monthly rainfall and temperature data (minimum, maximum and mean temperature) were requested for each sampled compartment. Reliable monthly measured temperature data was not available for the majority of compartments sampled and was therefore not considered in this research.

Monthly rainfall was received for each compartment (with the exception of compartments B2 and D10b). The total rainfall measured between the time of planting until the time for each compartment was sampled and at each combination of MAP and SWS (level of water availability) in the subtropical and warm temperate regions is shown in Figures 5.1 and 5.2 respectively.

The total amount of rainfall received varied among compartments and among levels of water availability. The varying ages of the compartments sampled contributed to this variability. It is important to note that these data for total rainfall have not been standardised to a base age of eight years whereas the

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mean wood properties have been standardised for age (section 5.2.5 of this chapter).

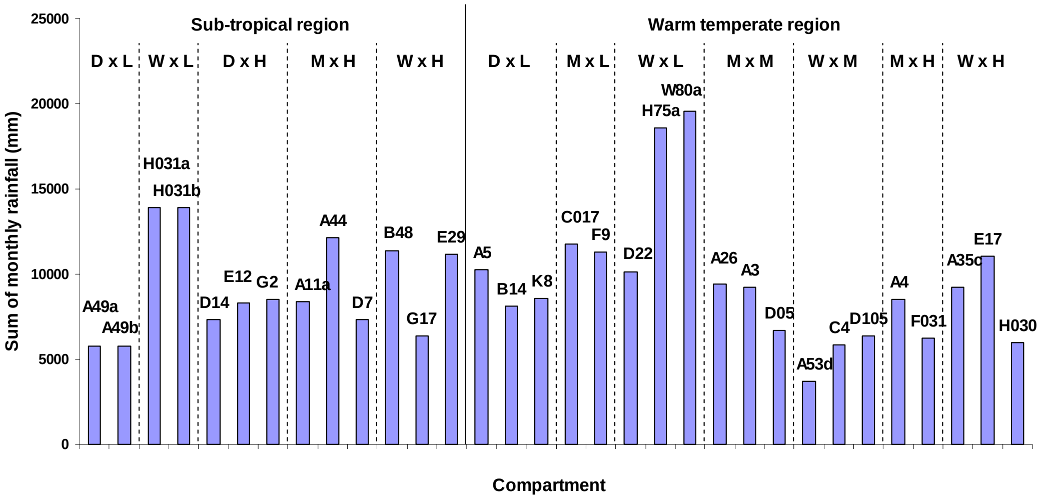


Figure 5.1. The total rainfall measured between the time of planting until the time of sampling for each compartment in the sub-tropical and warm temperate regions (Levels of MAP: 'D' = dry, 'M' = medium, 'W' =wet; levels of SWS: 'L' = low, 'M' = medium, 'H' = high)

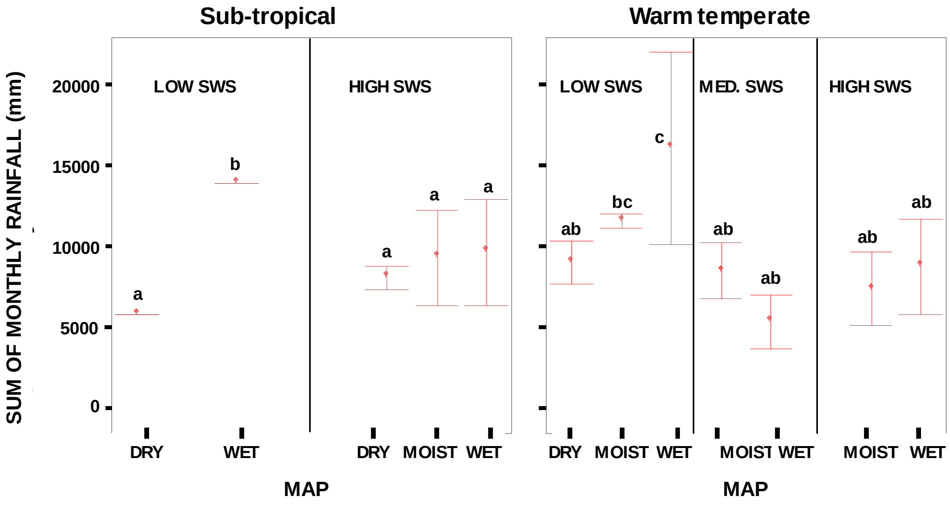


Figure 5.2. The total rainfall measured between the time of planting until the time of sampling is compared at each MAP x SWS level in the sub-tropical and warm temperate regions. Letters above the bars indicate differences at $p \leq 0.05$. Error bar is equal to two standard errors

In this chapter, these data on the total rainfall measured between the time of planting until the time of sampling serves to add to the overall description of each compartment with regards to differences between the two regions and within each region.

In the warm temperate region, the total rainfall received by compartments H75a and W80a was higher than total rainfall received by other compartments sampled in the 'wet' MAP range in both regions. Total rainfall did not differ significantly between dry, moist and wet levels of MAP with the exception of wet MAP at low SWS in the both the subtropical and warm temperate regions (Figure 5.2).

5.2.2.3. Soil analyses

Soil samples for each compartment were taken from two sampling points within the enumeration plot (10 m radius) and measurements of organic carbon and particle size distribution (proportions of sand, silt and clay) were made. The soil properties were averaged for each compartment to contribute to the overall description of the compartments. Methods of measurement of soil properties are discussed in detail in Chapter three, section 3.7.

5.2.3. Description of climatic and soil characteristics among compartments

The location and description of compartments in terms of MAT, MAP, SWS, age, and site index (SI_5) and soil properties (*viz.* organic carbon (OC%) and particle size analysis) are provided in Tables 5.2 and 5.3, for the sub-tropical and warm temperate regions respectively.

Compartments sampled in the sub-tropical region (Table 5.2) ranged between 8-13 years of age and SI_5 values ranged between 15 and 25. In the warm temperate region (Table 5.3), compartments ranged between 5.6–13 years of age, SI_5 ranged between 15 and 28. There was little variation in soil texture among compartments in the same geographical region (Tables 5.2 and 5.3). All compartments (n=9) in the high SWS category in the subtropical region are from coastal Zululand, whilst, four compartments grown at low SWS were from Mpumalanga.

Table 5.2. Compartment names, location and age of compartments, and description of site and soil characteristics in the sub-tropical region

Compartment name	Longitude	Latitude	MAT (°C)	MAP (mm)	SWS (mm)	MAP level	SWS level	Age (years)	SI_5	OC %	Fine sand (%)	Med. sand (%)	Coarse sand (%)	Clay (%)	Silt (%)
A49A	30° 52'	-25° 40'	19	809	111	dry	low	10.0	17.0	2.0	17.3	14.2	40.8	16.2	11.5
A49B	30° 52'	-25° 40'	19	809	111	dry	low	10.0	15.3	2.6	10.7	9.4	17.0	51.4	11.4
B2	30° 23'	-30° 25'	19	867	136	dry	low	9.3	19.8	3.9	13.8	11.6	32.1	23.1	19.5
D10b	30° 33'	-30° 19'	19	999	136	moist	low	12.9	20.4	3.1	20.9	15.8	28.0	17.7	17.6
H031A	31° 25'	-25° 42'	19	1517	136	wet	low	12.1	19.5	3.8	26.1	18.1	9.3	20.8	25.8
H031B	31° 25'	-25° 42'	19	1517	136	wet	low	12.1	19.5	4.5	22.4	22.3	14.2	22.9	18.2
D14	32° 13'	-28° 21'	21	908	257	dry	high	8.3	16.5	0.4	62.2	25.7	1.2	4.8	6.0
E12	32° 12'	-28° 23'	21	862	257	dry	high	9.2	18.3	0.7	46.9	39.2	6.6	0.8	6.7
G2	32° 12'	-28° 21'	21	917	257	dry	high	9.6	17.9	3.1	54.8	17.3	1.0	9.1	17.8
A11a	32° 14'	-28° 24'	21	989	257	moist	high	9.4	22.4	0.3	49.8	40.0	4.5	0.3	5.3
A44	32° 8'	-28° 33'	21	1008	257	moist	high	9.0	22.6	3.1	53.8	24.4	3.4	6.4	12.1
D7	32° 11'	-28° 30'	21	985	257	moist	high	10.1	19.0	0.4	60.4	15.5	4.2	4.5	15.4
B48	32° 6'	-28° 40'	21	1118	257	wet	high	8.6	24.5	0.3	50.7	38.0	4.9	1.1	5.3
E29	31° 48'	-28° 54'	21	1467	257	wet	high	8.7	22.5	0.5	56.2	27.7	1.6	7.7	6.7
G17	32° 14'	-28° 32'	21	1130	257	wet	high	8.9	24.2	0.5	41.7	40.2	8.4	2.5	7.2

Table 5.3. Compartment names, location and age of compartments, and description of site and soil characteristics in the warm temperate region

Compartment name	Longitude	Latitude	MAT (°C)	MAP (mm)	SWS (mm)	MAP level	SWS level	Age (years)	SI_5	OC %	Fine sand (%)	Med. sand (%)	Coarse sand (%)	Clay (%)	Silt (%)
A5	29° 50'	-30° 41'	17	811	91	dry	low	9.8	17.7	8.1	4.0	0.8	1.6	51.9	41.7
B14	31° 12'	-28° 33'	17	866	100	dry	low	9.8	21.8	6.5	35.5	9.8	5.3	17.9	31.6
K8	30° 08'	-30° 17'	17	792	100	dry	low	10.5	21.1	4.7	16.7	4.5	1.8	39.8	37.3
C017	30° 18'	-29° 49'	16	974	136	moist	low	11.7	20.3	9.9	11.7	3.0	5.0	29.9	50.4
F9	30° 11'	-29° 55'	17	927	136	moist	low	10.9	27.9	6.8	17.8	13.7	11.4	29.6	27.5
D22	30° 04'	-29° 57'	17	1079	136	wet	low	11.2	20.4	8.5	19.0	6.5	5.7	24.8	43.9
H75a	30° 21'	-29° 23'	18	1106	136	wet	low	10.3	24.3	7.8	15.5	1.5	7.5	24.9	50.6
W80a	30° 26'	-29° 18'	17	1071	136	wet	low	11.0	23.2	8.6	12.2	2.0	5.9	32.3	47.5
A26	30° 34'	-29° 30'	17	961	187	moist	medium	12.5	21.7	5.0	24.7	22.7	8.9	23.3	20.4
A3	30° 32'	-29° 29'	17	880	187	moist	medium	11.9	19.7	3.5	28.4	18.8	15.2	22.1	15.5
D05	30° 16'	-29° 34'	16	919	160	moist	medium	7.5	19.6	9.2	6.8	1.7	3.7	43.3	44.5
A53d	30° 33'	-29° 31'	18	1051	187	wet	medium	5.6	22.5	5.3	17.4	18.4	9.0	22.6	32.6
C4	31° 12'	-28° 35'	17	996	187	wet	medium	7.4	21.9	5.7	28.7	18.4	9.1	19.0	24.7
D105	31° 18'	-28° 36'	17	1020	187	wet	medium	8.0	20.1	5.1	39.1	15.1	6.9	18.0	20.9
A4	31° 16'	-28° 32'	17	948	309	moist	high	9.9	17.2	6.8	20.4	19.0	7.8	32.7	20.2
F031	31° 17'	-28° 31'	17	901	260	moist	high	7.6	19.5	5.8	21.0	11.8	5.0	29.6	32.6
A35c	31° 15'	-28° 32'	16	980	309	wet	high	10.8	21.8	7.0	18.3	12.4	11.1	27.3	30.9
E17	30° 14'	-29° 26'	16	1067	257	wet	high	12.6	19.8	7.1	18.5	2.5	11.7	32.5	34.8
H030	31° 11'	-28° 36'	17	995	309	wet	high	7.4	20.2	5.3	12.6	12.3	12.4	36.1	26.6

Soils in the warm temperate region had a comparatively higher proportion of clay and silt and the organic carbon in soils was on average three times higher in the warm temperate region than in the sub-tropical region (Tables 5.2 and 5.3). Levels of organic carbon affect soil structure and adsorption properties thus also affecting soil water retention properties.

5.2.4. Wood properties

Two non-destructive pith to bark cores (one above the other) per tree were sampled at breast height (1.3 m above ground) from five trees per compartment. One core was used for the assessment of density (using gamma-ray densitometry) and NIR-predicted percentage cellulose and lignin. The second core was used for measurements of vessel and fibre characteristics (using light microscopy combined with image analysis). A detailed description of the rapid screening tools used to measure the above wood properties is discussed in Chapter three, section 3.6.

5.2.4.1. Wood air-dry density

A core sample was stored at 23ºC and 50% relative humidity to achieve an equilibrium moisture content of approximately 10%. Strips of uniform thickness were cut along the radius using a twin-blade saw. The sample dimensions were 12 mm in the longitudinal direction, 2.5 mm in the tangential direction and length was determined by the radius of the tree. Strips were scanned from bark to pith at consecutive 0.5 mm intervals using a gamma-ray densitometer to determine the density profile.

5.2.4.2. Vessel and fibre characteristics

Radial strips, 2.5 mm thick, were obtained from the cores or discs taken at breast height samples. Strips were softened by soaking in water. Thereafter, the strips were sectioned in the transverse plane with a sledge microtome to obtain 20-25 μm thick sections. Sections were mounted in ethanol on a glass slide, covered with a cover-slip, and examined using a Leica fluorescent microscope. Anatomical measurements were performed every 0.5 mm for vessel measurements and every alternate 0.5 mm for fibre measurements, from bark to pith using an image analysis system (Leica QWin, version 2.8). Anatomical characteristics measured included: vessel diameter (μm), vessel frequency (the number of vessels per unit area), vessel percentage (the percentage area occupied by vessels), fibre diameter (μm), fibre lumen diameter (μm) and cell wall thickness (μm).

5.2.4.3. Near infrared (NIR) spectroscopy

NIR reflectance spectra were acquired for radial strips (the same as those used for density measurements) over the 1 100-2 250 nm wavelengths using an XDS SmartProbe® Analyzer. NIR reflectance spectra were obtained at consecutive 5 mm intervals from bark to pith using a fibre optic probe of diameter 4.5 mm oriented at a right angle to the sample surface. Thirty-two scans were obtained from each scanning location and averaged into a single spectrum. Background corrections were conducted at 30-minute intervals using a reference ceramic sample (Zboňák and Bush, 2006). Cellulose and lignin models, from a multi-species calibration model outlined in a report by Zboňák (2006), were applied to the NIR spectra collected for each strip to obtain radial variation in predicted percentage cellulose and lignin.

5.2.5. Standardising age of measured wood properties

The intention of this research was to assess the effects of environmental variables on wood properties of trees within a narrow, comparable physiological age range, between six- eight years (approximately rotation age), therefore no explicit ‘age’ factor was included in the experimental design. However, not enough E. grandis compartments with the age range of six-eight years were available for sampling which met the requirements of the experimental design therefore older compartments were also considered. It was acknowledged that the inclusion of older compartments would introduce more variability in properties.

Compartments sampled were between six-thirteen years of age (Tables 5.2 and 5.3), and a range of ages were compared within each MAP x SWS combination in each region (Tables 5.4 a and b). The various combinations of compartment ages within cells resulted in younger material being compared with older material, or some cells consisting of mainly older material whilst others represented only younger compartments. For this reason, it became necessary to standardize the age of material compared within each block and thus minimize the effect of age on wood properties.

A method to separate growth rings on wood density profiles of *E. grandis* into annual rings using annual measurements of diameter at breast height (DBH) from permanent sample plot (PSP) datasets was described and discussed in Chapter four of this thesis. PSP data was not available for most compartments assessed in this research therefore the estimation of annual growth rings from the density profiles could not be verified with annual measurements of DBH. However, it was confirmed in Chapter four that growth rings on density profiles of *E. grandis*, closer to the bark-end, could serve as a reliable representation of annual growth. The above finding was used as an alternative approach to standardize the age of wood properties of trees from compartments sampled in this research.

Table 5.4 a and b. The ages of compartments sampled in the sub-tropical (a) and warm temperate regions (b). Varying combination of compartment ages within cells in each region

a		***MAP***		
SWS		DRY	MOIST	WET
	LOW	10 10 9	13	12 12 11
	MED.	x	x	x
	HIGH	9.5 9 8	10 9.5 9	9 9 8.5

b		***MAP***		
SWS		DRY	MOIST	WET
	LOW	10.5 10 10	15 11	11 11 10
	MED.	x	12.5 12 7.5	8 7 6
	HIGH	x	10 7.5	12.5 11 7.5

Trees from compartments aged nine years and older were selected and density profiles from bark to pith were constructed for each tree. An example of a density profile of *E. grandis* is illustrated in Figure 5.3. This profile represents a ten-year old tree planted in 1996 (the pith-end) and sampled in 2006 (the bark end). Lower wood density is formed during the first months of the growing season with an increase in density later in the season. An annual growth ring consisted of low density earlywood and high density latewood (as indicated by the vertical dotted lines in Figure 5.3).

Growth rings formed after approximately age eight were selected and a separation point was identified for each profile (indicated by shaded area in Figure 5.3). Values of density between the bark end and the separation point were removed from each profile and weighted means were re-calculated. This exercise was repeated for all density profiles of trees over 9 years of age and separation points were noted.

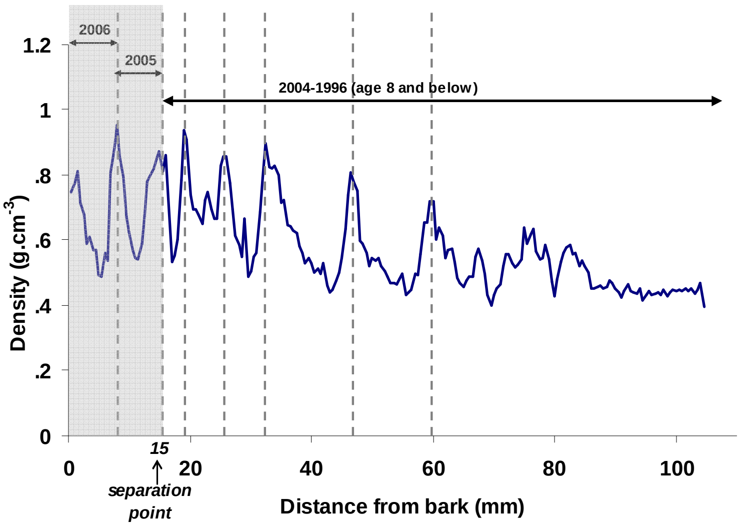


Figure 5.3. An example of a density profile illustrating growth rings from bark to pith. The shaded block highlights the growth rings that represented ages nine to ten years, this portion of the profile was removed at the separation point, and weighted means were recalculated

The density profiles were used as ‘templates’ and the separation points identified using the density profiles were also used on bark-to-pith profiles for vessel and fibre properties. Portions of the vessel and fibre profiles representing wood older than eight years of age (between the bark end and the separation point) were also ‘removed’. Weighted mean wood properties were then recalculated for each tree and compartment. This enabled the comparison of wood formed during the first eight years of growth. The effect of age on wood properties was thereby minimised as a confounding variable in the assessment of the effect of water availability on wood properties. These standardized values were used in the results presented in this chapter.

It is acknowledged that this method is subjective and it was therefore necessary to assess the level of sensitivity of this method in terms of selection of separation points. Therefore, five percent of the total strip length for each density profile was calculated. This value was added to the original separation point (‘plus 5%’) and subtracted from the original separation point (‘minus 5%’). Weighted means were recalculated for both ‘plus 5%’ and ‘minus 5%’ of the original separation point to assess whether weighted means differed significantly based on the position of the separation point. An analysis of variance (ANOVA) was conducted to compare the original separation point chosen, and plus and minus 5% on either side of the original separation point.

