A fibre optimisation index developed from a material investigation of *Eucalyptus grandis* for the Kraft pulping process

by
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Abstract

A primary reason for the existence of the forest industry is to provide a renewable and natural resource for much needed timber and fibre products. Substantial improvements in management practices are required to increase forest volume and pulp yields for increased demand. *Eucalyptus grandis* clonal trees of age 6.75 years, grown in a Nelder 1a spacing experiment, were sampled and analysed to describe the effect of planting density on i) growth and yield, ii) wood properties and iii) pulp and paper quality. The main objective was to populate a fibre productivity index (FPI) which would be suitable from technical and economical perspectives.

A material study was conducted on the wood and in addition, two methods were developed to further describe the variability of the forest resource to i) separate growth rings by means of wood density peaks from gamma-ray densitometry and ii) calibrate near infrared (NIR) prediction models. The results indicated that planting density did not influence the variability of wood density but mechanisms affecting available soil water are important. NIR prediction models were developed to rapidly and reliably assess wood properties on a non-destructive basis. The validation models for wood density, total pulp yield, kappa number and insoluble lignin returned high predictive ability. When applied to predict chemical properties from an independent data set, the outcomes were accurate in comparison with measured data. Growth and yield functions were developed for tree survival, dominant height and basal area. They accurately predicted outcomes as demonstrated by the goodness of fit and their logical behaviour tested over the range of planting densities.

When the most extreme stand density treatments, 6809 and 275 trees per hectare (TPH) were evaluated for wood and fibre properties, the larger trees grown at 275 TPH, produced wood of better quality for pulp processing; basic wood density at 0.520 g cm^{-3} (21 % higher), fibre cell wall thickness at 2.10 µm (18.6 % thicker) and fibre lumen diameter at 8.16 µm (9.9 % lower) than for 6809 TPH. Intra-specific tree variability of wood and product properties increased from diameter at breast height (DBH) to 35 % and then decreased to 65 % of tree height. The effect of planting density was carried throughout the product value chain up to the paper manufacturing phase. Paper with higher bulk mass and thickness and more porous sheets is most likely to be made from lower planting densities (801 and 275 TPH), and stronger, smoother and denser paper is most likely to be made with trees at high planting densities (6809 or 2336 TPH).

From the growth and yield and materials investigation, technical indicators identified to populate a fibre productivity index were: i) **mean annual increment** (MAI) as a forestry growth indicator, ii) **wood density,** summarising the composition of wood and, iii) **pulp yield**, the indicator of the amount of fibre processed through a chemical cooking process. Delivered **cost of timber** to the mill, was identified as the most suitable economic indicator which included fixed costs elements, variable costs and aspects of mill efficiency.

The product of the technical and economic indicators concluded in a profit/loss scenario of producing 1 ton of pulp was deemed the best index to describe the entire and integrated value chain. This index, termed the Fibre Productivity Index (FPI) at the Mill, denoted as **FPMill**, is an integrated index that is easy to interpret in the realms of a forestry - pulp manufacturing, and can be used for differential pricing of timber for wood quality.

Opsomming

'n Primêre rede vir die bestaan van die bosbouindustrie is om ‘n hernubare, natuurlike hulpbron vir hout en vesel te voorsien. Aansienlike verbeterings in bestuurspraktyke is nodig om die houtvolume en pulpopbrengste vir die toename in aanvraag te verhoog. *Eucalyptus grandis* klonale bome met ‘n ouderdom van 6.75 jaar en wat in 'n Nelder 1a spasiëring eksperiment gegroei is, is versamel en ontleed om die effek van opstandsdigtheid te beskryf op a) groei en opbrengs, b) houteienskappe en c) pulp- en papiergehalte. Die hoofdoel was om 'n veselproduktiwiteitsindeks (FPI), wat geskik sou wees in terme van tegniese en ekonomiese perspektiewe, te ontwikkel.