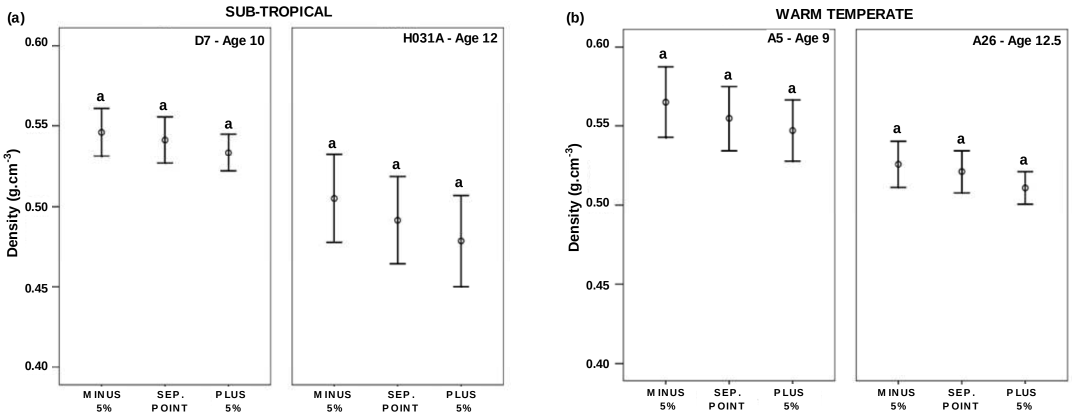


Figure 5.4 a and b. Comparison of mean density between the original separation point chosen, and plus and minus 5% on either side of the separation point in the sub-tropical (a) and warm temperate (b) regions. Letters above the bars indicate differences at $p \leq 0.05$. Error bar is equal to two standard errors

Table 5.5 a and b. Mean density “after age separation” (at separation point) is shown for compartments older than nine years at the time of sampling. Comparisons were made between the mean density at separation point chosen, and plus and minus 5% on either side of the separation point in the sub-tropical (a) and warm temperate (b) regions

(a)

REGION	COMP	AGE	MINUS 5%	PLUS 5%	AT SEPARATION POINT	p-value
ST	A11a	9.4	0.55	0.52	0.54	0.447
ST	A49A	10	0.61	0.60	0.61	0.962
ST	A49B	10	0.64	0.62	0.63	0.667
ST	B2	9.2	0.49	0.47	0.48	0.865
ST	D10b	12.9	0.46	0.45	0.46	0.813
ST	D7	10.1	0.55	0.53	0.54	0.443
ST	E12	9.2	0.57	0.55	0.56	0.717
ST	G081	11	0.48	0.46	0.47	0.865
ST	G2	9.6	0.55	0.53	0.54	0.431
ST	H031A	12.1	0.51	0.48	0.49	0.424
ST	H031B	12.1	0.45	0.43	0.44	0.888

(b)

REGION	COMP	AGE	MINUS 5%	PLUS 5%	AT SEPARATION POINT	p-value
WT	A26	12.5	0.53	0.51	0.52	0.285
WT	A3	11.9	0.52	0.51	0.51	0.925
WT	A35c	10.8	0.48	0.47	0.48	0.961
WT	A4	9.9	0.54	0.53	0.54	0.948
WT	A5	9.8	0.57	0.55	0.55	0.487
WT	B14	9.8	0.53	0.50	0.52	0.707
WT	C017	11.7	0.60	0.57	0.58	0.565
WT	D22	11.2	0.45	0.44	0.44	0.926
WT	E17	12.6	0.54	0.52	0.53	0.859
WT	F9	10.9	0.46	0.44	0.45	0.651
WT	H75a	10.3	0.51	0.48	0.50	0.674
WT	K8	10.5	0.50	0.48	0.49	0.734
WT	W80a	11	0.54	0.53	0.53	0.934

Results of the ANOVA are shown in Figures 5.4 a and b and Tables 5.5 a and b. Examples illustrating changes in the weighted mean density with the use of the different separation points are shown in Figures 5.4 a and b. A multiple range test showed that the weighted means were not statistically significantly different among separation points.

The p-values from the analysis of variance are shown for all compartments that were subjected to this ‘age-separation’ approach (Tables 5.5a and b). No significant differences in weighted mean density were found among the different separation points (‘plus 5%’ and ‘minus 5%’ of the original separation point) for any of the compartments. This suggests that this is not a sensitive method and as such, outputs from this method will not be user-dependant, i.e.: a possible small error in identifying a separation point did not have a significant effect on the results.

5.2.6. Data representation

Wood properties standardized to age eight were used in the results presented in this chapter. Density, vessel diameter and fibre diameter are expressed as radial maps to illustrate radial variation from bark to pith. These wood properties were selected to represent the three wood properties measured in this research *viz*. density, vessels and fibres. Results for related wood properties (vessel frequency, fibre lumen diameter and cell wall thickness) and NIR-predicted chemical properties (percentage cellulose and lignin) are presented as weighted means to assess main effects of environmental variables on wood properties.

5.2.6.1. Radial Maps

To allow for comparisons among trees of varying diameters, measurements for pith to bark profiles were averaged at 10% intervals and wood property values were expressed in terms of relative distance from the pith. Disc maps were constructed in order to illustrate the radial distribution of wood properties among the varying levels of water availability. The maps enabled easy visualization of the radial variability and differences between compartments at each combination of MAP and SWS in the experimental design. The diameter of each map was scaled down and represents the mean tree diameter per block (in the experimental design).

5.2.6.2. Weighted means

Weighted mean values were calculated for each wood property for each radial strip using Equation 3.6 in Chapter three, section 3.9.2. Weighted mean wood properties were used to assess main effects of MAP X SWS combinations on wood properties.

5.2.6.3. Statistical analyses

Data were analysed using univariate analysis of variance (ANOVA) using the General Linear Models procedure conducted in SPSS, Version 15 (SPSS, 2006). Main effects between wood properties and MAP x SWS combinations were assessed and a ‘Duncan's multiple range test’ was used to determine whether values differed significantly at a 95% confidence level. Pearson's correlation coefficient was carried out to examine the statistical significance of the correlations between variables.

5.3. Results and discussion

5.3.1. Correlation analyses

Correlations between site characteristics and wood properties measured are shown in Table 5.6 and Appendix 1 for the sub-tropical region, and in Table 5.7 and Appendix 2 for the warm temperate region. Correlations are based on compartment means (five trees per compartment).

Table 5.6. Correlation coefficients between site characteristics and wood properties of compartment means in the sub-tropical region (n = 15) (* = significant correlation at $p < 0.05$ and ** = significant correlation at $p < 0.01$)

SITE CHARACTERISTICS	**SUB-TROPICAL REGION - WOOD PROPERTIES**								
	Density (g.cm^{-3})	**Vessel diam. (μm)**	**Vessel freq. (no.mm^{-2})**	**Vessel %**	**Lumen diam. (μm)**	**Cell wall thickness (μm)**	**Fibre diam. (μm)**	**Cellulose %**	**Lignin %**
MAP (mm)	-0.32	0.22	-0.28	0.22	0.27	-0.09	0.36	0.23	-0.32
SWS (mm)	0.19	-0.43	-0.03	-0.48	-0.17	-0.01	-0.25	0.29	-0.14
SI	-0.44	0.27	**-0.72(**)**	0.06	0.37	-0.31	0.36	**0.74(**)**	**-0.70(**)**
OC (%)	-0.43	0.44	0.03	**0.62(*)**	0.45	-0.34	0.45	0.04	-0.05
CLAY(%)	0.06	0.19	0.23	0.33	-0.04	0.26	0.11	-0.38	0.28
SILT(%)	-0.47	0.51	-0.04	**0.64(**)**	0.47	-0.27	**0.53(*)**	0.11	-0.03
SAND(%)	0.12	-0.33	-0.17	-0.49	-0.14	-0.10	-0.28	0.25	-0.21

Table 5.7. Correlation coefficients between site characteristics and wood properties of compartment means in the warm temperate region (n = 19) (* = significant correlation at $p < 0.05$ and ** = significant correlation at $p < 0.01$)

SITE CHARACTERISTICS	**WARM TEMPERATE REGION - WOOD PROPERTIES**								
	Density (g.cm^{-3})	**Vessel diam. (μm)**	**Vessel freq. (no.mm^{-2})**	**Vessel %**	**Lumen diam. (μm)**	**Cell wall thickness (μm)**	**Fibre diam. (μm)**	**Cellulose %**	**Lignin %**
MAP (mm)	-0.20	-0.24	-0.26	**-0.54(*)**	**0.46(*)**	-0.08	**0.47(*)**	0.30	-0.36
SWS (mm)	0.03	-0.19	0.13	0.04	0.20	**-0.46(*)**	-0.13	**-0.57(*)**	0.36
SI	**-0.53(*)**	0.11	-0.27	-0.24	**0.47(*)**	-0.04	**0.50(*)**	**0.50(*)**	**-0.46(*)**
OC (%)	0.40	-0.06	-0.43	**-0.53(*)**	-0.11	**0.54(*)**	0.29	0.38	-0.18
CLAY(%)	0.39	0.18	-0.04	0.22	**-0.46(*)**	**0.47(*)**	-0.16	-0.01	0.11
SILT(%)	0.24	0.05	**-0.49(*)**	**-0.47(*)**	-0.15	**0.61(**)**	0.31	0.45	-0.27
SAND(%)	-0.37	-0.13	0.34	0.19	0.35	**-0.66(**)**	-0.11	-0.28	0.12

MAT represents the very broadest of indices of the environmental status of a location. A drawback of MAT is that it integrates diurnal, monthly and seasonal patterns of minimum and maximum temperature (Schulze, 1997). In this research, MAT was used to describe a broad temperature range within the design and define two unique regions. MAT was not correlated with any of the wood properties measured due to the narrow range of MAT values within each region.

In the sub-tropical region, few significant correlations were found between site variables and wood properties (Table 5.6). Site index, a widely used indicator of site quality, was negatively correlated with mean vessel frequency (r = -0.72) and explained approximately 50% of the variation. This result suggests that vessel frequency was lower on higher quality sites. For many genera and species, diameter and vessel element length increase while vessel frequency decreases with increasing water availability (Carlquist, 1975; Malan, 1991; February *et al*., 1995; Leal *et al*., 2004; Drew and Pammenter, 2006). Site index showed strong relationships between NIR predicted cellulose and lignin (Table 5.6). These results indicated that high SI corresponded with higher cellulose and lower lignin values.

Similarly, in the warm temperate region (Table 5.7), significant correlations were found between site index (SI) and some wood properties. SI was negatively correlated with density and NIR predicted lignin, and positively correlated with NIR predicted cellulose, suggesting that areas with higher site indices had lower density wood with higher percentages of cellulose and lower percentages of lignin. SI was positively correlated with fibre diameter and fibre lumen diameter which corresponded with the inverse relationship between SI and density. MAP was significantly correlated with fibre diameter, fibre lumen diameter, and vessel percentage in the warm temperate region (Table 5.7). However, while correlations were statistically significant, they usually explained less than 25% of the variation and correlations were poor from a predictive point of view.

Soil texture and soil depth play a vital role in the availability of water to the tree, which is more complex than a one-dimensional comparison with MAP only (Roberts, 1994). The influence of soil characteristics, through their influence on water retention characteristics, impacts on cell growth and subsequently tree growth. Vessel percentage in the sub-tropical region was correlated positively with soil organic carbon and silt, and negatively with fine sand (Table 5.6). In the warm temperate region, cell wall thickness was the wood property which correlated with many of the soil characteristics (Table 5.7).

Density and vessel diameter were not strongly significantly correlated with site variables. Density was strongly correlated with fibre lumen diameter and fibre diameter, with correlations in the warm temperate region slightly weaker than those found in the sub-tropical region (Appendices 1 and 2). Correlations between vessel diameter and vessel frequency with density suggested that higher density was associated with smaller, more frequent vessels and lower vessel percentage. As would be expected, vessel frequency and vessel diameter were negatively correlated, i.e.: fewer vessels per unit area when vessels are larger in diameter.

5.3.2. Radial maps – wood density, fibre diameter and vessel diameter

Radial profiles of wood properties reflect the history of cambial response to the environment (Downes *et al*., 2000; Drew *et al*., 2009). The radial pattern of distribution from pith to bark for mean values of density, fibre diameter and vessel diameter are illustrated across ranges of MAP and SWS in the sub-tropical (Figures 5.5, 5.7 and 5.9) and warm temperate regions (Figure 5.6, 5.8 and 5.10). These figures visually illustrate differences in diameter at breast height (at an average age of eight years) since the maps were constructed based on scaled down values of the mean radii for each compartment (using the pith to bark distance of wood property profiles that were standardised for age).

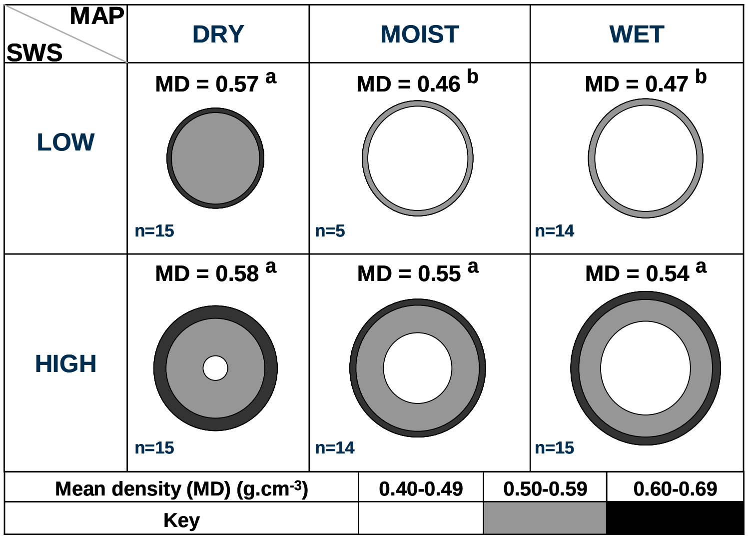


Figure 5.5. Maps of radial distribution of wood density across different levels of MAP and SWS in the sub-tropical region. The number of trees measured is indicated in each block. Superscripted letters next to mean values per block indicate significant differences ($p \leq 0.05$)

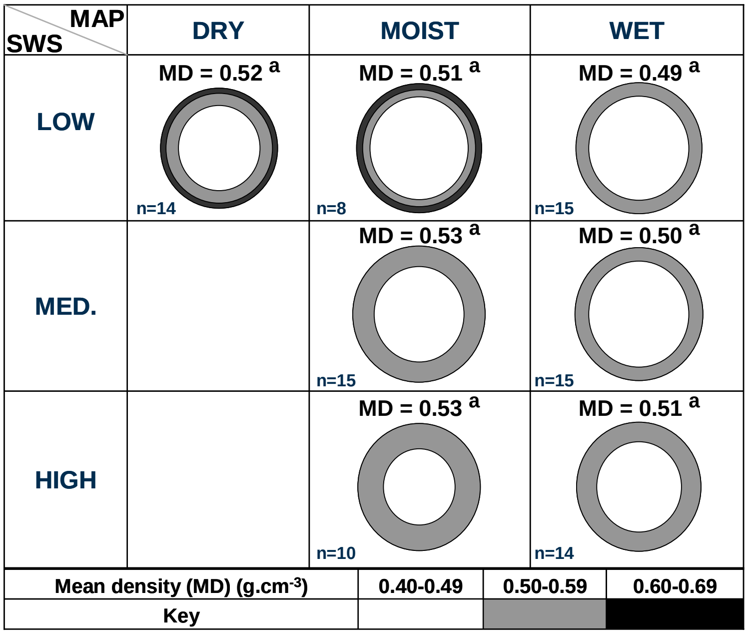


Figure 5.6. Maps of radial distribution of wood density across different levels of MAP and SWS in the warm temperate region. The number of trees measured is indicated in each block. Superscripted letters next to mean values per block indicate significant differences ($p \leq 0.05$)

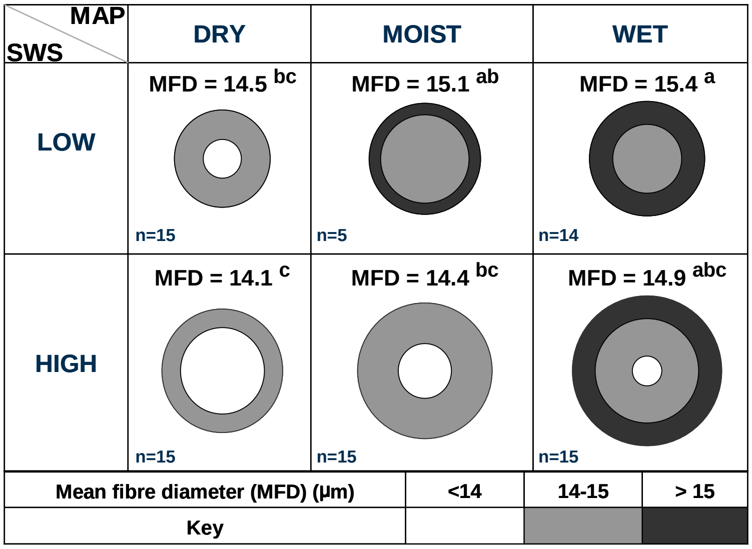


Figure 5.7. Maps of radial distribution of fibre diameter across different levels of MAP and SWS in the sub-tropical region. The number of trees measured is indicated in each block. Superscripted letters next to mean values per block indicate significant differences ($p \leq 0.05$)

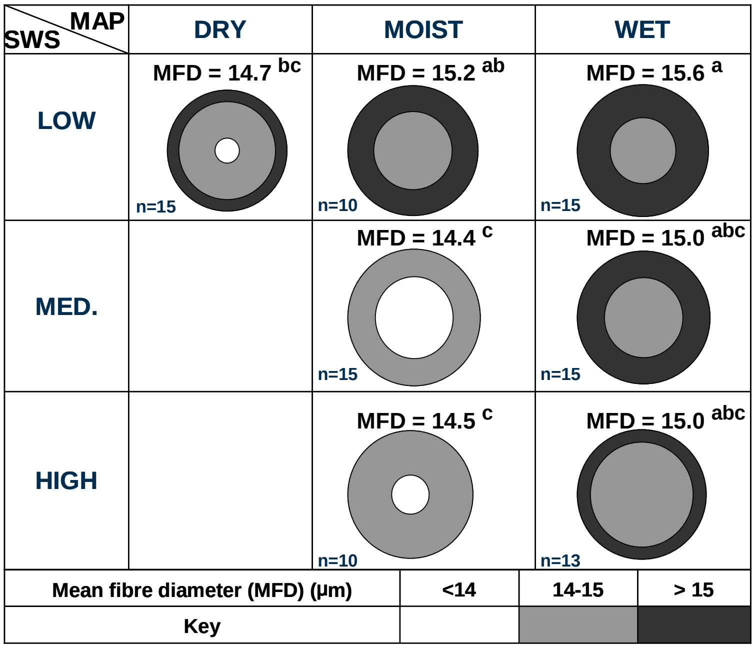
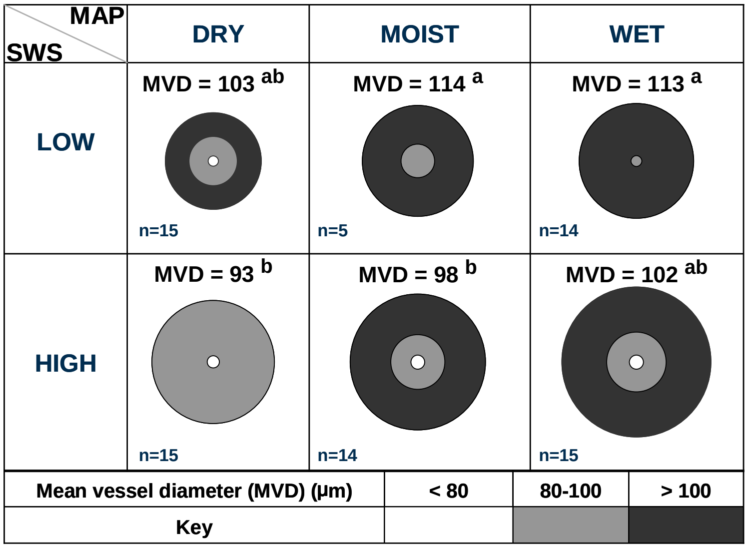


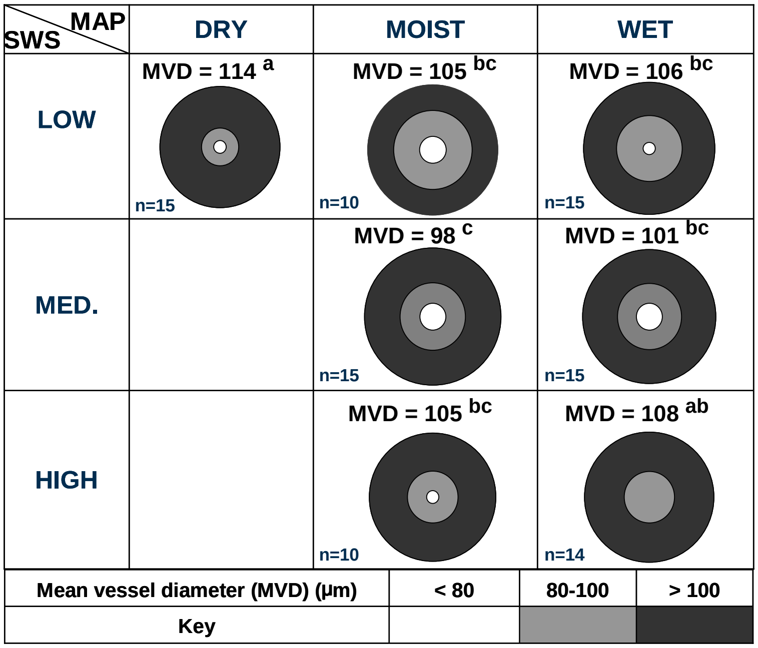
Figure 5.8. Maps of radial distribution of fibre diameter across different levels of MAP and SWS in the warm temperate region. The number of trees measured is indicated in each block. Superscripted letters next to mean values per block indicate significant differences ($p \leq 0.05$)



SWS \ MAP	DRY	MOIST	WET
LOW	MVD = 103 ^{ab} n=15	MVD = 114 ^{a} n=5	MVD = 113 ^{a} n=14
HIGH	MVD = 93 ^{b} n=15	MVD = 98 ^{b} n=14	MVD = 102 ^{ab} n=15

Mean vessel diameter (MVD) (µm)	< 80	80-100	> 100
Key	☐	▨	■

Figure 5.9. Maps of radial distribution of vessel diameter across different levels of MAP and SWS in the sub-tropical region. The number of trees measured is indicated in each block. Superscripted letters next to mean values per block indicate significant differences (p ≤ 0.05)



SWS \ MAP	DRY	MOIST	WET
LOW	MVD = 114 ^{a} n=15	MVD = 105 ^{bc} n=10	MVD = 106 ^{bc} n=15
MED.		MVD = 98 ^{c} n=15	MVD = 101 ^{bc} n=15
HIGH		MVD = 105 ^{bc} n=10	MVD = 108 ^{ab} n=14

Mean vessel diameter (MVD) (µm)	< 80	80-100	> 100
Key	☐	▨	■

Figure 5.10. Maps of radial distribution of vessel diameter across different levels of MAP and SWS in the warm temperate region. The number of trees measured is indicated in each block. Superscripted letters next to mean values per block indicate significant differences (p ≤ 0.05)

Weighted mean density declined with increasing MAP at each level of soil water storage in the sub-tropical region. However, this trend was significant only at the low SWS levels (Figure 5.5). Despite the mean values not differing significantly, radial changes in density are clearly illustrated in the pattern of distribution of density from bark to pith with increasing water availability. Blocks in the experimental design in the lower MAP range showed a larger proportion of higher density wood across the radius, whereas compartments in the higher MAP ranges had larger proportions of lower density wood

Mean density in the warm temperate region did not differ significantly across all blocks compared, and the pattern of density radial variation did not show much variation either (Figure 5.6), with the exception of denser wood in the outer 10 % at low SWS. The mean diameter at breast height (DBH) in the sub-tropical region also increased as MAP increased, with trees in the dry x low block almost 30% smaller than those in the wet x high block (Figures 5.5, 5.7 and 5.9). DBH was similar across MAP x SWS combinations in the warm temperate region (Figure 5.6, 5.8 and 5.10).

In *E. grandis*, the density of wood is strongly related to the cross-sectional morphology of fibres (Taylor 1973). Density relates well to fibre wall thickness and this applies strongly to eucalypts (Haygreen and Bowyer, 1989; Taylor, 1973). Mean fibre diameter increased significantly with an increase in MAP at low SWS in both the sub-tropical region and warm temperate regions (Figures 5.7 and 5.8). Results for the fibre diameter maps were similar to those found for density, where the pattern of radial fibre diameter distribution showed marked increases with increasing MAP. This similarity was expected due to the strong correlations between density and fibre diameter (Appendices 1 and 2). Similar relationships between water availability and the wood density of *E. globulus* were reported by Drew *et al*. (2009) where wood density increased and fibre radial diameter decreased in response to reduced water availability. In this research, differences were more pronounced at low SWS, with a larger proportion of the stem radius having larger fibre diameters at higher levels of MAP.

A tree may increase transport efficiency either by producing more cross sectional xylem or by changing anatomical features that affect conductivity such as vessel diameter, length and frequency. One of the most important of these variables in angiosperm wood is vessel diameter as hydraulic conductivity is proportional to the vessel radius raised to the 4th power (Zimmerman, 1983). This means that a slight increase in vessel radius is equivalent to a large increase in ability to transport sap. Thus, larger vessel diameters are usually associated with higher water availability (Carlquist, 1975; Malan, 1991; February *et al*., 1995; Searson *et al.*, 2004, Leal *et al*., 2004; Verheyden *et al.*, 2005; Drew and Pammenter, 2006; Drew *et al*., 2009).

Radial maps of mean vessel diameter in the sub-tropical region revealed a pattern of increase in vessel diameter with an increase in MAP at both SWS levels (Figure 5.9). The weighted mean vessel diameter differed significantly between compartments represented in the dry x high (DH) block and the wet x low (WL) block. Similarly, the pattern of vessel diameter distribution showed a clear contrast between these two blocks with the vessel diameter in the DH blocks having smaller vessels compared to those in the WL block.

Species on dry sites need narrow, shorter vessels to avoid embolizing and require more vessels per unit area to provide the needed water transport, since narrow vessels provide exponentially less flow than wide vessels (Zimmerman, 1983). February *et al*. (1995) showed significant correlations between water consumed and vessel diameter of *E. grandis* and *E. grandis* x *camaldulensis*. These authors suggested that eucalypts have plasticity in vessel morphology that allowed them to optimise use of plant-available water. Leal *et al*. (2004), in a study on *E. globulus*, reported that low water availability was related to more and smaller vessels. Similar findings for various eucalypt species were reported by Searson *et al*. (2004), Drew and Pammenter (2006), and Drew *et al*. (2009).

Figure 5.10 illustrates changes in vessel diameter in the warm temperate region. In general, no differences were seen in the means for this wood property in response to changing MAP or in the radial pattern of distribution. However, an exception was found in the dry x low (DL) block where mean vessel diameter was significantly larger than vessel diameter in the moist x low (ML) and wet x low (WL) blocks. This result was not expected since larger vessel diameters are associated with high water availability. Dye (1996) found that *E. grandis* trees were able to extract soil water to a depth of eight meters. In that study, deep drilling revealed that live roots reached 28 m below the surface and it was concluded that water was possible recharged by infiltration along old root channels.

5.3.3. Weighted means – fibre lumen diameter, fibre wall thickness, vessel percentage, vessel frequency, NIR-predicted percentage cellulose and lignin

The remaining wood properties measured included fibre lumen diameter, cell wall thickness, vessel frequency, and NIR predicted cellulose and lignin. These results are illustrated using standard error bar graphs to outline differences in the weighted means of these properties in response to changing water availability.

Mean fibre lumen diameter increased significantly with increasing MAP at low SWS in both the sub-tropical and warm temperate regions (Figures 5.11 a and b); and a trend of increase in this property with increasing MAP was found at the other SWS levels. This result was supported by correlations between MAP and fibre lumen diameter (Appendix 2).

In the sub-tropical region, cell wall thickness declined significantly at low SWS (Figure 5.12 a). A decline in mean cell wall thickness with increase water availability was expected since cell wall thickness is closely correlated with density (Appendix 1) (Taylor, 1973). However, density does not always correlate well with fibre cell wall dimensions as density is also influenced by vessels and parenchyma, which have thinner walls and wider lumens and reduce density. This could explain why cell wall thickness does not vary significantly with MAP in the high SWS cells in the sub-tropical region and within each SWS range in the warm temperate region (Figures 5.12 a and b).

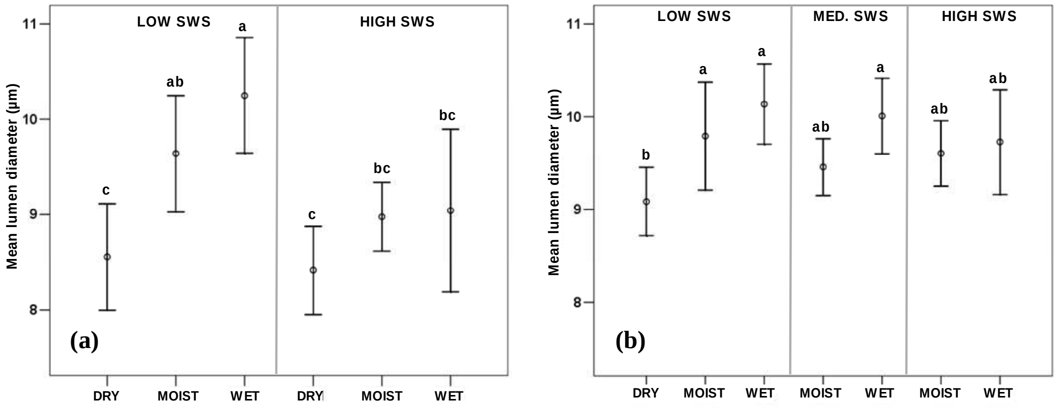


Figure 5.11 a and b. Comparison of mean lumen diameter at each MAP x SWS level in the sub-tropical (a) and warm temperate (b) regions. Letters above the bars indicate differences at p ≤ 0.05. Error bar is equal to two standard errors

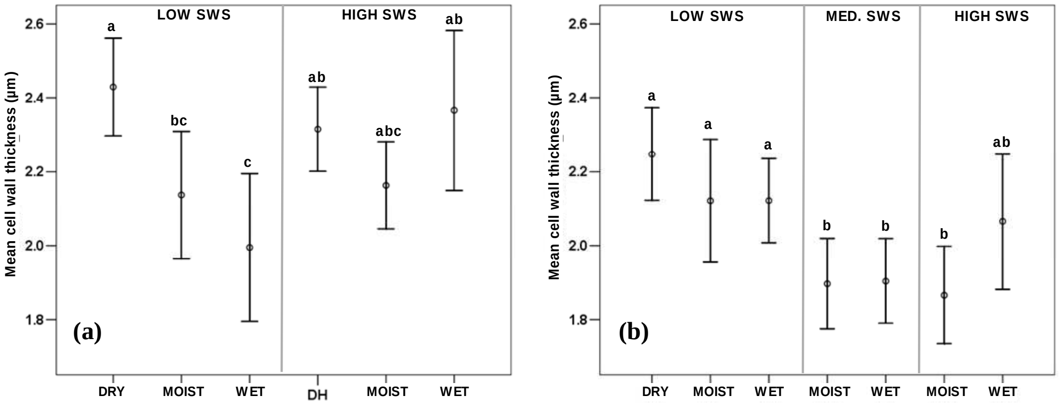


Figure 5.12 a and b. Comparison of mean cell wall thickness at each MAP x SWS level in the sub-tropical (a) and warm temperate (b) regions. Letters above the bars indicate differences at p ≤ 0.05. Error bar is equal to two standard errors

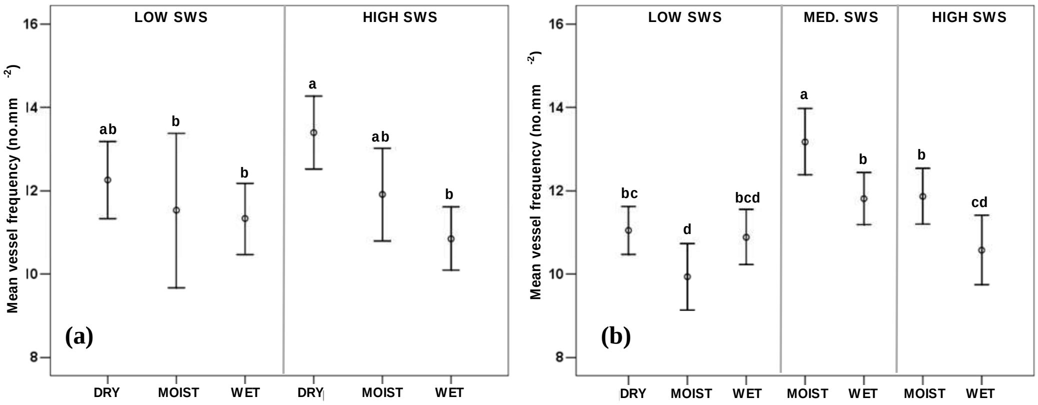


Figure 5.13 a and b. Comparison of mean vessel frequency at each MAP x SWS level in the sub-tropical (a) and warm temperate (b) regions. Letters above the bars indicate differences at $p \leq 0.05$. Error bar is equal to two standard errors

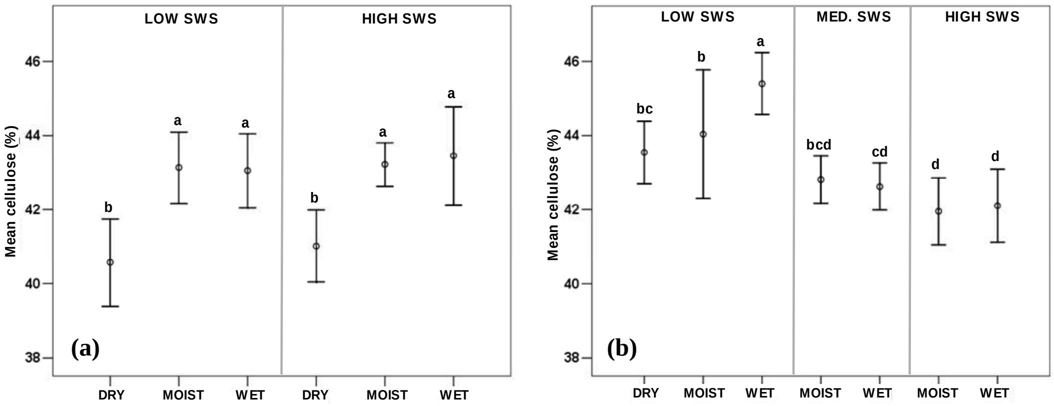


Figure 5.14 a and b. Comparison of mean cellulose percentage at each MAP x SWS level in the sub-tropical (a) and warm temperate (b) regions. Letters above the bars indicate differences at $p \leq 0.05$. Error bar is equal to two standard errors

Vessel frequency is a measure of the number of vessels that occur per unit area. For many genera and species, diameter and vessel element length increases while vessel frequency decreases with increasing water availability (Carlquist, 1975; Bamber *et al.*, 1982; Malan, 1991; February *et al.*, 1995). Vessel frequency declined significantly with increasing MAP at high SWS in the sub-tropical region (Figure 5.13 a) and at medium and high SWS in the warm temperate region (Figure 5.13 b). Contrary to other wood properties discussed, vessel frequency did not vary significantly at low SWS (Figures 5.13 a and b).

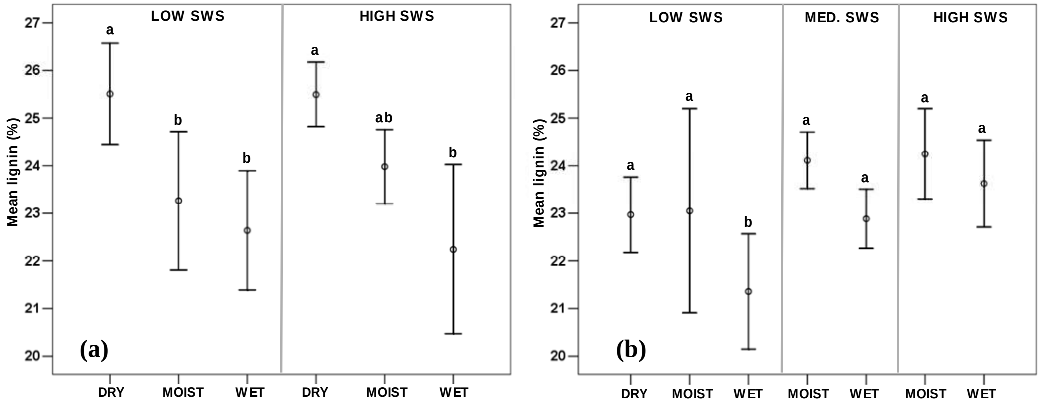


Figure 5.15 a and b. Comparison of mean lignin percentage at each MAP x SWS level in the sub-tropical (a) and warm temperate (b) regions. Letters above the bars indicate differences at $p \leq 0.05$. Error bar is equal to two standard errors

NIR predicted cellulose increased significantly with an increase in MAP at both SWS levels in the sub-tropical region (Figure 5.14 a) and at low SWS in the warm temperate region (Figure 5.14 b). In contrast, NIR predicted lignin decreased significantly with increasing MAP in the sub-tropical region (Figure 5.15 a) and in the warm temperate region at low SWS (Figure 5.15 b).

5.4. Conclusion

This research utilised rapid screening tools to characterize the wood properties of *Eucalyptus grandis* sampled from compartments grown in the sub-tropical and warm temperate regions of South Africa. Relationships among wood properties were assessed and discussed in terms of their responses to soil characteristics and water availability. Density, vessel diameter and fibre diameter were expressed as radial maps to illustrate radial variation from bark to pith and vessel frequency, fibre lumen diameter, cell wall thickness and NIR-predicted chemical properties (percentage cellulose and lignin) are illustrated as weighted means at different levels of water availability in both regions.

Correlations in the sub-tropical region indicated that vessel characteristics were significantly correlated with site characteristics, whereas in the warm temperate region, fibre characteristics had strong correlations with site characteristics. Site index, a term which is a composite expression of the effects of site variables on height growth, was moderately correlated with wood properties such as vessel frequency, NIR-predicted cellulose and lignin in the sub-tropical region (r = > 0.7). Site index, in the warm temperate region, was correlated with density, fibre diameter, fibre lumen diameter and NIR predicted cellulose and lignin (r = < 0.6). Of the soil factors considered, those that influenced wood properties were organic carbon and silt in both regions, as well as fine sand and medium sand in the subtropical and warm temperate regions respectively.

In the sub-tropical region, a comparison of weighted mean values of the wood properties showed some consistent patterns of response to varying levels of MAP. In this research, compartments sampled from areas with higher MAP values had lower density wood with larger vessel and fibre diameters, thinner cell walls, higher cellulose percentages, lower lignin percentages and fewer vessels per unit area. Results from the warm temperate region revealed similar results with wood from areas with higher MAP having larger fibre diameters, higher cellulose percentages, lower lignin percentages and lower vessel frequencies. Density, cell wall thickness and vessel diameter did not show as clear trends. In general, wood properties in the sub-tropical region showed more marked responses to varying levels of MAP than wood properties measured in the warm temperate region. The response of wood properties to water availability in the sub-tropical region was thought to have been amplified by higher temperatures since the pattern observed for sum of rainfall over the total period of growth for compartments sampled was similar in both regions.

The results presented in this chapter will evaluated further in Chapter six, in which empirical models were developed to describe the relationship between wood properties and selected environmental factors.