'n Materiaalkundigestudie is op hout uitgevoer. Twee metodes is ontwikkel om die variasie in hout as natuurlike hulpbron te beskryf deur a) vroeëhout- en laathoutdigtheidspieke deur gammastraal-densitometrie van mekaar te skei en variasie in groeiringe te beskryf en b) daarstelling van naby-infrarooispektroskopiese (NIR) voorspellingsmodelle. Die resultate het aangedui dat aanplantingsdigtheid nie ‘n invloed het op die variasie van houtdigtheid nie, maar dat meganismes wat beskikbare grondwater bepaal, belangrik is. NIR-voorspellingsmodelle is ontwikkel om houteienskappe op 'n nie-destruktiewe manier betroubaar te kan evalueer. Die validasiemodelle vir houtdigtheid, pulpopbrengs, kappanommer en onoplosbare lignien, openbaar akkurate voorspellingsvermoë. Wanneer dit toegepas word om chemiese eienskappe van 'n onafhanklike datastel te voorspel, was die resultate akkuraat in vergelyking met gemete data. Groei- en opbrengsfunksies is ontwikkel vir mortaliteit, dominante boomhoogte en basale area. Akkurate voorspellingsuitkomste is verkry soos gedemonstreer deur die logiese gedrag wat getoets is vir alle plantdigthede.

Toe die mees ekstreme opstansdigtheidbehandelings vir hul hout- en veseleienskappe geëvalueer is, was die hout van die groter bome, teen 275 stamme per hektaar (SPH), van beter gehalte. Dit was veral prominent vir houtdigtheid van 0.520 g cm^{-3} (21 % hoër), veselselwanddikte van 2.10 µm (18.6 % dikker) en vesellumendeursnit van 8.16 µm (9.9 % laer) as by die hoër (6809) SPH. Intra-spesifieke boomvariasie van hout- en produkeienskappe het toegeneem van deursnee op borshoogte (DBH) tot 35 % en dan weer afgeneem tot 65 % van die boomhoogte. Die effek van plantdigtheid is regdeur die produkwaardeketting tot by die papiervervaardigingstadium sigbaar. Papier met hoër basismassa en dikte, en meer poreuse papiervelle kan meer waarskynlik van laer aanplantdigtheid (801 en 275 TPH) bome gemaak kan word. Papier wat sterker, gladder en digter is, kan waarskynlik gemaak word van hout van bome teen hoë aanplantdigthede (6809 of 2336 SPH).

Die veselproduktiwiteitindeks wat ontwikkel is uit die materiaalondersoek en tegniese aanwysers wat geïdentifiseer is sluit in i) **gemiddelde jaarlikse aanwas**, as 'n bosbou groei-indikator, ii) **houtdigtheid**, wat ‘n opsomming van die samestelling van hout is, en iii) **pulpopbrengs;** die aanduiding van die hoeveelheid vesel verwerk deur 'n chemiese verpulpingsproses. Gelewerde **koste**

van hout by die pulpmeul is geïdentifiseer as die mees geskikte ekonomiese aanwyser wat vaste kosteelemente, veranderlike koste en aspekte van die meul se doeltreffendheid insluit.

Die produk van die tegniese en ekonomiese aanwysers is saamgevat in 'n wins / verlies opsie vir die vervaardiging van 1 ton pulp, en is beskou as die mees geskikte indeks om die geïntegreerde waardeketting te beskryf. Dié indeks, die sogenaamde Vesel Produktiwiteitsindeks (VPI) by die Pulpmeul, aangedui as **VPMeul**, is 'n geïntegreerde indeks wat maklik is om te interpreteer in 'n bosbou - pulpvervaardigingsopset, en kan gebruik word in die differensiële prysbepaling van hout waarby die kwaliteit in ag geneem word.

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Psalm 37. 3Trust in the Lord and do good; dwell in the land and enjoy safe pasture, 4Take delight in the Lord, and he will give you the desires of your heart (NIV).

Psalm 37. 3Vertrou liewer op die Here en doen wat goed is, woon en werk rustig voort,4 Vind jou vreugde in die Here, en Hy sal jou gee wat jou hart begeer (Die Bybel, 1983).