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Appendix 1. Correlation matrix of site characteristics and wood properties of compartment means in the sub-tropical region. (n = 15) (‘r-value’ = Pearson’s correlation coefficient) (‘p’ = significance of correlation where * = significant correlation at $p < 0.05$ and ** = significant correlation at $p < 0.01$)

		MAP (mm)	SWS (mm)	SI	OC (%)	CLAY(%)	SILT(%)	SAND(%)	Density (g.cm^{-3})	Vessel diam. (µm)	Vessel freq. (no.mm^{-2})	Vessel %	Lumen diam. (µm)	Cell wall thickness (µm)	Fibre diam. (µm)	Cellulose %	Lignin %
MAP (mm)	r-value	1	-0.028	0.415	0.206	-0.044	0.278	-0.068	-0.324	0.218	-0.281	0.224	0.267	-0.086	0.356	0.228	-0.318
	p		0.92	0.124	0.462	0.876	0.316	0.811	0.239	0.435	0.31	0.422	0.335	0.762	0.192	0.414	0.248
SWS (mm)	r-value	-0.028	1	0.461	__-.698(**)__	__-.825(**)__	__-.598(*)__	__.859(**)__	0.192	-0.431	-0.026	-0.484	-0.166	-0.006	-0.251	0.289	-0.138
	p	0.92		0.083	0.004	0	0.018	0	0.494	0.109	0.928	0.067	0.553	0.983	0.366	0.296	0.624
SI	r-value	0.415	0.461	1	-0.27	__-.552(*)__	-0.281	__.532(*)__	-0.436	0.27	__-.721(**)__	0.062	0.372	-0.313	0.364	__.739(**)__	__-.698(**)__
	p	0.124	0.083		0.33	0.033	0.31	0.041	0.104	0.331	0.002	0.826	0.173	0.257	0.182	0.002	0.004
OC (%)	r-value	0.206	__-.698(**)__	-0.27	1	__.612(*)__	__.840(**)__	__-.782(**)__	-0.43	0.44	0.031	__.619(*)__	0.45	-0.337	0.446	0.039	-0.051
	p	0.462	0.004	0.33		0.015	0	0.001	0.11	0.1	0.914	0.014	0.093	0.219	0.096	0.889	0.858
CLAY(%)	r-value	-0.044	__-.825(**)__	__-.552(*)__	__.612(*)__	1	0.463	__-.946(**)__	0.063	0.188	0.229	0.327	-0.041	0.257	0.109	-0.38	0.281
	p	0.876	0	0.033	0.015		0.082	0	0.824	0.502	0.411	0.234	0.885	0.355	0.698	0.162	0.31
SILT(%)	r-value	0.278	__-.598(*)__	-0.281	__.840(**)__	0.463	1	__-.725(**)__	-0.47	0.514	-0.035	__.643(**)__	0.467	-0.266	__.528(*)__	0.113	-0.033
	p	0.316	0.018	0.31	0	0.082		0.002	0.077	0.05	0.902	0.01	0.079	0.338	0.043	0.688	0.906
SAND(%)	r-value	-0.068	__.859(**)__	__.532(*)__	__-.782(**)__	__-.946(**)__	__-.725(**)__	1	0.123	-0.334	-0.165	-0.489	-0.139	-0.102	-0.278	0.254	-0.206
	p	0.811	0	0.041	0.001	0	0.002		0.662	0.224	0.556	0.064	0.621	0.717	0.316	0.361	0.461
Density (g.cm^{-3})	r-value	-0.324	0.192	-0.436	-0.43	0.063	-0.47	0.123	1	__-.863(**)__	__.682(**)__	__-.801(**)__	__-.969(**)__	__.832(**)__	__-.904(**)__	__-.826(**)__	__.800(**)__
	p	0.239	0.494	0.104	0.11	0.824	0.077	0.662		0	0.005	0	0	0	0	0	0
Vessel diam. (µm)	r-value	0.218	-0.431	0.27	0.44	0.188	0.514	-0.334	__-.863(**)__	1	__-.749(**)__	__.864(**)__	__.787(**)__	__-.609(*)__	__.781(**)__	__.660(**)__	__-.605(*)__
	p	0.435	0.109	0.331	0.1	0.502	0.05	0.224	0		0.001	0	0	0.016	0.001	0.007	0.017
Vessel freq. (no.mm^{-2})	r-value	-0.281	-0.026	__-.721(**)__	0.031	0.229	-0.035	-0.165	__.682(**)__	__-.749(**)__	1	-0.382	__-.588(*)__	0.431	__-.607(*)__	__-.765(**)__	__.645(**)__
	p	0.31	0.928	0.002	0.914	0.411	0.902	0.556	0.005	0.001		0.16	0.021	0.108	0.016	0.001	0.009
Vessel %	r-value	0.224	-0.484	0.062	__.619(*)__	0.327	__.643(**)__	-0.489	__-.801(**)__	__.864(**)__	-0.382	1	__.772(**)__	__-.600(*)__	__.760(**)__	__.540(*)__	__-.591(*)__
	p	0.422	0.067	0.826	0.014	0.234	0.01	0.064	0	0	0.16		0.001	0.018	0.001	0.038	0.02
Lumen diam. (µm)	r-value	0.267	-0.166	0.372	0.45	-0.041	0.467	-0.139	__-.969(**)__	__.787(**)__	__-.588(*)__	__.772(**)__	1	__-.859(**)__	__.930(**)__	__.814(**)__	__-.825(**)__
	p	0.335	0.553	0.173	0.093	0.885	0.079	0.621	0	0	0.021	0.001		0	0	0	0
Cell wall thickness (µm)	r-value	-0.086	-0.006	-0.313	-0.337	0.257	-0.266	-0.102	__.832(**)__	__-.609(*)__	0.431	__-.600(*)__	__-.859(**)__	1	__-.612(*)__	__-.722(**)__	__.673(**)__
	p	0.762	0.983	0.257	0.219	0.355	0.338	0.717	0	0.016	0.108	0.018	0		0.015	0.002	0.006
Fibre diam. (µm)	r-value	0.356	-0.251	0.364	0.446	0.109	__.528(*)__	-0.278	__-.904(**)__	__.781(**)__	__-.607(*)__	__.760(**)__	__.930(**)__	__-.612(*)__	1	__.749(**)__	__-.797(**)__
	p	0.192	0.366	0.182	0.096	0.698	0.043	0.316	0	0.001	0.016	0.001	0	0.015		0.001	0
Cellulose %	r-value	0.228	0.289	__.739(**)__	0.039	-0.38	0.113	0.254	__-.826(**)__	__.660(**)__	__-.765(**)__	__.540(*)__	__.814(**)__	__-.722(**)__	__.749(**)__	1	__-.880(**)__
	p	0.414	0.296	0.002	0.889	0.162	0.688	0.361	0	0.007	0.001	0.038	0	0.002	0.001		0
Lignin %	r-value	-0.318	-0.138	__-.698(**)__	-0.051	0.281	-0.033	-0.206	__.800(**)__	__-.605(*)__	__.645(**)__	__-.591(*)__	__-.825(**)__	__.673(**)__	__-.797(**)__	__-.880(**)__	1
	p	0.248	0.624	0.004	0.858	0.31	0.906	0.461	0	0.017	0.009	0.02	0	0.006	0	0	

Appendix 2. Correlation matrix of site characteristics and wood properties of compartment means in the warm temperate region. (n = 19) (‘r-value’ = Pearson’s correlation coefficient) (‘p’ = significance of correlation where * = significant correlation at $p < 0.05$ and ** = significant correlation at $p < 0.01$)

		MAP (mm)	**SWS (mm)**	**SI**	**OC (%)**	**CLAY(%)**	**SILT(%)**	**SAND(%)**	**Density (g.cm^{-3})**	**Vessel diam. (µm)**	**Vessel freq. (no.mm^{-2})**	**Vessel %**	**Lumen diam. (µm)**	**Cell wall thickness (µm)**	**Fibre diam. (µm)**	**Cellulose %**	**Lignin %**
MAP (mm)	r-value	1	0.246	0.278	0.261	-0.421	0.225	0.081	-0.196	-0.244	-0.255	**-.536(*)**	**.463(*)**	-0.076	**.472(*)**	0.298	-0.359
	p		0.309	0.249	0.28	0.072	0.354	0.743	0.42	0.314	0.291	0.018	0.046	0.756	0.041	0.215	0.131
SWS (mm)	r-value	0.246	1	-0.305	-0.26	-0.083	**-.481(*)**	0.359	0.025	-0.188	0.126	0.039	0.196	**-.459(*)**	-0.133	**-.572(*)**	0.36
	p	0.309		0.204	0.282	0.734	0.037	0.132	0.918	0.441	0.609	0.873	0.421	0.048	0.588	0.011	0.131
SI	r-value	0.278	-0.305	1	-0.006	-0.348	0.118	0.111	**-.531(*)**	0.107	-0.269	-0.24	**.465(*)**	-0.041	**.500(*)**	**.501(*)**	**-.463(*)**
	p	0.249	0.204		0.979	0.144	0.63	0.651	0.019	0.663	0.265	0.323	0.045	0.868	0.029	0.029	0.046
OC (%)	r-value	0.261	-0.26	-0.006	1	0.387	**.811(**)**	**-.738(**)**	0.397	-0.059	-0.426	**-.528(*)**	-0.114	**.543(*)**	0.292	0.382	-0.182
	p	0.28	0.282	0.979		0.102	0	0	0.092	0.81	0.069	0.02	0.644	0.016	0.225	0.107	0.455
CLAY(%)	r-value	-0.421	-0.083	-0.348	0.387	1	0.4	**-.801(**)**	0.385	0.18	-0.037	0.217	**-.462(*)**	**.471(*)**	-0.159	-0.012	0.105
	p	0.072	0.734	0.144	0.102		0.09	0	0.104	0.462	0.88	0.373	0.046	0.042	0.517	0.961	0.669
SILT(%)	r-value	0.225	**-.481(*)**	0.118	**.811(**)**	0.4	1	**-.869(**)**	0.242	0.047	**-.485(*)**	**-.472(*)**	-0.153	**.613(**)**	0.306	0.445	-0.265
	p	0.354	0.037	0.63	0	0.09		0	0.318	0.849	0.035	0.041	0.531	0.005	0.202	0.056	0.273
SAND(%)	r-value	0.081	0.359	0.111	**-.738(**)**	**-.801(**)**	**-.869(**)**	1	-0.366	-0.128	0.337	0.191	0.35	**-.655(**)**	-0.114	-0.284	0.116
	p	0.743	0.132	0.651	0	0	0		0.123	0.602	0.159	0.433	0.142	0.002	0.642	0.238	0.636
Density (g.cm^{-3})	r-value	-0.196	0.025	**-.531(*)**	0.397	0.385	0.242	-0.366	1	-0.32	-0.055	-0.382	**-.756(**)**	0.304	**-.651(**)**	-0.442	**.699(**)**
	p	0.42	0.918	0.019	0.092	0.104	0.318	0.123		0.181	0.824	0.107	0	0.206	0.003	0.058	0.001
Vessel diam. (µm)	r-value	-0.244	-0.188	0.107	-0.059	0.18	0.047	-0.128	-0.32	1	**-.532(*)**	**.468(*)**	-0.186	**.512(*)**	0.21	0.338	-0.393
	p	0.314	0.441	0.663	0.81	0.462	0.849	0.602	0.181		0.019	0.043	0.446	0.025	0.387	0.157	0.096
Vessel freq. (no.mm^{-2})	r-value	-0.255	0.126	-0.269	-0.426	-0.037	**-.485(*)**	0.337	-0.055	**-.532(*)**	1	0.43	0.128	**-.641(**)**	-0.362	-0.178	0.112
	p	0.291	0.609	0.265	0.069	0.88	0.035	0.159	0.824	0.019		0.066	0.6	0.003	0.128	0.465	0.647
Vessel %	r-value	**-.536(*)**	0.039	-0.24	**-.528(*)**	0.217	**-.472(*)**	0.191	-0.382	**.468(*)**	0.43	1	-0.052	-0.149	-0.159	0.004	-0.244
	p	0.018	0.873	0.323	0.02	0.373	0.041	0.433	0.107	0.043	0.066		0.832	0.543	0.515	0.987	0.314
Lumen diam. (µm)	r-value	**.463(*)**	0.196	**.465(*)**	-0.114	**-.462(*)**	-0.153	0.35	**-.756(**)**	-0.186	0.128	-0.052	1	**-.539(*)**	**.728(**)**	0.267	**-.457(*)**
	p	0.046	0.421	0.045	0.644	0.046	0.531	0.142	0	0.446	0.6	0.832		0.017	0	0.269	0.049
Cell wall thickness (µm)	r-value	-0.076	**-.459(*)**	-0.041	**.543(*)**	**.471(*)**	**.613(**)**	**-.655(**)**	0.304	**.512(*)**	**-.641(**)**	-0.149	**-.539(*)**	1	0.184	0.345	-0.131
	p	0.756	0.048	0.868	0.016	0.042	0.005	0.002	0.206	0.025	0.003	0.543	0.017		0.45	0.148	0.594
Fibre diam. (µm)	r-value	**.472(*)**	-0.133	**.500(*)**	0.292	-0.159	0.306	-0.114	**-.651(**)**	0.21	-0.362	-0.159	**.728(**)**	0.184	1	**.590(**)**	**-.648(**)**
	p	0.041	0.588	0.029	0.225	0.517	0.202	0.642	0.003	0.387	0.128	0.515	0	0.45		0.008	0.003
Cellulose %	r-value	0.298	**-.572(*)**	**.501(*)**	0.382	-0.012	0.445	-0.284	-0.442	0.338	-0.178	0.004	0.267	0.345	**.590(**)**	1	**-.807(**)**
	p	0.215	0.011	0.029	0.107	0.961	0.056	0.238	0.058	0.157	0.465	0.987	0.269	0.148	0.008		0
Lignin %	r-value	-0.359	0.36	**-.463(*)**	-0.182	0.105	-0.265	0.116	**.699(**)**	-0.393	0.112	-0.244	**-.457(*)**	-0.131	**-.648(**)**	**-.807(**)**	1
	p	0.131	0.131	0.046	0.455	0.669	0.273	0.636	0.001	0.096	0.647	0.314	0.049	0.594	0.003	0	

CHAPTER SIX

MODELLING WOOD PROPERTIES OF *EUCALYPTUS GRANDIS* GROWN IN KWAZULU-NATAL

Based on:

Naidoo, S., Ahmed, F. and Pammenter, N.W. Modeling the effects of environmental factors on the wood properties of *E. grandis* in the warm temperate and sub-tropical regions of South Africa. (In preparation for submission to *Southern Forests: a Journal of Forest Science*)

6.1. Introduction

The environment to which a tree is exposed is an integrated complex of climatic and topographical factors as well as a number of soil-related and biological factors (Landsberg and Gower, 1997; Louw and Scholes, 2002). This environmental influence, however, occurs within the limits set by genetic make-up of each individual tree. Interactions between trees, geographic location, site conditions and management actions (i.e.: the total environment of the tree) on wood formation and properties is complex and the components are interrelated. This results in difficulties in separating the influence of the individual factors on wood and fibre quality attributes (Kang *et al*., 2004).

An improvement in understanding the actors that control tree growth, and the limitations of the sites on which they are planted, is needed to achieve sustainable plantations (Louw, 1999). Controlling conditions in the plantation environment to consistently produce the most desirable fibre properties is, unfortunately, not easy. However, the ability to predict wood quality as a function of the environment will improve our ability to optimise site-species matching (Jacobs and Drew, 2002).

The development of models provides opportunities to understand problems posed by the complexity of a system. To do this empirical models are widely used as prediction tools in forest management (Downes *et al*., 2009). These models are made up of sets of equations based on observed data and which provide accurate predictions provided they are based on data obtained from standard commercial regimes (Sands, 2003). These predictions, however, are accurate only under the defined conditions as extremes have not been included. Extrapolation out of the norm and into the novel is therefore unwise (Sands, 2003). Despite their perceived ‘short-comings’, empirical models are useful tools in assisting one in interpretating experimental results and understanding the system one studies.

Empirical models, relating selected wood properties of *Eucalyptus grandis* to site and climatic conditions, are presented in this chapter. Multiple linear regression models were developed using weighted mean wood properties and long-term mean climatic variables. In addition, non-linear regression models were developed using bark-to-pith radial wood properties and measured rainfall experienced during the total growth period of each compartment.

6.2. Experimental approach

6.2.1. Compartment details

More compartments from KwaZulu-Natal were sampled compared to Mpumalanga, with only four compartments being sampled in the latter (Figure 6.1.).

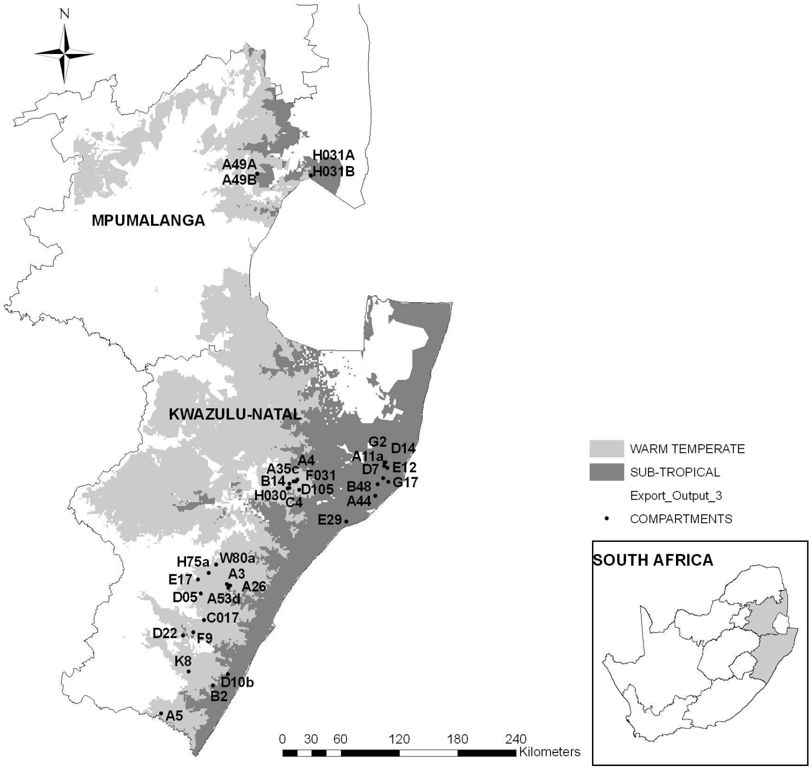

Figure 6.1. Map of KwaZulu-Natal and Mpumalanga illustrating the location of compartments used for model development in the warm temperate and sub-tropical regions

This was a result of compartments not being found for all blocks in the experimental matrices as defined by the selection criteria outlined in the experimental design, i.e. within specific MAT, MAP and SWS combinations

(Chapter 3, section 3.2.3). For this reason, compartments sampled in Mpumalanga were excluded from model development.

The location of compartments within the context of the experimental design used in this research is shown in Table 6.1. Compartments B2 and D10b (Figure 6.1) were excluded from model development due to the unavailability of monthly rainfall data. A summary of compartments details are provided in Appendix 3.

Table 6.1. Location of compartments sampled in KZN (n=28) in the experimental design with ranges for MAP and SWS. Compartment codes are shown in each block, compartments from the sub-tropical are italicized; the warm temperate compartments are not italicized.

MAP (mm) ***SWS (mm)***	**DRY** **600-875 mm**	**MOIST** **876-975 mm**	**WET** **976-3500 mm**
LOW **(72-151 mm)**	B14	F9	H75a
	K8	C017	W80a
	A5		D22
MEDIUM **(152-230 mm)**		A3	A53d
		A26	C4
		D05	D105
HIGH **(231-309 mm)**		A4	A35c
		F031	E17
			H030
	E12	*A11a*	*B48*
	G2	*A44*	*G17*
	D14	*D7*	*E29*

6.2.2. Wood property data

Two non-destructive pith to bark cores per tree were sampled at breast height (1.3 m above ground) from five trees per compartment. One core was used for density evaluation, and the other for measurements of wood anatomical properties *viz.* vessel and fibre characteristics.

6.2.2.1. Wood air-dry density

A core sample was stored at 23ºC and 50% relative humidity to achieve an equilibrium moisture content of about 10%. Solid wood strips of uniform thickness were cut along the radius using a twin-blade saw. The strip dimensions were 12 mm in the longitudinal direction, 2.5 mm in the tangential direction and length was determined by the radius of the core. Radial strips were scanned at consecutive 0.5 mm intervals, from bark to pith, using a gamma-ray densitometer with a Fe^{55} radiation source to determine the density profile.

6.2.2.2. Vessel and fibre characteristics

Radial strips, 2.5 mm thick, obtained from core samples taken at breast height samples, were sectioned with a microtome to obtain a 20-25 µm thick section and mounted in ethanol on a glass slide and examined using a Leica fluorescent microscope. Anatomical measurements were performed every 0.5 mm for vessel measurements and every alternate 0.5 mm for fibre measurements, from bark to pith, using an image analysis system (Leica QWin). Anatomical characteristics measured included: vessel diameter (µm), vessel frequency (the number of vessels per unit area ($no.mm^{-2}$)), vessel percentage (the percentage area occupied by vessels (%)), fibre diameter (µm), fibre lumen diameter (µm) and cell wall thickness (µm).

6.2.3. Climatic data, site index, and soil properties

Linking environmental factors with wood properties at a broad scale requires detailed climatic and site information over a range of sites. This was achieved by using the South African Atlas of Agrohydrology and Climatology (SAAAC) (Schulze, 1997), Sim-A-Tree (3-PG) (version 1.2) (Sim-A-Tree (3-PG), 2005) and weather stations managed by the South African Weather Service (SAWS) (SAWS, 2007) and South African Sugar Research Institute (SASRI) (SASRI, 2007). In addition, site index at reference age five (SI_5) was calculated and soil properties were measured to provide an indication of the overall quality of each compartment.

A brief summary is provided below on the sources of climatic data, site index and soil properties. Detailed descriptions on methods of measurement of site index, soil properties, and sources of climatic data are discussed in Chapter three in section 3.4, 3.7 and 3.8 respectively.

6.2.3.1. Climatic data

Sim-A-Tree 3-PG was used to identify weather stations close to compartments and the SAWS and SASRI were contacted to update weather records, where possible for weather stations selected.

Monthly rainfall was obtained for each compartment from the SAWS and SASRI. Reliable temperature data for each compartment was not available for the majority of compartments sampled and was therefore not reported for any compartments in this research. For this reason, only long term means for temperature variables (such as MAT, solar radiation and heat units), extracted from the SAAAC, was reported (Chapter 3, section 3.8). In addition, other long term mean values used included median rainfall January and H_20 stress January[18] (only variables that were normally distributed were used).

Lang's Climatic Index (LCI) is the ratio between mean annual precipitation and mean annual temperature (MAT). LCI is useful as a general indication of site conditions when site specific information is lacking (du Plessis and Zwolinski, 2003).

6.2.3.2. Site index and soil properties

Site index, an indicator of the growth rate of trees in a compartment, was used to describe the overall quality of each compartment. Site indices were derived by calculating the mean height of the tallest 20% of the trees in each stand using a reference age of five years (Bredenkamp, 1993).

Soil samples for each compartment were taken from two sampling points within the enumeration plot (10 m radius) and measurements of organic carbon percentage (OC%) and particle size distribution were made (proportions of sand, silt and clay) and expressed as percentage values. The soil properties were averaged for each compartment to contribute to the overall description of the compartments.

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[18] January Soil Water Stress Per Cent Days Under Stress (Schulze, 1997)

6.2.4. Data modelling approaches

Regression models were developed to predict selected basic wood properties of *E. grandis* in KwaZulu-Natal as follows:

A. Warm temperate and sub-tropical regions combined (KZN)
B. Warm temperate region only (WT)
C. Sub-tropical region only (ST)
D. Varying MAP levels within the warm temperate and sub-tropical regions combined - dry, moist and wet MAP
E. Varying SWS levels within the warm temperate and sub-tropical regions combined - low, medium and high SWS

The modelling approaches used were multiple linear regression and non-linear regression models. Multiple linear regression models were developed using long term mean climatic variables extracted from the SAAAC and weighted mean wood properties. Non-linear regression models were developed using bark-to-pith radial wood properties and total rainfall measured over the growth period of each compartment (data obtained from the SAWS and SASRI).

It was not possible to develop individual models for each of the MAP and SWS combinations in the individual regions since the number of compartments assessed in each region within individual blocks representing varying levels of water availability was small ($n \leq 3$).

6.2.4.1. Multiple linear regression – weighted mean wood properties and climatic variables

Normality tests were conducted in SPSS Version 15 (SPSS, 2006) using a Kolmogorov-Smirnov *z*-test as part of the preliminary analysis. Only variables that were normally distributed were used in subsequent analyses. A list of the variables used in model development is shown in Table 6.2 and descriptive statistics for each of the variables is presented in Table 6.3. Pearson's correlation coefficients were used to assess linear relationships between environmental and site variables in KZN (WT and ST regions combined), ST region and WT region.

Table 6.2. Climatic, site and soil variables and wood properties used for statistical analysis

Climatic variables	**Site and soil variables**	**Wood properties**
MAP (mm)	Site index (SI_5)	Density ($g.cm^{-3}$)
LCI ($mm.^oC^{-1}$)	Organic carbon%	Vessel diam. (µm)
Cumulative rainfall (mm)	Clay%	Vessel freq. ($no.mm^{-2}$)
Median rainfall January (mm)	Silt%	Vessel %
H_20 Stress January (%)	Sand%	Fibre diam. (µm)
Heat units (October-March) (^{o}days)		Cell wall thickness (µm)
Solar radiation ($MJ.m^{-2}.day^{-1}$)		

Table 6.3. Descriptive statistics showing variation at the compartment level (n=28) in climatic, site and soil variables and wood properties

VARIABLES		**Mean**	**Std. Error of mean**	**Minimum**	**Maximum**	**Range**
Climatic variables	MAP (mm)	990	24	792	1467	675
	LCI ($mm.^oC^{-1}$)	54.8	1.4	41.0	69.9	28.8
	Cumulative rainfall (mm)	9332	653	3678	19537	15858
	Med. Rain-Jan (mm)	124.9	4.6	86.0	165.0	79.0
	H20Stress-Jan (%)	55.2	1.2	44.3	65.8	21.5
	Heat units (Oct-Mar) (^{o}days)	1995	69	1568	2545	977
	Solar radiation ($MJ.m^{-2}.day^{-1}$)	21.3	0.1	19.8	22.8	3.0
Site and soil variables	SI_5	21.0	0.5	16.5	27.9	11.4
	Organic carbon%	4.9	0.6	0.3	9.9	9.6
	Clay%	21.2	2.7	0.3	51.9	51.6
	Silt%	25.6	2.8	5.3	50.6	45.3
	Sand%	53.2	5.2	6.4	94.4	88.0
Wood properties	Density ($g.cm^{-3}$)	0.54	0.01	0.45	0.67	0.22
	Vessel diam. (µm)	99.8	1.4	82.0	113.3	31.3
	Vessel freq. ($no.mm^{-2}$)	11.7	0.3	9.0	14.9	5.9
	Vessel %	10.0	0.2	7.1	11.4	4.3
	Fibre diam. (µm)	14.9	0.1	13.5	16.5	3.0
	Cell wall thickness (µm)	2.2	0.0	1.8	2.8	1.1

A multiple linear regression method (Equation 6.1) was used to develop models for the estimation of selected wood properties i.e.: density, vessel and fibre properties. The wood property variables were treated as dependant variables of rainfall, temperature and soil variables (Table 6.2). Independent variables that had highly significant correlations with the dependent variables were selected for inclusion in the model. Site index was included as both an independent and dependant variable because it is a variable that is a composite expression of the effects of interacting site variables on wood properties.

$$Y = \beta o + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_i X_i \qquad \textit{Equation 6.1}$$

Using a forward ‘step-wise’ procedure in SPSS, the independent variables with the most influence on the dependant variable were identified. This ‘step-wise’ procedure involves fitting the model and iteratively removing (or including) variables until the model has identified variables that fall within the predefined statistical limits. Limits were set for the significance of the F-value[19] to determine which independent variables would be included or removed from the model at the various steps of the analysis. The limit for inclusion of variables was set to a F-value significance of <0.05 and the limit for exclusion of variables was set to a limit of <0.1.

The coefficients of determination values (R^2) were corrected for sample size and standard error (calculated by SPSS) and expressed as adjusted R^2 (R^2_{adj}). The R^2_{adj} was used to provide a less biased value of the strength of the relationships.

Residual analysis was used to quantify the difference between measured and predicted wood properties (Equation 6.2) where the performance of the regression models was evaluated based on root-mean-square error (RMSE). RMSE provides an indication of the average magnitude of the error of a regression model and since errors are squared before they are averaged, RMSE gives a relatively high weight to large errors. RMSE was expressed as a percentage of the mean of the measured wood property values, i.e. absolute root-mean-square error percentage (ARMSE%) (Equation 6.3).

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[19] The F-value determines how significant the contribution of a variable has to be in the regression equation in order for it to be included or removed from the equation

$$\mathrm{RMSE} = \sqrt{\frac{\sum (X_{pred} - X_{obs})^2}{n}} \qquad \textit{Equation 6.2}$$

$$\mathrm{ARMSE\%} = \frac{\mathrm{RMSE}}{\mu_{meas}} \times 100 \qquad \textit{Equation 6.3}$$

where X_{pred} is the model-predicted value, X_{meas} is the measured value, and μ_{meas} is the mean of the measured wood property values.

6.2.4.2. Linear and non-linear regression – bark-to-pith radial wood properties and cumulative measured rainfall

To relate rainfall data (measured on a time scale) with the wood property data (measured on a distance scale), both rainfall and wood property data needed to be standardized. Therefore, to enable comparisons among trees of varying diameters with rainfall measured over varying time periods, both measured rainfall and wood property measurements for bark-to-pith profiles were each averaged at 10% intervals. This method was used as *E. grandis* does not have well-defined growth rings and as such, rainfall could not be related to average wood properties at the level of individual growth rings. In addition, it was not possible to apply the technique developed in Chapter 4 where permanent sample plot (PSP) data were used to identify growth rings, since PSP data were not available for most compartments assessed. Data was not standardised for age.

Monthly rainfall was expressed as cumulative values from bark to pith, where the bark end equaled 100% (i.e.: total rainfall over entire period of tree growth), the sum of rainfall at 90% represented the sum of the first nine intervals, the sum of rainfall at 80% represented the sum of the first eight intervals…and so on…till the pith end represented the sum of rainfall in the first 10% interval (i.e.: sum of rainfall between date planted and the first 10% of the period of tree growth). Wood properties were averaged at each percentage interval (n= 5 trees per compartment), with the bark end representing an average of all ten intervals (100%), the average at 90% representing an average of the first nine intervals, the sum of rainfall at 80% represented the sum of the first eight intervals…and so on…till the pith end thus represented only the first 10% interval. This was done for each compartment.

Paired-observations were compared between rainfall and each wood property at each percentage interval using a curve estimation procedure in SPSS (v15) non-linear regressions models were developed for KZN, individual regions, and at each MAP and SWS level in the combined region data set.

It is acknowledged that the relationship between measured rainfall and wood properties is complex and is further confounded by the effect of age. Since data was not standardised for age, it is important to note that this particular modelling approach was used only as a means of comparing and illustrating the response of wood properties to varying levels of rainfall across the radius and to identify which wood property was most influenced.

6.3. Results: Correlations - weighted mean wood properties and climatic variables

Pearson's correlation coefficients were used to assess linear relationships, if any, between variables. Correlations between environmental and site variables in KZN, ST region and WT region are shown in Tables 6.4 a, b and c respectively. Correlations are based on compartment means (five trees per compartment); the number of compartments assessed in KZN (ST and WT combined), the ST region and WT region were 28, 19 and 9 respectively.

Overall, site variables explained less than 40% of the variation for most of the wood properties, and their effect was not very consistent from one region to the other (Tables 6.4 a, b and c). In KZN, site index was correlated with most wood properties but the correlations, though statistically significant, were weak (Table 6.4 a). SI_5 was negatively correlated with density and vessel frequency, and positively correlated with vessel diameter, fibre diameter and fibre lumen diameter suggesting that areas with higher site indices had lower density wood with fewer larger vessels and larger fibres with larger lumens. The correlation between SI_5 and vessel diameter, fibre diameter and fibre lumen diameter also corresponded with the inverse relationship between SI_5 and density. MAP was significantly ($p<0.05$) correlated with vessel percentage and SI_5. Fibre diameter was positively correlated with soil organic carbon and percentage silt (Table 6.4 a).

In the WT region, vessel percentage was significantly correlated with site variables mainly associated with rainfall and soil characteristics (Table 6.4 b). Soil organic carbon had a positive relationship with wood density and cell wall thickness and percentage silt had a positive relationship with cell wall thickness and a negative relationship with vessel percentage and vessel frequency.There was more variability in terms of soil characteristics in the WT region compared to soils in the ST region which were predominantly sandy in nature; soils in the WT region had a comparatively higher proportion of clay and silt. The organic carbon in soils was on average three times higher in the WT region than in the ST region (Naidoo *et al*., 2007).

In the ST region, very few significant correlations were found between site variables and wood properties (Table 6.4 c). This was a result of a small sample size and little variability among sites in terms of temperature and soil-related variables among the compartments sampled where the range between the minimum and maximum values for these variables was small. Site index, a widely used indicator of site quality, was negatively correlated with mean vessel frequency ($r = -0.79$). This result suggests that vessel frequency was lower on higher quality sites, which could be a result of vessel diameter being larger, however vessel diameter was not significantly correlated with site. Site index was negatively correlated with site variables associated with temperature *viz*. heat units (March-October) and solar radiation.

Tables 6.4 a, b and c. Correlations between wood properties and climatic, site and soil variables in KZN (WT and ST combined), the WT region and the ST region (* = significant correlations at $p < 0.05$ and ** = significant correlation at $p < 0.01$)

(a) KZN - WT and ST regions combined (n=28)

SITE VARIABLES	Wood properties							
	Density (g.cm^{-3})	Vessel diam. (µm)	Vessel freq. (no.mm^{-2})	Vessel %	Lumen diam. (µm)	Cell wall thickness (µm)	Fibre diam. (µm)	SI5
MAP (mm)	0.078	-0.109	-0.265	**-0.409(*)**	-0.132	0.293	0.047	**0.411(*)**
LCI (mm.^{o}C^{-1})	-0.096	0.209	**-0.465(*)**	-0.244	0.242	-0.019	0.330	0.341
SI$_5$	**-0.475(*)**	**0.374(*)**	**-0.501(**)**	-0.022	**0.401(*)**	-0.130	**0.463(*)**	1
Cumulative rainfall (mm)	0.107	-0.005	-0.276	-0.342	0.032	0.362	0.331	0.361
Median rainfall January (mm)	-0.204	0.218	-0.333	-0.117	**0.377(*)**	-0.224	0.358	0.285
H$_2$0 Stress January (%)	0.201	-0.220	0.337	0.119	**-0.376(*)**	0.222	-0.358	-0.288
Heat units (October-March)(^{o}days)	0.266	**-0.411(*)**	0.231	-0.268	**-0.445(*)**	**0.420(*)**	-0.299	0.025
Solar radiation (MJ.m^{-2}.day^{-1})	-0.048	0.137	-0.085	-0.018	0.226	-0.100	0.240	0.019
OC%	-0.122	0.293	-0.297	0.045	**0.404(*)**	-0.212	**0.404(*)**	0.012
CLAY%	-0.115	0.349	-0.139	0.285	0.272	-0.188	0.237	-0.128
SILT%	-0.102	0.311	-0.367	-0.019	0.333	-0.074	**0.414(*)**	0.043
SAND%	0.114	-0.348	0.269	-0.137	-0.319	0.137	-0.345	0.043

(b) WT region (n=19)

SITE VARIABLES	Wood properties							
	Density (g.cm^{-3})	Vessel diam. (µm)	Vessel freq. (no.mm^{-2})	Vessel %	Lumen diam. (µm)	Cell wall thickness (µm)	Fibre diam. (µm)	SI5
MAP (mm)	-0.127	-0.143	-0.316	**-0.507(*)**	0.405	-0.036	0.436	0.278
LCI (mm.^{o}C^{-1})	0.058	-0.131	-0.420	**-0.605(**)**	0.283	0.088	0.404	0.158
SI$_5$	-0.408	0.188	-0.318	-0.224	0.454	-0.001	**0.521(*)**	1
Cumulative rainfall (mm)	0.226	-0.014	-0.327	-0.439	-0.065	**0.561(*)**	0.407	0.368
Median rainfall January (mm)	-0.031	-0.238	-0.198	**-0.501(*)**	0.284	-0.031	0.301	0.268
H$_2$0 Stress January (%)	0.024	0.238	0.205	**0.509(*)**	-0.280	0.026	-0.300	-0.274
Heat units (October-March)(^{o}days)	-0.250	0.032	-0.088	-0.117	0.285	0.059	0.375	**0.503(*)**
Solar radiation (MJ.m^{-2}.day^{-1})	0.143	-0.011	-0.202	-0.316	-0.083	0.343	0.196	0.357
OC%	**0.480(*)**	-0.127	**-0.459(*)**	**-0.578(**)**	-0.213	**0.566(*)**	0.239	-0.006
CLAY%	0.324	0.103	0.037	0.183	-0.443	0.400	-0.166	-0.348
SILT%	0.341	-0.029	**-0.496(*)**	**-0.541(*)**	-0.236	**0.604(**)**	0.247	0.118
SAND%	-0.398	-0.037	0.304	0.254	0.394	**-0.610(**)**	-0.071	0.111

(c) ST region (n=9)

SITE VARIABLES	Wood properties							
	Density (g.cm^{-3})	Vessel diam. (µm)	Vessel freq. (no.mm^{-2})	Vessel %	Lumen diam. (µm)	Cell wall thickness (µm)	Fibre diam. (µm)	SI5
MAP (mm)	0.086	0.116	-0.414	-0.249	-0.236	0.486	-0.042	0.611
LCI (mm.^{o}C^{-1})	0.086	0.116	-0.414	-0.249	-0.236	0.486	-0.042	0.611
SI$_5$	-0.606	0.628	**-0.785(*)**	0.288	0.442	-0.357	0.433	1
Cumulative rainfall (mm)	-0.138	-0.121	-0.138	-0.198	0.148	-0.044	0.192	0.439
Median rainfall January (mm)	0.163	-0.025	-0.328	-0.380	-0.306	0.535	-0.114	0.553
H$_2$0 Stress January (%)	-0.162	0.017	0.331	0.370	0.305	-0.535	0.113	-0.555
Heat units (October-March)(^{o}days)	0.077	-0.122	0.444	0.211	0.051	-0.313	-0.122	**-0.667(*)**
Solar radiation (MJ.m^{-2}.day^{-1})	0.221	-0.340	0.613	0.057	-0.083	-0.211	-0.258	**-0.767(*)**
OC%	-0.021	-0.291	0.484	0.172	0.142	-0.242	0.056	-0.151
CLAY%	0.450	-0.512	0.605	-0.183	-0.344	0.440	-0.235	-0.293
SILT%	-0.013	-0.084	0.365	0.288	0.155	-0.054	0.197	-0.380
SAND%	-0.189	0.280	-0.505	-0.108	0.050	-0.158	-0.025	0.378

6.4. Results: Multiple linear regression - weighted mean wood properties and climatic variables

6.4.1. Model development

A multiple linear regression method was used to develop models for the estimation of selected wood properties i.e.: density, vessel and fibre properties in KZN (both regions combined) (n=28). The wood property variables were treated as dependant variables of rainfall, temperature and soil variables (a list of the variables used in model development is shown in Table 6.2, section 6.2.4.1).

The R^2_{adj} statistic from multiple regression models developed to describe the response of weighted mean wood properties to environmental variables, although statistically significant, were weak (Table 6.5) suggesting that a single model was not adequate to predict wood properties in KZN. Therefore, the dataset was also assessed at a regional level where wood properties in the sub-tropical and warm temperate regions within KZN were modelled separately. In addition, models were also developed at the varying levels of MAP and SWS (Table 6.5).

It is important to note that by modelling the regions and the MAP and SWS levels separately, this resulted in a difference in the number of compartments used to develop each model since the experimental matrices were incomplete as a result of compartments not being found for all blocks as defined by the selection criteria outlined in the experimental design, i.e. within specific MAT, MAP and SWS combinations. This was a consequence of the available compartments not falling within the required age range, or coppiced trees, or in some instances, *E. grandis* was simply not grown in those areas.

The WT region represents two thirds (n=19) of compartments sampled in KZN, while the ST region represents one-third (n=9). Similarly, there were twice as many compartments used to develop models at ‘wet’ MAP than at ‘dry’ MAP. Nevertheless, it was thought that by attempting to develop models at a regional level and at varying MAP and SWS levels, this would provide additional information to assess whether the predictor variables that influenced wood properties changed across varying levels of MAP and SWS and in different regions. Only models that were statistically significant were considered therefore it was not possible to predict all wood properties in all regions (Table 6.5).