CONTENT OF THESIS:

List of Abbreviations

Constants/ Concepts

CCT	Correlated Curve Trend
H-factor	Energy spent on pulping
HPLC	High Performance Liquid chromatography
Kappa no.	Residual lignin
Kraft	Chemical Pulping
NIR	Near infrared

Variables

β_0, β_1, $\beta_{2..n}$	Parameters to be estimated
T_i	i^{th} - Tree
TPH	Trees per hectare
TPH_0	Planting density

Variables with units

BA	Basal Area per hectare	[m^2 ha^{-1}]
CSA	Cross Sectional Area	[μm^2]
CWT	Cell Wall Thickness	[µm]
D	Basic Density (at Green Volume)	[kg m^{-3}]
DBH	Diameter breast height *c*.1.3 m	[cm]
D_q	Quadratic mean diameter	[cm]
FC	Fibre Coarseness	[mg $100m^{-1}$]
HD	Dominant height	[m]
H_q	Mean tree height	[m]
M	Mass	[g]
MAI	Mean Annual Increment	[m^3 ha^{-1} yr^{-1}]
MAP	Mean Annual Precipitation	[mm]
MAT	Mean Annual Temperature	[^oC]
MRI	Mean Radial Increment	[mm]
PY (TPY)	Total Pulp Yield	[%]
RBH	Radius at Breast Height	[mm]
EAr	Residual Effective Alkali	[g_{NaOH} ml^{-1}]
RH	Relative Humidity	[%]
RI	Radial Increment	[mm]
V	Green Volume	[cm^3]
Vol_{ib}	Stand level tree volume inside bark	[m^3 ha^{-1}]
VD	Vessel Element Diameter	[µm]
VF	Vessel Frequency	[no μm^{-2}]
VP	Vessel Percentage	[%]
WD	Wood Density (*air dry*)	[g cm^{-3}]

Elements

NaOH	Sodium hydroxide
Na_2S	Sodium sulphide
Fe^{55}	Iron Isotope

Statistical terms

ANOVA	Analysis of Variance
$\overline{B}$	Mean Bias
CV	Coefficient of Variation
CVA	Canonical Variate Analysis
Factors	Number of PCA latent variables
MSE	Mean Square Error
PCA	Principal Component Analysis
PLS	Partial Least Squares
RCB	Randomized Complete Block
R^2	R-square; coefficient of determination
$R^2_{cal.}$	R-square of calibration data
$R^2_{val.}$	R-square of validation data
RMSEC	Root mean square error of calibration
RMSEP	Root mean square error of prediction
RPD	Residual Predictive Deviation
SD	Standard Deviation
TSE	Total Square Error
μ	Overall Mean
WFL	Weighted Fibre Length (weight weighted)
WMD	Weighted Mean Disc value
WMT	Weighted Mean Tree value

CHAPTER 1 : Introduction and objectives of the Study

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1.1 INTRODUCTION

Principally to the existence of the forest industry is the provision of a renewable and natural resource for much needed timber and fibre products. The demand on these resources will keep on escalating as economies of the world keep on growing and hence the overall world demand for timber and other forest products increases. As pressure to produce more wood increases with limited land, water and financial resources, the forest industry is faced with the challenge of sustaining its socio-economic and environmental viability and competitiveness through improved yields and reduced costs while at the same time produce timber of acceptable quality. Under such conditions, the importance to improve the quality of wood produced from plantations cannot be over-emphasised. Numerous benefits of improved wood quality would accrue from site-specifically managed forests, reduced wastage of wood and increased value recovery at processing industries - thus ultimately improving the economic returns and reducing the pressure on the forest.

Quality has been defined as the totality of characteristics of a product or service that bear on its ability to meet stated or implied needs (Jozsa and Middleton 1994). Wood quality therefore can only be defined with a particular end use in mind – such as pulp and paper products, wood based composite boards or timber for structural and construction purposes. Each product requires specific standards of wood quality that impact on its integrity to meet service requirements. For example, wood which is not uniform in a property such as density lowers the pulp yield and makes it very difficult to produce pulp and paper with consistent good quality and strength (Jozsa and Middleton 1994). During pulp and paper manufacturing, many aspects such as pulp yield, consumption of cooking liquor, and potential for bleaching, are dependent on the chemical composition of wood, which is determined by the relative proportions of cellulose, lignin, hemicelluloses and extractives. Furthermore, the physical attributes of fibres, such as fibre length, cell wall thickness and diameter are major determinants of pulp and paper qualities including brightness, opacity, absorption, light scattering, tear, tensile and burst strength. Therefore, wood quality is of critical importance to the wood products industry.

It is widely known that wood quality is influenced by three major factors - genetic, environmental and management factors. The environmental factors include soil, geology, climate and topography; and a forest site is defined in terms of its homogeneity with respect to these factors (Louw and Scholes 2002). A classification of such forest units with homogeneous conditions of mean annual precipitation and mean annual temperatures, as described by Smit et al. (2005), is essential for a study of wood quality versus forest site factors.

1.2 EUCALYPT PRODUCTION IN SOUTH AFRICA

As a result of its economic importance, the genus *Eucalyptus* is one of the most widely cultivated hardwood genera in tropical and subtropical regions of the world. Eucalypt plantations occur over a wide range of sites of varying productive potential. The success of this genus can be attributed to its adaptability to a variety of climatic and soil 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 and Geraldi 2004, Clarke 2008).

The total commercial timber plantation area in South Africa (SA) in 2006/2007 was 1,266,194 hectares, of which hardwoods (*Eucalyptus* spp.) were *c.* 477,704 ha. (FSA 2007). In 2009, *Eucalyptus* plantations produced 6.3 million tonnes (59.7%) of all pulp wood delivered, while *Pinus* spp. (3.1 million tonnes) and *Acacia mearnsii* (1.1 million tonnes) made up the remaining South African timber production (FSA 2007). *Eucalyptus* spp. are planted most extensively in KwaZulu-Natal (KZN) and Mpumalanga (MPU), where 57.8% and 33.8% of *Eucalyptus* plantations occur respectively (FSA 2007). Most of the eucalypts grown on the subtropical Zululand Coastal Plains of KZN are for pulp and paper production (Swain and Gardner 2003). The dominant hybrids are *E. grandis* x *E. urophylla* or *E. grandis* x *E. camaldulensis* in the sub-tropical zones while *E. grandis* x *E. nitens* are pre-dominant in the cooler temperate zones.

1.3 GROWTH AND YIELD

The economical importance of *Eucalyptus* and suitability of its wood for various products, necessitates further investigation into the variability of the resource, given the genetic make-up and forest management options. A suitable way to analyse management options is to establish the crop at a series of planting densities (du Toit 2010). This option will be investigated further in this research study.

In contrast with the larger Randomized Complete Blocks (RCB) design, used by O'Connor (1935), Marsh (1957), Bredenkamp (1990), Coetzee (1994), Coetzee et al. (1996), the Nelder design which was first described by Nelder (1962) is a compact systematic experimental design based on single tree plots. The design is known to be suitable for plantation spacing experiments and the statistical analysis is conducted accordingly (Mark 1983). The Nelder 1a experimental design was selected to manipulate resources to produce a wood resource of variable constitution, mainly of juvenile composition, for the study of its pulp and paper properties. The design comprises of single tree plots in which the available growing space or rectangularity, or both, is varied in a continuous and systematic way in the experiment. The experimental lay-out for the study described here was a full circle design known as the 1a-variant in which the rectangularity was kept constant. The area per plant increases from the centre to the outside and only the most inner and outer tree circles acted as guard rows (Nelder 1962). According to (Mark 1983) it is uncommon to conduct an analysis of variance to the data as the layout is systematic and not random. However, in contrast, it was stated by Nelder (1962) that if the site is reasonably uniform and therefore the reaction to site characteristics also regarded as uniform, the experimental errors are regarded as random. In support of this observation of Nelder (1962), it was shown by Hummel (2000) that due to the large number of treatments in the design, regression analysis, whereby an dependent variable (height, diameter) is regressed with an independent variable (stand density level), it is deemed suitable for analysing the Nelder 1a experiment. The reasoning by Hummel (2000) was adopted and normal statistical analysis, based on the random distribution of error, and demonstrated by Clutter et al. (1983), was used to analyse growth data. The trial design incorporates very dense stands, from 6809 TPH to a very sparsely populated stand density (161 TPH). Field observations showed markedly, visible differences between individual trees from different spacing treatments; also reported by Miranda et al. (2009). It was reported that stand density is an effective manner to control the resources necessary for tree growth such as water, sunlight and nutrients effectively (Stape et al. 2004). It is hypothesized that the optimum forest yield is achieved over time in a stand density treatment between the two extremes, mentioned above. Chapter 3 focuses on the analysis and modelling of growth and yield to equip the forest manager with a series of functions and when applied in a planning system, to accurately predict utilisable forest products over a range of stand density treatments. This work was recently published by du Plessis and Kotze (2011).