Table 6.5. Summary of multiple linear regression models developed to predicted weighted mean wood properties using climatic and site variables. Shaded blocks = models were not statistically significant

MODEL SUMMARY - DEPENDANT VARIABLES VS CLIMATIC AND SITE VARIABLES									
DEPENDANT VARIABLES	**KZN - ST and WT**			**WT**			**ST**		
	n=28			n=19			n=9		
	Predictor/s	**R^2_{adj}**	**SE**	**Predictor/s**	**R^2_{adj}**	**SE**	**Predictor/s**	**R^2_{adj}**	**SE**
Density (g.cm^{-3})	SI$_5$	0.20	0.05	OC%	0.19	0.04	-	-	
Vessel diam. (µm)	SI$_5$, Clay%	0.24	6.44	-	-		-	-	
Vessel freq. (no.mm^{-2})	SI$_5$, Silt%	0.32	1.14	Silt%	0.20	1.13	SI$_5$	0.56	1.03
Vessel %	MAP	0.14	0.95	LCI, Silt%	0.46	0.72	-	-	
Fibre diam. (µm)	SI$_5$, OC%	0.32	0.57	SI$_5$	0.23	0.52	-	-	
Cell wall thickness (µm)	-	-		Sand%	0.34	0.19	-	-	
Site index (SI$_{5)}$	MAP	0.14	2.35	-	-		Solar rad.	0.53	2.03
	MAP LEVEL								
DEPENDANT VARIABLES	**DRY**			**MOIST**			**WET**		
	n=6			n=10			n=12		
	Predictor/s	**R^2_{adj}**	**SE**	**Predictor/s**	**R^2_{adj}**	**SE**	**Predictor/s**	**R^2_{adj}**	**SE**
Density (g.cm^{-3})	SI$_5$	0.62	0.03	-	-		LCI, OC%	0.58	0.03
Vessel diam. (µm)	SI$_5$, MAP	0.90	3.57	-	-		-		
Vessel freq. (no.mm^{-2})	SI$_5$	0.71	0.94	-	-		-		
Vessel %	Silt%	0.91	0.31	-	-		LCI	0.58	0.56
Fibre diam. (µm)	-			SI$_5$	0.39	0.37	-		
Cell wall thickness (µm)	SI$_5$	0.67	0.06	MAP	0.52	0.14	LCI, Clay%	0.58	0.19
Site index (SI$_{5)}$	-	-		-	-		Clay, cumulative rainfall	0.51	1.21
	SWS LEVEL								
DEPENDANT VARIABLES	**LOW**			**MEDIUM**			**HIGH**		
	n=8			n=6			n=14		
	Predictor/s	**R^2_{adj}**	**SE**	**Predictor/s**	**R^2_{adj}**	**SE**	**Predictor/s**	**R^2_{adj}**	**SE**
Density (g.cm^{-3})	-	-		-	-		-	-	
Vessel diam. (µm)	Silt%	0.79	2.52	-	-		-	-	
Vessel freq. (no.mm^{-2})	-			LCI	0.86	0.39	SI$_5$, Solar rad.	0.46	1.06
Vessel %	LCI	0.49	0.99	-	-		-		
Fibre diam. (µm)	-			Clay%	0.61	0.19	-		
Cell wall thickness (µm)	SI$_5$	0.62	0.08	-	-		-		
Site index (SI$_{5)}$	-			Median rainfall Jan.	0.63	0.76	Solar rad.	0.31	2.13

In KZN, site index or a combination of site index and soil variables were most frequently identified as predictors of wood properties while in the WT region, models that were statistically significant included soil variables as predictors of wood properties. The coefficients of determination (R^2_{adj}) of multi-linear regression models developed for the estimation wood properties and site index did not improve for all wood properties at a regional level, however, models for selected wood properties had higher R^2_{adj} at a regional level (Table 6.5). For example, the model to predict vessel % in the WT region had a higher R^2_{adj} of

0.46 and lower standard error compared to R^2_{adj} of 0.14 in the KZN model. Variables that best predicted vessel % in the WT region were silt and Lange's climatic index (LCI). In the ST, the only statistically significant regression models for the region were the models for predicting vessel frequency and site index which had R^2_{adj} of 0.56 and 0.53 respectively.

At 'dry' MAP, the R^2_{adj} of multi-linear regression models developed for the estimation of density, vessel and fibre properties were much higher compared to models developed at a regional level with R^2_{adj} of 0.62 for density, 0.90 for vessel diameter, 0.71 for vessel frequency, 0.91 for vessel percentage and 0.67 for cell wall thickness (Table 6.5). Similarly, regression models for the 'wet' MAP level, density, vessel percentage, cell wall thickness and site index each had R^2_{adj} values greater than 0.5. Site index was a better predictor of wood properties in the dry' MAP level, while at 'wet' MAP level, LCI (which is a ratio of MAP and MAT) was a stronger predictor of wood properties in combination with organic carbon % (to predict density) and clay % (to predict cell wall thickness).

Density could not be predicted at any of the SWS levels, and vessel diameter, vessel percentage and cell wall thickness could only be predicted at 'low' SWS with R^2_{adj} statistics of 0.79, 0.49 and 0.62 respectively (Table 6.5).

6.4.2. Model validation

Model validation is an important step in the model building process. The R^2 statistic from the 'fit' of the model does give an indication of the predictive power of the model. The model 'fit' is a measure of a fraction of the total variability in the response that is accounted for by the model. However, a high R^2 does not guarantee that the model fits the data well and models thus need to be validated (Probert and Keating, 2000).

Validation enables one to demonstrate that the model is a reasonable representation of the actual system. However, in practice, it can be difficult to achieve full validation of the model, and this was the situation in this research.

The R^2 statistic from models developed to describe the response of weighted mean wood properties to environmental variables in KZN, although statistically significant, were weak (Table 6.5). In addition, the compartments used for validation represented four compartments each from the warm temperate and sub-tropical regions in KZN. Therefore, it was not possible to validate the models developed at a regional level and at each MAP and SWS level using the independent dataset provided by compartments which were sampled and measured for this research (a description of compartments used for validation is provided in Appendix 3).

For this reason, two validation approaches were used *viz*. validation using an independent data set and cross-validation using the leave-one-out cross-validation technique. An independent set of compartments selected for validation when sampling for this research commenced was used to validate the regression models for KZN (ST and WT combined) (Table 6.5) and leave-one-out cross validation was used to validate models at a regional level and at each MAP and SWS level. Leave-one-out cross validation is the most extreme form of *k*-cross validation (Lachenbruch and Mickey, 1968). In *k*-cross validation, the available data is divided into *k* subsets; a single subset is retained as the validation data set for testing the model and *k*-1 subsets are used for model training. This process is repeated *k* times with each of the *k* subsets used only once as the validation data. This procedure is useful on small datasets and makes good use of the available data as each observation used is used both as training and test data (Cawley and Talbot, 2008).

In both validation approaches used, residual analysis was used to quantify the difference between measured and predicted wood properties using root-mean-square error (RMSE). RMSE provides an indication of the average magnitude of the error of a regression model, and since errors are squared before they are averaged, RMSE provides a relatively high weight to large errors. RMSE was also expressed as a percentage of the mean of the measured wood property values, i.e. absolute root-mean-square error percentage (ARMSE%). Generally, a high R^2, low RMSE value, and an ARMSE% < 10%, are indicative of a good model fit (M.T. Gebreslasie, Pers. Comm[20]).

A summary of regression models, RMSE and ARMSE% from the comparison of measured and predicted wood properties in KZN (n = 8) is presented in Table 6.6. Errors of estimation for weighted mean wood properties from validation compartments are also illustrated in Figures 6.2 a-f.

Table 6.6. Regression models used to predict wood properties and site index in KZN and residual analysis from the comparison of measured and predicted values (n = 8)

Dependant variables	**Regression models - KZN**	**Residual analysis**	
		RMSE	**ARMSE%**
Density ($g.cm^{-3}$)	$y=(-0.01007*SI_5)+0.7502$	0.06	11.24
Vessel diam. (µm)	$y= (1.2453*SI_5)+(0.2116*Clay\%)+69.09$	7.35	6.93
Vessel freq. ($no.mm^{-2}$)	$y=(-0.2638*SI_5)+(-0.0324*Silt\%)+18.046$	1.90	17.98
Vessel %	$y=(-0.0033*MAP)+13.24$	0.73	7.22
Fibre diam. (µm)	$y=(0.1246*SI_5)+(0.08914*OC\%)+11.8169$	0.75	5.11
Site index (SI_5)	$y=(0.00807*MAP)+13.0321$	2.32	11.31

The models for KZN were not expected to predict wood properties with a high degree of accuracy due to the weak R^2_{adj} statistics (Table 6.5). The differences between observed and predicted values for vessel % and fibre diameter are small (Figures 6.2 d and e) and supported by an ARMSE% lower than 10% of 7.22 and 5.11 for vessel % and fibre diameter respectively.

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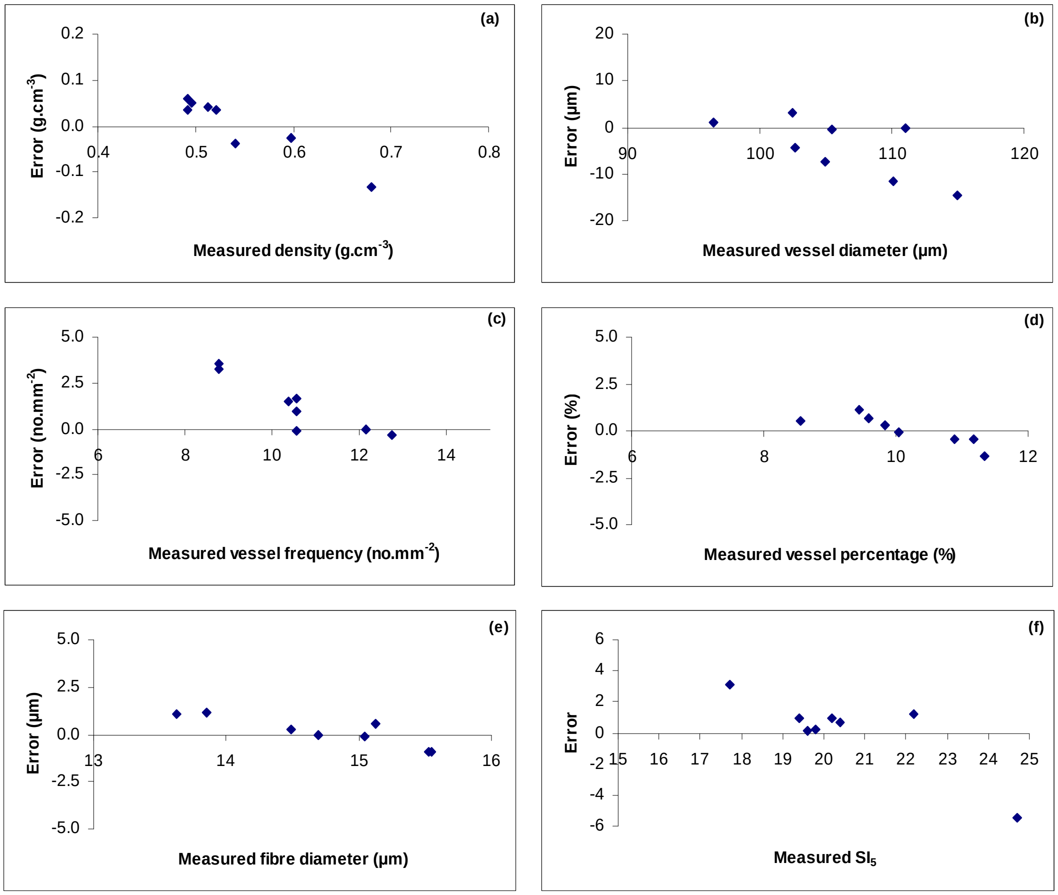


Figure 6.2 a-f. Comparison of estimation error for weighted mean wood properties and site index from validation compartments in KZN.

Regression models used to predict wood properties and site index in the WT and ST (n=19 and n=9 respectively) and residual analysis from leave-one-out cross validation are provided in Table 6.7. In the warm temperate region, models to predict vessel % and fibre diameter have ARMSE% values lower than 10% (2.45 and 3.46 for vessel % and fibre diameter respectively) (Table 6.7).

Regression models and residual analysis for wood properties and site index at dry, moist and wet MAP levels (n=6, n=10 and n=12 respectively) are shown in Table 6.8. and regression models used to predict wood properties and site index at low, medium and high SWS levels (n=8, n=6 and n=14 respectively) are provided in Table 6.9.

Table 6.7. Regression models used to predict wood properties and site index in the warm temperate (WT) and sub-tropical regions (ST) and residual analysis

Dependant variables	**Regression models - WT**	**Residual analysis**	
		RMSE	**ARMSE%**
Density (g.cm^{-3})	y = (0.0136*OC%) + 0.436	0.05	9.28
Vessel diam. (µm)	-	-	-
Vessel freq. (no.mm^{-2})	y = (-0.0586*SILT%) + 13.408	1.22	10.63
Vessel %	y = (-0.0910*LCI) + (-0.0377*SILT%) + 16.668	0.82	2.45
Fibre diam. (µm)	y = (0.1277*SI_5) + 12.348	0.52	3.46
Cell wall thickness (µm)	y = (-0.0086*SAND%) + 2.444	0.29	13.86
Site index (SI_5)	-	-	-
Dependant variables	**Regression models - ST**	**Residual analysis**	
		RMSE	**ARMSE%**
Density (g.cm^{-3})	-	-	-
Vessel diam. (µm)	-	-	-
Vessel freq. (no.mm^{-2})	y = (-0.4115*SI_5) + 20.722	1.08	8.90
Vessel %	-	-	-
Fibre diam. (µm)	-	-	-
Cell wall thickness (µm)	-	-	-
Site index (SI_5)	y = (-4.3665*Solar radiation) + 111.514	2.58	12.36

Table 6.8. Regression models used to predict wood properties and site index at dry, moist and wet MAP levels (n=6, n=10 and n=12 respectively) and residual analysis

Dependant variables	**Regression models - DRY MAP**	**Residual analysis**	
		RMSE	**ARMSE%**
Density (g.cm^{-3})	y = (-0.0208*SI_5) + 0.956	0.05	8.14
Vessel diam. (µm)	y = (3.0058*SI_5) + (-0.1265*MAP) + 149.636	6.56	6.71
Vessel freq. (no.mm^{-2})	y = (-0.7359*SI_5) + 26.423	1.03	8.25
Vessel %	y = (0.0637*Silt%) + 8.742	0.40	3.93
Fibre diam. (µm)	-	-	-
Cell wall thickness (µm)	y = (-0.0381*SI_5) + 3.093	0.06	2.68
Site index (SI_5)	-	-	-
Dependant variables	**Regression models - MOIST MAP**	**Residual analysis**	
		RMSE	**ARMSE%**
Density (g.cm^{-3})	-	-	-
Vessel diam. (µm)	-	-	-
Vessel freq. (no.mm^{-2})	-	-	-
Vessel %	-	-	-
Fibre diam. (µm)	y = (0.1099*SI_5) + 12.354	0.63	4.30
Cell wall thickness (µm)	y = (0.0037*MAP) + (-1.377)	0.15	7.34
Site index (SI_5)	-	-	-
Dependant variables	**Regression models - WET MAP**	**Residual analysis**	
		RMSE	**ARMSE%**
Density (g.cm^{-3})	y = (0.0092*LCI) + (-0.0081*OC%) + (-0.0025)	0.04	7.54
Vessel diam. (µm)	-	-	-
Vessel freq. (no.mm^{-2})	-	-	-
Vessel %	y = (-0.1408*LCI) + 18.516	0.68	6.82
Fibre diam. (µm)	-	-	-
Cell wall thickness (µm)	y = (0.0533*LCI) + (-0.0127*Clay%) + (-0.786)	0.20	9.33
Site index (SI_5)	y = (-0.1005*Clay%) + (0.0002*Cumulative rainfall) + 22.409	1.35	6.09

The ARMSE% for models to predict wood properties at varying levels of MAP are all <10 (Table 6.8). Site index was often a stronger predictor of variation in wood properties at ‘dry’ MAP, in most instances; however, it was not possible to explain variation in site index. At ‘wet’ MAP, LCI (which is a ratio of MAT and MAP) was the best predictor of vessel percentage, and LCI in combination with organic carbon % and clay % was used to predict density and cell wall thickness respectively. Similar patterns were not observed at varying levels of SWS (Table 6.9). The ARMSE% for models to predict wood properties at varying levels of SWS were <5% for vessel diameter and cell wall thickness at ‘low’ SWS and vessel frequency and fibre diameter at ‘medium’ SWS (Table 6.8).

Table 6.9. Regression models used to predict wood properties and site index at low, medium and high SWS levels (n=8, n=6 and n=14 respectively) and residual analysis

Dependant variables	**Regression models - LOW SWS**	**Residual analysis**	
		RMSE	**ARMSE%**
Density (g.cm^{-3})	-	-	-
Vessel diam. (μm)	y = (-0.5892*Silt%) + 127.761	3.00	2.90
Vessel freq. (no.mm^{-2})	-	-	-
Vessel %	y = (-0.1502*LCI) + 18.3246	1.10	11.15
Fibre diam. (μm)	-	-	-
Cell wall thickness (μm)	y = (-0.0334*SI_5) + 3.032	0.08	3.68
Site index ($SI_{5)}$	-	-	-
Dependant variables	**Regression models - MEDIUM SWS**	**Residual analysis**	
		RMSE	**ARMSE%**
Density (g.cm^{-3})	-	-	-
Vessel diam. (μm)	-	-	-
Vessel freq. (no.mm^{-2})	y = (-0.3485*LCI) + 32.469	0.47	3.75
Vessel %	-	-	-
Fibre diam. (μm)	y = (-0.0272*Clay%) + 15.423	0.36	2.44
Cell wall thickness (μm)	-	-	-
Site index ($SI_{5)}$	y = (0.1081*Median rainfall Jan.) + 5.784	1.18	5.66
Dependant variables	**Regression models - HIGH SWS**	**Residual analysis**	
		RMSE	**ARMSE%**
Density (g.cm^{-3})	-	-	-
Vessel diam. (μm)	-	-	-
Vessel freq. (no.mm^{-2})	y = (-1.3615*Solar radiation) + (-0.5233*SI_5) + 51.023	1.30	10.98
Vessel %	-	-	-
Fibre diam. (μm)	-	-	-
Cell wall thickness (μm)	-	-	-
Site index ($SI_{5)}$	y = (-2.5689*Solar radiation) + 74.251	2.60	12.69

6.5. Results: Linear and non-linear regression – bark-to-pith radial wood properties and cumulative measured rainfall

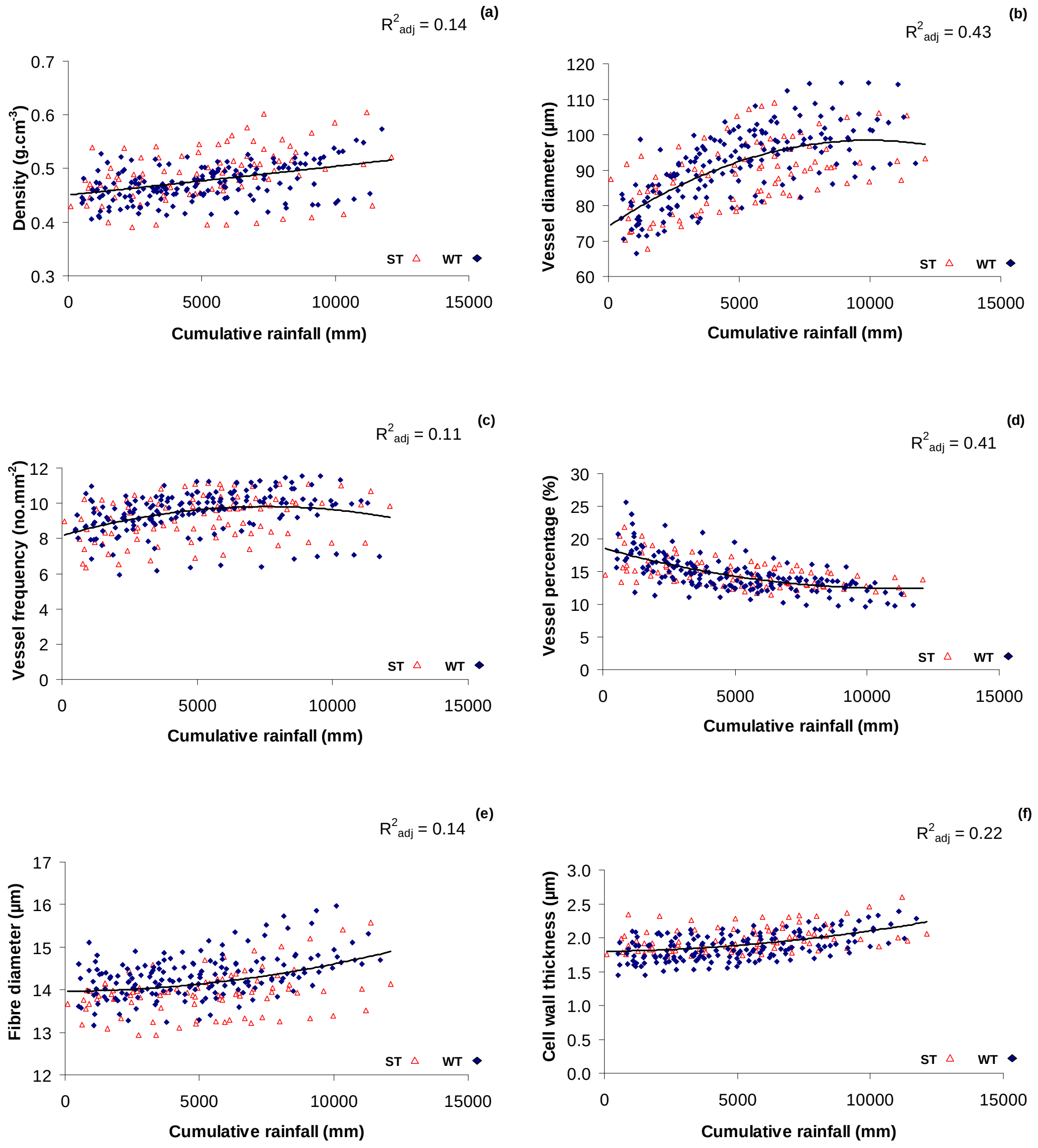
6.5.1. Model development

Paired-observations were compared between cumulative measured rainfall and average wood properties at each percentage interval using a curve estimation procedure in SPSS. Model summaries for linear and non-linear models and parameter estimates are provided in Appendix 4. The non-linear quadratic model was selected since it fit the data marginally better than the other models assessed and produced a higher R^2_{adj} for each wood property (Appendix 4).

Table 6.10. Summary of outputs from quadratic regression models to predict average wood properties versus cumulative rainfall

MODEL SUMMARY - AVERAGE WOOD PROPERTIES VS CUMULATIVE RAINFALL						
WOOD PROPERTIES	**KZN - ST and WT**		**WT**		**ST**	
	n=26		n=17		n=9	
	R^2_{adj}	**SE**	**R^2_{adj}**	**SE**	**R^2_{adj}**	**SE**
Density ($g.cm^{-3}$)	0.14	0.04	0.18	0.03	0.10	0.05
Vessel diam. (µm)	0.43	7.58	0.53	6.97	0.27	8.00
Vessel freq. ($no.mm^{-2}$)	0.11	1.14	0.12	1.10	0.10	1.21
Vessel %	0.41	1.99	0.45	2.06	0.33	1.77
Fibre diam. (µm)	0.14	0.50	0.21	0.44	0.09	0.49
Cell wall thickness (µm)	0.22	0.18	0.28	0.17	0.13	0.18
	MAP LEVEL					
WOOD PROPERTIES	**DRY**		**MOIST**		**WET**	
	n=6		n=10		n=10	
	R^2_{adj}	**SE**	**R^2_{adj}**	**SE**	**R^2_{adj}**	**SE**
Density ($g.cm^{-3}$)	0.18	0.03	0.26	0.03	0.06	0.05
Vessel diam. (µm)	0.57	6.58	0.43	6.67	0.47	7.84
Vessel freq. ($no.mm^{-2}$)	0.43	0.74	0.09	1.30	0.11	1.03
Vessel %	0.59	1.42	0.32	2.07	0.45	2.07
Fibre diam. (µm)	0.24	0.43	0.29	0.32	0.11	0.58
Cell wall thickness (µm)	0.37	0.11	0.23	0.15	0.31	0.19
	SWS LEVEL					
WOOD PROPERTIES	**LOW**		**MEDIUM**		**HIGH**	
	n=6		n=6		n=14	
	R^2_{adj}	**SE**	**R^2_{adj}**	**SE**	**R^2_{adj}**	**SE**
Density ($g.cm^{-3}$)	0.17	0.03	0.38	0.02	0.14	0.04
Vessel diam. (µm)	0.58	6.77	0.58	5.84	0.31	8.34
Vessel freq. ($no.mm^{-2}$)	0.07	1.46	0.08	1.04	0.17	1.03
Vessel %	0.69	1.36	0.42	2.25	0.30	1.90
Fibre diam. (µm)	0.27	0.46	-0.02	0.41	0.12	0.48
Cell wall thickness (µm)	0.15	0.11	0.06	0.11	0.21	0.20

The R^2_{adj} and standard errors from the quadratic models used to estimate wood properties for KZN, the warm temperate and sub-tropical regions and at each MAP and SWS level are summarized in Table 6.10. Average wood property variables were treated as dependant variables of cumulative measured rainfall.



Figures 6.3 a-f. Scatterplots of cumulative rainfall vs. average wood properties in KZN are illustrated in figures a-f. The solid line represents the fit of the quadratic equation used to describe the relationship between wood properties and cumulative rainfall; the R^2_{adj} is provided for each figure. Sub-tropical (ST) region =Δ, and the warm temperate (WT) region = ♦.

Scatterplots of cumulative rainfall versus average measured wood properties in KZN are illustrated in Figures 6.3 a-f; in each figure n= 260 paired observations which represent 26 compartments each with 10 paired observations at 10% intervals from bark-to-pith.

Vessel diameter and vessel percentage seem to be the only wood properties to to be affected, to some extent, by rainfall. A similar trend was seen at a regional level (Table 6.10 and Figures 6.3 b and d) and at individual MAP and SWS levels (Table 6.10). There was a slight increase in the R^2_{adj} for these wood properties at the dry MAP and low SWS levels compared to the R^2_{adj} for models developed for KZN. The non-linear quadratic models developed for wood density, vessel frequency, fibre diameter and cell wall thickness were weak with lower R^2_{adj} (Table 6.10). No clear trends were seen between the WT and ST regions in figures for each wood property (Figures 6.3 a-f).

6.5.2. Model validation

Validation compartments used to validate wood properties in KZN (ST and WT combined) using the non-linear regression models described in Table 6.10 were the same as those used to validate models described in section 6.4 of this chapter, with the exception of compartments B2 and D10b since a complete set of monthly rainfall data was not available for these compartments (the validation compartment list provided in Appendix 3). The non-linear regression models for KZN (ST and WT combined) (Table 6.10) were used to predict the values of the wood properties density, vessel diameter, vessel frequency, vessel percentage, fibre diameter and cell wall thickness for the validation compartments with cumulative rainfall as the independent variable.

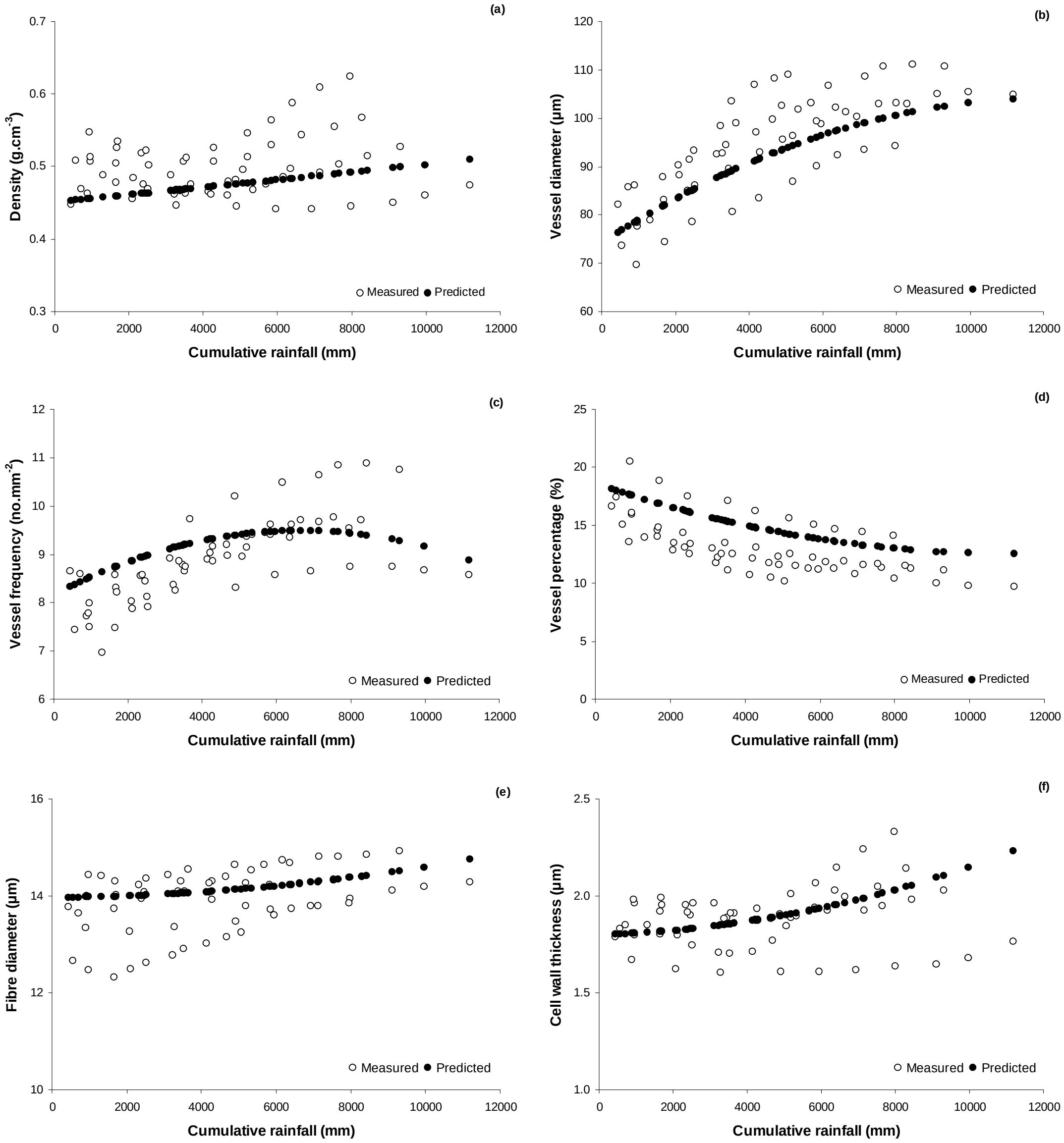
To reiterate, the objective behind averaging cumulative rainfall and wood properties across the radius was to compare and illustrate the response of each wood property to varying levels of rainfall measured for each compartment and to identify which wood property was most influenced. Based on the results from Table 6.10 and Figures 6.3 b and d, vessel diameter and vessel percentage showed a relationship to varying levels of rainfall. This trend is evident at a regional level and at individual MAP and SWS levels with only a slight increase in the R^2_{adj} at the dry MAP and low SWS levels compared to the R^2_{adj} from KZN models. In addition, models developed for wood density, vessel frequency, fibre diameter and cell wall thickness were all weak with much lower R^2_{adj} values. Therefore, since the objective of this modelling exercise was achieved and the KZN (combined ST and WT regions) model was validated using an independent dataset for validation, leave-one-out cross-validation was not conducted on the models at a regional level and at individual MAP and SWS levels.

A summary of the non-linear regression models and residual analysis from the comparison of measured and predicted wood properties in KZN (n = 60, 6 compartments with 10 observations each) is presented in Table 6.11. Measured and predicted wood properties were plotted against cumulative rainfall to compare measured and predicted wood properties (Figures 6.4 a-f).

Table 6.11. Non-linear regression models used to predict average wood properties using cumulative measured rainfall in KZN and residual analysis from the comparison of measured and predicted wood properties (n = 60)

Wood properties	**Non-linear regression models - KZN**	**Residual analysis**	
		RMSE	**ARMSE%**
Density ($g.cm^{-3}$)	$y = 2E\text{-}11x^2 + 5E\text{-}06x + 0.4506$	0.05	9.53
Vessel diam. (µm)	$y = -2E\text{-}07x^2 + 0.0049x + 74.207$	7.01	7.45
Vessel freq. ($no.mm^{-2}$)	$y = -3E\text{-}08x^2 + 0.0004x + 8.1548$	0.70	7.84
Vessel %	$y = 5E\text{-}08x^2 - 0.0011x + 18.59$	2.53	19.25
Fibre diam. (µm)	$y = 6E\text{-}09x^2 + 3E\text{-}06x + 13.965$	0.64	4.58
Cell wall thickness (µm)	$y = 3E\text{-}09x^2 + 5E\text{-}06x + 1.7983$	0.17	9.14

Non-linear regression models for vessel diameter, vessel frequency and fibre diameter predicted average wood properties reasonably well in terms of modelling the pattern of response (ARMSE% <10%) (Table 6.11). Predicted values of vessel diameter were, however, an underestimate (Figure 6.4 b), and vessel frequency and fibre diameter were often overestimated at low rainfall (Figures 6.4 c and e). Predicted values of vessel percentage were overestimated across the range of rainfall with an ARMSE% of 19.25 (Table 6.11 and Figure 6.4 d).



Figures 6.4 a-f. Comparison of measured and predicted wood properties with cumulative rainfall as the independent variable

6.6. Discussion and conclusions

Multiple linear regression and non-linear regression modelling techniques were used to develop models to predict selected basic wood properties of *E. grandis* from compartments in KwaZulu-Natal. Multiple linear regression models were developed using long term mean climatic variables extracted from the SAAAC and weighted mean wood properties and non-linear regression models were developed using bark-to-pith radial wood properties and rainfall measured during the total growth period of each compartment.

Models were initially developed for KwaZulu-Natal (KZN) (which combined the WT and ST regions), however, based on the weak R^2_{adj} statistics from multiple regression models developed to describe the response of weighted mean wood properties to environmental variables in KZN, it was concluded that a single model was not adequate to predict wood properties in KZN. For this reason, additional models were developed for individual regions (WT and ST) and at each MAP level (‘dry’, ‘moist’ and ‘wet’) and at each SWS level (‘low’, ‘medium’ and ‘high’) in the KZN dataset.

Validation of the multiple regression and non-linear regression models developed for KZN was completed using an independent data set and leave-one-out cross validation was used to validate all models at a regional level and at each MAP and SWS level. Residual analysis was used to quantify the difference between measured and predicted wood properties where the performance of the regression models was evaluated based on root-mean-square error (RMSE). RMSE was also expressed as a percentage of the mean of the measured wood property values, i.e. absolute root-mean-square error percentage (ARMSE%).

In multiple regression models developed for KZN, site index or a combination of site index and soil variables were most frequently identified as predictors of wood properties while in the WT region, models that were statistically significant included soil variables as predictors of wood properties. In the ST, only one model to predict wood properties was statistically significant, site index was selected as the best predictor of vessel frequency. Variation in site index was best explained by MAP in KZN (R^2_{adj} = 0.14), and by solar radiation in the ST region (R^2_{adj} = 0.53). Site index is a composite expression of the effects of interacting site variables on wood properties. Site index currently remains an important variable in the forestry industry (H. Kassier, Pers. Comm[21]). Relatively small changes in site index may lead to large increases in production and profitability (Wimmer *et al*., 2008).

There was more variability in terms of soil characteristics in the WT region compared to soils in the ST region which were predominantly sandy in nature. Soils in the WT region had a comparatively higher proportion of clay and silt. The organic carbon in soils was on average three times higher in the WT region than in the ST region (Naidoo *et al*., 2007). These differences in site characteristics were reflected in models developed for KZN which included site index and soil properties while variation in the WT region was best explained by soil properties.

Soil texture and soil depth play a vital role in the availability of water to the tree and is more complex than a one-dimensional comparison with MAP only (Roberts, 1994). The influence of soil characteristics, through their influence on water retention characteristics and nutrient supply, impacts on cell growth and subsequently tree growth (Watt *et al*., 2005). Levels of organic carbon affect soil structure and adsorption properties thus also affecting soil water retention properties (Roberts, 1994). The capacity of soil to store water is known to be strongly correlated to site productivity (Louw, 1999).

At ‘dry’ MAP, the R^2_{adj} of multi-linear regression models developed for the estimation of density, vessel and fibre properties were higher compared with models developed at a regional scale. Site index was a better predictor of wood properties in the dry’ MAP level, while at ‘wet’ MAP level, Lange’s climatic index (LCI), which is a ratio of MAP and MAT, was a stronger predictor of wood properties in combination with organic carbon % (to predict density) and clay % (to predict cell wall thickness). While site index was often a stronger predictor of

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wood properties in KZN and at ‘dry’ MAP, in most instances, however, it was not possible to explain variation in site index. At ‘wet’ MAP, site index was best explained by both clay% and cumulative rainfall.

In this research, MAT was used only as a good first approximation to describe broad differences between two macro zones since a drawback of this variable is that it integrates diurnal, monthly and seasonal patterns of minimum and maximum temperature (Schulze, 1997). MAP, however, was used as a basis for comparison between areas because seasonal rainfall distribution is broadly similar in the summer rainfall areas of South Africa, where major plantation forestry areas are located (Herbert, 2000). LCI, a variable that represented both MAP and MAT, was the best predictor of wood properties at ‘wet’ MAP level and together with OC% and clay %, explained variability in wood density and cell wall thickness. LCI is a useful avariable to obtain a general indication of site conditions when site specific information is lacking (du Plessis and Zwolinski, 2003).

Gava and Gonçalves (2008) reported on the effect of soil attributes on the wood quality of *Eucalyptus grandis*. These authors found that wood productivity and quality were affected by physical attributes of soil, mainly clay content (which is related to the amount of available water). Tree growth was directly associated with soil type and textural classes. Wood density did not change at different soil types, however, the total lignin content decreased as clay content increased (until about 350-400 $g.kg^{-1}$ clay) (Gava and Gonçalves, 2008).

Non-linear regression models developed using bark-to-pith radial wood properties and rainfall measured during the total growth period of each compartment revealed that vessel characteristics were more strongly influenced by rainfall than were wood density and fibre characteristics. Vessel diameter and vessel percentage showed the clearest pattern of response to varying levels of rainfall and a similar trend was seen at a regional level and at individual MAP and SWS levels. In addition, there was a slight increase in the

R^2_{adj} for these vessel properties at the ‘dry’ MAP and ‘low’ SWS levels compared to the R^2_{adj} for models developed for KZN. The non-linear quadratic models developed for wood density, vessel frequency, fibre diameter and cell wall thickness were weak with much lower R^2_{adj}. Varying levels of water availability appeared to have a greater effect on physiologically active cells (vessels) compared to that of the mechanical cells (fibres) (Bamber *et al*., 1982).

It has been well documented that for many genera and species, vessel diameter and vessel element length decreases while vessel frequency increases with decreasing water availability (Carlquist, 1975; Bamber *et al*., 1982; Malan, 1991; February *et al*., 1995, Searson *et al*., 2004; Leal *et al*., 2004; Drew and Pammenter, 2006, and Drew *et al*., 2009a). Species on dry sites need narrow, shorter vessel elements to reduce the risk of embolisms and require more vessels per unit area to provide the needed water transport, since narrow vessels provide exponentially less flow than wide vessels (Zimmerman, 1983). February *et al*. (1995) showed significant correlations between water consumed and vessel diameter of *E. grandis* and *E. grandis* x *camaldulensis* but vessel frequency was not correlated with available water. These authors suggested that eucalypts have plasticity in vessel morphology that allowed them to optimise use of plant-available water.

Searson *et al*. (2004) reported that the mean vessel lumen area of *E. grandis* was significantly reduced by water limitation, however, this was balanced by a trend of increase in vessel frequency in water-limited plants, resulting in no difference in the proportion of stem area allocated to vessels. Leal *et al*. (2004), in a study on *E. globulus*, reported that low water availability was related to more frequent and smaller vessels. Similar findings were reported by Drew and Pammenter (2006) for two eucalypt clones and by Drew *et al*. (2009a) for *E. globulus*.

Pith-to-bark variation in wood properties is a function of changing environmental and physiological factors, therefore a close relationship between wood properties and growth rate is expected (Downes *et al*., 2009), but these relationships are complex and vary widely (Zobel and van Buijtenen, 1989; Sandercock *et al*., 1995; Downes *et al*., 1997). Factors that cause variation in the different types of cells produced by trees are usually interactive, so there is rarely a single factor that controls variation. It is likely that short-term climatic extremes have a greater influence on tree growth in short rotation stands compared to average climatic conditions (Pama and Zwolinski, 2008).

In a study by Downes *et al*. (1999) where stem growth and wood production of *E. globulus* and *E. nitens* were related to environmental variables, rainfall was, to a large extent, the more influential environmental variable, however, the determining factors varied between species and throughout the growing season. Similarly in a study which compared patterns of daily stem size variation in eucalypt clones, Drew *et al*. (2009b) concluded that discrete rainfall events, through the release of drought stress, were the drivers of short-term growth responses. It is important to understand such growth responses as this intermittant growth can be expected to have an important effect on wood properties (Downes *et al*., 2000; Downes and Drew, 2008).

In this research, rainfall was the only continuously measured climatic variable that could be linked to pith-to-bark variation in wood properties since reliable temperature data were not available for the majority of compartments sampled and was therefore not reported for any compartment in this research. In addition, PSP data could not be used to identify growth rings since PSP data were not available for most compartments assessed. The modelling approach used in this research to relate measured rainfall and wood properties was, however, useful as a means of comparing and illustrating the response of wood properties to varying levels of rainfall across the radius and to identify which wood property was most influenced.

Coefficients of determination of the models developed were generally far to low to use the equations in a predictive way. The low predictive power of the models developed is a clear indication that factors other than the independent variables considered are involved. A large proportion of the variation cannot be explained in terms of the effects of the variables considered. Large differences between trees within sites are probably the most important contributing factor towards the low predictive levels found in this research.

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Appendix 3. Brief description of compartments sampled in the warm temperate and sub-tropical region of KwaZulu-Natal which were used to develop and validate models.

Region		Comp. name	MAT (^{o}C)	MAP (mm)	SWS (mm)	MAP level	SWS level	Age (years)
Model development	Warm temperate (WT) region	A5	17	811	91	dry	low	9.8
		B14	17	866	100	dry	low	9.8
		K8	17	792	100	dry	low	10.5
		C017	16	974	136	moist	low	11.7
		F9	17	927	136	moist	low	10.9
		D22	17	1079	136	wet	low	11.2
		H75a	18	1106	136	wet	low	10.3
		W80a	17	1071	136	wet	low	11.0
		A26	17	961	187	moist	medium	12.5
		A3	17	880	187	moist	medium	11.9
		D05	16	919	160	moist	medium	7.5
		A53d	18	1051	187	wet	medium	5.6
		C4	17	996	187	wet	medium	7.4
		D105	17	1020	187	wet	medium	8.0
		A4	17	948	309	moist	high	9.9
		F031	17	901	260	moist	high	7.6
		A35c	16	980	309	wet	high	10.8
		E17	16	1067	257	wet	high	12.6
		H030	17	995	309	wet	high	7.4

Region		Comp. name	MAT (^{o}C)	MAP (mm)	SWS (mm)	MAP level	SWS level	Age (years)
Model development	Sub-tropical (ST) region	D14	21	908	257	dry	high	8.3
		E12	21	862	257	dry	high	9.2
		G2	21	917	257	dry	high	9.6
		A11a	21	989	257	moist	high	9.4
		A44	21	1008	257	moist	high	9.0
		D7	21	985	257	moist	high	10.1
		B48	21	1118	257	wet	high	8.6
		E29	21	1467	257	wet	high	8.7
		G17	21	1130	257	wet	high	8.9

Region		Comp. name	MAT (^{o}C)	MAP (mm)	SWS (mm)	MAP level	SWS level	Age (years)
Model validation KZN (WT and ST combined)	WT	K12	16	908	175	moist	medium	8.6
		F5a	16	862	257	moist	high	9.2
		A26a	17	917	94	dry	low	11.6
		F119	17	989	260	wet	high	10.3
	ST	A49	19	1008	94	dry	low	6.6
		B2	19	985	136	dry	low	9.3
		D10b	19	1118	136	moist	low	12.9
		E14	21	1467	257	wet	high	8.7

Appendix 4. Model summaries and parameter estimates for each wood property using the curve estimation procedure in SPSS (V15). The independent variable used was cumulative rainfall and the dependant variables were average wood properties

Dependent Variable: Density (g.cm^{-3})								
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Linear	0.15	44.73	1	258	1.4E-10	0.450	0.000	
Logarithmic	0.13	36.97	1	258	4.3E-09	0.324	0.018	
Quadratic	0.15	22.28	2	257	1.2E-09	0.451	0.000	1.72E-11
Power	0.12	35.79	1	258	7.3E-09	0.347	0.038	
Exponential	0.14	42.10	1	258	4.4E-10	0.450	0.000	

Dependent Variable: Vessel percentage (%)								
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Linear	0.38	159.89	1	258	7.6E-29	17.502	-0.001	
Logarithmic	0.38	160.85	1	258	5.7E-29	32.138	-2.104	
Quadratic	0.41	89.66	2	257	2.9E-30	18.590	-0.001	5.03E-08
Power	0.38	157.83	1	258	1.5E-28	44.977	-0.137	
Exponential	0.40	169.56	1	258	3.9E-30	17.457	0.000	

Dependent Variable: Vessel diameter (μm)								
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Linear	0.39	162.03	1	258	3.9E-29	79.495	0.002	
Logarithmic	0.39	165.90	1	258	1.2E-29	22.180	8.232	
Quadratic	0.43	97.08	2	257	3.9E-32	74.207	0.005	-2.45E-07
Power	0.40	173.55	1	258	1.2E-30	41.410	0.093	
Exponential	0.39	164.24	1	258	2.0E-29	79.471	0.000	

Dependent Variable: Fibre diameter (μm)								
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Linear	0.13	40.03	1	258	1.1E-09	13.833	0.000	
Logarithmic	0.10	27.51	1	258	3.3E-07	12.361	0.219	
Quadratic	0.14	21.61	2	257	2.1E-09	13.965	0.000	6.09E-09
Power	0.09	26.98	1	258	4.2E-07	12.488	0.015	
Exponential	0.13	38.90	1	258	1.8E-09	13.833	0.000	

Dependent Variable: Vessel frequency (no.mm^{-2})								
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Linear	0.08	22.17	1	258	4.1E-06	8.783	0.000	
Logarithmic	0.10	27.78	1	258	2.9E-07	5.248	0.499	
Quadratic	0.12	17.80	2	257	5.8E-08	8.155	0.000	-2.90E-08
Power	0.09	24.53	1	258	1.3E-06	5.966	0.054	
Exponential	0.07	19.07	1	258	1.8E-05	8.726	0.000	

Dependent Variable: Cell wall thickness (μm)								
Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Linear	0.21	70.14	1	258	3.6E-15	1.743	0.000	
Logarithmic	0.15	45.48	1	258	1.0E-10	1.059	0.102	
Quadratic	0.23	37.54	2	257	5.0E-15	1.798	0.000	2.58E-09
Power	0.15	46.39	1	258	6.8E-11	1.216	0.054	
Exponential	0.21	69.68	1	258	4.3E-15	1.742	0.000	

CHAPTER SEVEN

SUMMARY AND RECOMMENDATIONS FOR FURTHER RESEARCH

7.1. Introduction

The environment to which a tree is exposed is an integrated complex of climatic and topographical factors as well as a number of soil-related and biological factors (Landsberg and Gower, 1997; Louw and Scholes, 2002). Trees entering pulp and paper mills come from trees growing in geographically diverse areas, and are exposed to widely varying conditions during their lifetime (Jacobs and Drew, 2002). The aim of capturing trends concerning fibres, pulp and paper quality is to provide forest decision makers with the knowledge necessary to make informative decisions (Megown *et al*., 2000). In industrial terms, it is important to understand and quantify the wood characteristics of the material being processed so that the parameters of the process can be adjusted in order to obtain the best results in terms of processing efficiency and product performance. The resource needs to be stratified based on factors affecting the resource with the goal of optimizing volume growth and optimizing wood fibre as it benefits the product, ultimately deriving a cost benefit (Megown *et al*., 2000).

In South Africa, *Eucalyptus grandis,* grown predominantly for pulp and paper production, is planted across a wide range of site conditions of varying productivity, with the required mean annual precipitation (MAP) and mean annual temperature (MAT) for *E. grandis* being above 900 mm and 16°C respectively (Schulze, 1997, Herbert, 2000). Extensive research on the *Eucalyptus grandis* resource in South Africa included studies by Taylor (1973), du Plooy (1980), Malan (1991, 1993), Malan and Hoon (1992), Malan *et al*. (1994), Malan and Verryn (1996), Clarke *et al*. (1999), Megown *et al*. (2000), Grzeskowiak and Turner (2000), Sefara and Turner (2001), Little *et al*. (2003) and Venter (2003). However, in these studies, climatic factors were rarely included as independent variables and often, factors such as age, genetics or silviculture confounded the results. Also, the sizes of wood property datasets were limited due to the time-consuming and expensive nature of wood property assessments.

This research intended to contribute to our understanding of wood properties by assessing the effects of climatic and site variables on wood properties of *Eucalyptus grandis* planted throughout the plantation forestry regions in South Africa.

7.2. Summary of research

The first aim of this research was to quantify and model the effects of specific environmental variables on the wood quality of *E. grandis* in the warm temperate and sub-tropical forestry regions in South Africa. The second aim of this research was to determine whether radial density profiles of *E. grandis* could be used in conjunction with annual assessments of diameter growth to identify annual growth ring boundaries in *E. grandis*. This research was needed since the growth ring boundaries of this species are not well defined and as a result, it is not possible to compare wood properties at specific ages of growth.

The objectives of this research were as follows: Each objective, listed below, was addressed separately in Chapters 3-6 of this thesis.

i. Develop an experimental design which will define regions to capture the wide range of sites and environmental conditions under which *E. grandis* is planted
ii. Develop a technique to identify annual growth ring boundaries in *E. grandis*
iii. Quantify and evaluate basic wood properties of *E. grandis* from trees grown in compartments at varying MAP x SWS combinations
iv. Develop models to predict selected basic wood properties of *E. grandis* grown at varying levels of water availability

A brief summary of the approaches used and key results and conclusions for each objective are presented below.

7.2.1. Develop an experimental design

The main objectives of this research were to quantify and evaulate wood properties of *E. grandis* in the plantation forestry regions in South Africa and to develop models to predict selected basic wood properties to explain variation in these properties.

To achieve these objectives, an appropriate experimental design was needed which captured the wide range of sites and environmental conditions under which *E. grandis* is planted. In the past, such a design would be severely limited by the expense of intensive sampling and laboratory work. However, the use of non-destructive rapid screening techniques to evaluate wood properties made it possible to work with a wide variety of sites both time- and cost-efficiently.

The warm temperate (WT) and sub-tropical (ST) macro zones, from a site classification system developed by the Institute for Commercial Forestry Research (ICFR) (Smith *et al*., 2005), were used as a basis for the experimental design of this research. Two unique regions, which differed from each other in terms of mean annual temperature (MAT) (warm temperate - 16.1-19°C and sub-tropical - 19.1-22°C) were identified.

Categories within each macro zone were modified from the original classes defined in the ICFR classification system. Instead of MAT and MAP categories within each macro-zone, the WT and the ST macro zones were each divided into nine combinations on the basis of three mean annual precipitation (MAP) classes (dry, moist and wet) and three soil water storage (SWS) capacities (low, medium and high) to achieve varying levels of water availability among blocks within each macro zone.

Since the criteria used to define the sub-divisions within each macro zone in this research differ from the criteria used in the ICFR classification system, the term ‘region’ was used thereafter instead of the term ‘macro zone’ when referring to either the WT or ST macro zones. In both the WT and ST regions, ‘new’ thresholds for dry, moist and wet values for MAP were calculated using the average of the threshold values that corresponded to the average temperature range for each macro zone in the ICFR system. The three levels of SWS took into account the variability in the range of soil forms that were present within and among regions.

7.2.2. Develop a technique to identify annual growth ring boundaries in *E. grandis*

Eucalyptus grandis, one of the most important commercial hardwood species in South Africa, is a tropical species that does not have well defined growth rings because of a lack of strong seasonal climatic variation. The light and dark bands visible on the cross-section of the wood of *E. grandis* do not always correspond with the growing season which makes it difficult to resolve wood property data into annual increments.

A method was developed to identify annual growth ring boundaries on wood density profiles of *E. grandis* into annual rings using annual measurements of diameter at breast height (DBH) from permanent sample plot (PSP) datasets. Mean radial increment (MRI) was calculated at a compartment-level, expressed as a percentage, and used to predict radial increment (RI) at an individual tree level. Predicted RI values (mm) for each tree were expressed as cumulative distances from the bark end and superimposed onto their respective density profiles to separate growth rings on the density profiles into annual rings (or annual increments). Predicted RI corresponded reasonably well with latewood density peaks, and although the separation points did not always lie directly on the maximum value of each latewood peak, these separation points were considered a reliable guide to define annual increments.

It was found that the density peaks formed especially in the outer layers of the stem corresponded to annual growth increment. This enabled the identification of wood formed after eight years of growth. This wood was excluded to enable the comparison of wood properties of relatively even-aged trees. This conclusion was used as the basis of a method to standardise the age of wood properties of trees from compartments sampled in this research that varied in age. The effect of age on wood properties was thereby minimised as a confounding variable in the assessment of the effect of water availability on wood properties.

7.2.3. Quantify and evaluate selected basic wood properties of *E. grandis* from trees grown in compartments at varying MAP x SWS combinations

Rapid screening tools were used to characterize the wood properties from *E. grandis* sampled from compartments grown in the ST and WT regions of South Africa. Gamma-ray densitometry, image analysis techniques and NIR-spectroscopy were used to assess wood density, vessel and fibre characteristics, and NIR-predicted percentage cellulose and lignin of breast-height core samples from trees in compartments representing varying levels of water availability. Radial maps illustrating pith to bark variation in wood properties and weighted mean values of material were assessed for each region in terms of responses to soil characteristics and water availability, and their effects on wood quality. The method used to standardize the age of wood properties was described and evaluated.

In the ST region, vessel characteristics were significantly correlated with site variables, whereas in the WT region, fibre characteristics had stronger correlations with site variables. Site index was strongly correlated with vessel frequency, NIR-predicted cellulose and lignin in the ST region ($r = > 0.7$). In the WT region, correlations between site index and wood properties were weaker ($r = < 0.6$). Of the soil factors considered, those that influenced wood properties were organic carbon and silt in both regions.

Compartments sampled from areas with higher MAP in the ST region usually had lower density wood with larger vessel and fibre diameters, thinner cell walls, higher cellulose percentages, lower lignin percentages and fewer vessels per unit area. Results from the WT region revealed similar results with wood from areas with higher MAP having larger fibre diameters, higher cellulose percentages, lower lignin percentages and lower vessel frequencies. Density, cell wall thickness and vessel diameter did not show as clear trends. In general, wood properties in the ST region showed more marked responses to varying levels of MAP than wood properties measured in the WT region. The response of wood properties to water availability in the ST region was thought to have been amplified by higher temperatures since the pattern observed for sum of rainfall over the total period of growth for compartments sampled was similar in both regions.

7.2.4. Develop models to predict selected basic wood properties of *E. grandis* grown at varying levels of water availability

Multiple linear regression and non-linear regression modelling techniques were used to develop models to predict selected basic wood properties of *E. grandis* from compartments in KwaZulu-Natal (KZN). Multiple linear regression models were developed using long term mean climatic variables and weighted mean wood properties, and non-linear regression models were developed using bark-to-pith radial wood properties and rainfall measured during the total growth period of each compartment. Models were developed for KZN (which combined the WT and ST regions), individual regions (WT and ST), and at each MAP level (‘dry’, ‘moist’ and ‘wet’) and at each SWS level (‘low’, ‘medium’ and ‘high’) in the KZN dataset. Models were validated using an independent data set and leave-one-out cross validation.

In multiple regression models developed for KZN, site index or a combination of site index and soil variables were most frequently identified as predictors of wood properties while in the warm temperate region, models that were statistically significant included soil variables as predictors of wood properties. In the ST region, only one model to predict wood properties was statistically significant, where site index was the best predictor of vessel frequency. Variation in site index was explained by MAP in KZN with a weak R^2_{adj} of 0.14, and by solar radiation in the ST region with a stronger R^2_{adj} of 0.53. At 'dry' MAP, it was not possible to explain variation in site index, however, at 'wet' MAP site index was best explained by a combination of clay% and cumulative rainfall.

Multi-linear regression models developed for the estimation of density, vessel and fibre properties at 'dry' MAP (lower water availability) had much higher R^2_{adj} compared to models developed at a regional level. Site index was a better predictor of wood properties in the dry' MAP level, while at 'wet' MAP level, Lange's climatic index (LCI), a variable that represented both MAP and MAT, in combination with percentage organic carbon (OC%) and percentage clay (clay%), explained variability in wood density and cell wall thickness.

Non-linear regression models relating bark-to-pith radial wood properties to measured rainfall revealed that vessel characteristics were more strongly influenced by rainfall compared to wood density and fibre characteristics. Varying levels of water availability appeared to have a greater effect on physiologically active cells (vessels) compared with that of the mechanical cells (fibres). Vessel diameter and vessel percentage showed the clearest pattern of response to varying levels of rainfall and a similar trend was seen at a regional level and at individual MAP and SWS levels. Models improved slightly at 'dry' MAP and at 'low' SWS. The non-linear regression models developed for wood density, vessel frequency, fibre diameter and cell wall thickness were weak with low R^2_{adj}.

A primary concern in wood property studies is trying to understand the extent to which environmental factors influence wood properties to provide recommendations on management strategies for improved timber optimisation and allocating specific sites to specific fibre markets (Jacobs and Drew, 2002). The models developed in this research could not be used in a predictive way because the coefficients of determination for most of the models were generally far to low. The low predictive power of the models developed is a clear indication that factors other than the independent variables considered are involved. A large proportion of the variation cannot be explained in terms of the effects of the variables considered.

A study by Sardinah (1974) which assessed variation in density and some structural features of *E. saligna* SM from Angola noted that only a small proportion of the between site variation in wood density was accounted for by variables related to rainfall, mean annual temperature and soil. Sardinah (1974) concluded that the prediction of wood properties for any set of site conditions is not feasible because of the large proportion of variation that could not be accounted for by models. A similar conclusion can be drawn from the findings described in this thesis. Models can, however, be made more accurate by increasing the level of replication within compartments and including additional sites. The number of trees sampled per compartment (n=5) in this research, sampled in a random manner and sampled at breast height only, was inadequate for getting a full picture and significance of the various factors controlling wood property and their variation.

7.3. Recommendations for further research

A proposed extension of this research is to bridge the gap in understanding between the wood anatomical properties of the raw material and the end product by investigating the effect of environmental factors on pulp and paper strength properties. The way forward, with reference to conclusions drawn in this research, is to assess pulp and paper strength properties from selected compartments used in this research. The reasoning behind this recommendation is that differences in productivity, as a result of site differences and water availability, would be reflected in wood properties and consequently, the properties of the wood pulp and the handsheets formed from that pulp (Clarke, *et al*., 1999; Wimmer *et al*., 2008).

Many studies have assessed the relationship between wood properties and pulp strength properties (du Plooy, 1980; Beadle *et* al., 1996; Clarke, *et al*., 1999, Grzeskowiak *et al*., 2000; Drew *et al*., 2001; Sefara *et al*., 2001; Turner *et* *al*., 2001; Wimmer *et al*., 2002; Venter, 2003; Wimmer, 2008). Beadle *et al*. (1996) showed that the pulp yield of *E. globulus* and *E. nitens* decreased with increasing altitude. Clarke *et al*. (1999) reported significant differences in growth, wood and pulp properties of eucalypt species between sites varying in temperature and rainfall where higher site quality yielded a larger volume of trees with lower wood density, lower levels of extractives and higher pulp yields. Sefara *et al*. (2001) assessed the influence of site and age on the rate of delignification (ROD) of *E. grandis* seedling material and concluded that older material from good quality sites (site index between 20 and 25) needed shorter cooking times compared to younger material from poorer quality sites.

The effects of environmental/site variables were included in some of the above studies to explain the relationships between properties of the raw material and selected pulp properties. However, detailed information on the relationships between wood and handsheet properties was often limited and the effect of environmental factors on paper strength properties was not included. It is necessary to separate direct and indirect effects of wood characteristics on pulp and handsheet properties to avoid inconclusive results being drawn from simple relationships (Wimmer *et al*., 2002).

For example, trees growing on a good quality site may have higher pulp yield, lower density and the best productivity which translates into a stronger paper. However, if printing or writing paper is the desired end product, specific optical properties, which include high brightness and opacity, are required. These requirements may be achieved using wood from a site with lower productivity (Wimmer *et al*., 2008).

The aim of further research in this field is to assess whether differences in site are reflected in the end product and develop models to predict the direct effects of site on pulp and paper properties. A pilot investigation would involve re-sampling compartments selected from extremes in the experimental design (very ‘dry’ sites and very ‘wet’ sites) and assessing the effects of the environment on hand-sheet properties. Pulp and handsheet properties can be integrated as variables in the models developed as part of this research. Establishing exploitable relationships between wood properties and the end-product add value to efforts to improve wood properties (Downes and Drew, 2008).

The ability to predict wood characteristics and pulp strength properties is important in terms of enhancing the current tools with which to rapidly assess the raw material and meet various quality requirements in forestry research with more accuracy. Outcomes from the recommended research will benefit the foresters and wood technologists by enhancing decision-making tools for the forestry industry. An increased understanding of variation in wood quality and the associated effects on the end-product will support foresters in their endeavours to produce a better quality and higher utilizable timber output from the limited available land resources.

7.4. References

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