1.4 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. 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. 2007). These tools that have been developed have assisted in providing a means of integrating plantation wood quality with specific product characteristics with the ultimate goal of minimized process costs and obtaining more consistent predictable outputs from the mill.

One of the key features required by these technologies is the use of non-destructive sampling of standing trees, as described by Oshima et al. (2005). Technologies currently being utilized in South Africa to characterize raw wood samples from pith to bark are light microscopy combined with image analysis, gamma ray densitometry and near infra-red (NIR) spectroscopy, typically done on a 12 mm diameter core, or wood strips taken from a core, sourced at breast height from the tree (Downes et al. 2010, Schimleck et al. 2010). More recently, computer tomography (CT scanning) has been employed and as illustrated by Seifert et al. (2010), it was successfully used on *Prunus avium* to study occlusion of pruning wounds and decay of stem wood in the production of high quality timber.

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 beam 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.

Near infra-red spectroscopy has 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, Downes et al. 2007). 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. Using these measurements, calibration models can be developed and the NIR spectra can be related to properties of interest.

The variability in wood properties of *Eucalyptus* species grown for pulp and paper production in South Africa is now more understood than ever before. The use of non-destructive sampling techniques combined with image analysis, gamma-ray densitometry and near infra-red spectroscopy has largely been responsible for this better understanding of the eucalypt resource. Efforts to improve and refine these techniques will undoubtedly go a long way in depending 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.

1.5 MATERIAL CHARACTERISTICS

1.5.1 Various levels of material investigation

Wood, which is an end product of cambial growth (Downes et al. 2000) is a very variable substance. Wood properties can be described at the following levels:

- *Macroscopic morphology* - the presence, extent and distribution of different types of wood tissue, e.g. juvenile wood, mature wood, early and latewood in growth rings, wood density, etc.
- *Anatomy* - types of cells and relative proportions, in this study two main cell types are referred to namely, hardwood tracheid fibres and vessel elements
- *Chemical composition* - cell wall cellulosic components, lignin and extraneous materials
- *Intermediate or final product* - pulp and paper products, often the pulp is described in terms of its fibre quality and constitution, *pulp fibres* is often freely used to describe the fibrous component of pulp and does not refer to the anatomy anymore, as described above.

The biological origin of wood makes it structurally very different from other natural and synthetic materials like ceramics and plastics. Large variation in properties as a result of its variable growth conditions exist. Large variation exists among species and genera, between trees of the same species and within trees and is well described. A wide spectrum on wood quality, causes, origin and sampling methods have been covered by these authors: Taylor (1973) reporting on anatomical wood properties of South African grown *Eucalyptus grandis*, Malan (1991) detailing the juvenile wood properties of *Eucalyptus grandis*, Clarke et al. (1999) describing the effect of differences in climate on growth, wood and pulp properties of nine eucalypt species, Downes (1997) publishing guidelines of the sampling plantation eucalypts for wood and fibre properties, Drew et al. (2001) detailing trends between various environmental factors and a number of wood, pulp and paper properties in a single *Eucalyptus grandis* clone and Naidoo et al. (2007) assessing the effects of water availability and soil characteristics on selected wood properties of *E. grandis* in South Africa. It was further reported by da Silva Perez and Fauchon (2003) and Molteberg (2004) that fibre and wood properties vary between species, between different growth localities within the same species, between different trees in the same growth locality and inside a single tree. Variations inside one tree can even be larger than differences between trees, growth localities and species.

Stated before; wood properties are determined by genetic, environmental and management factors. 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. Wood properties that show marked within-tree variation are anatomical characteristics like fibre (cell) diameter, fibre length, fibre wall thickness, vessel frequency and physical properties like density (Malan 1991, Downes et al. 1997, Naidoo et al. 2007).

1.5.2 Wood density

The wood density of a stem (or a log or piece of lumber) can be described as a gross measurement of its internal anatomy; it is not a single wood property but represents a combination of characteristics and hence is often referred to as the "bulk" property of wood (measured as size, mass or volume). Wood density is determined largely by cell wall thickness as well as the proportions of thick and thin-walled cells that are present (Philipson et al. 1971, Taylor 1973, Haygreen and Bowyer 1989). The cell wall has three major constituents; cellulose, hemicelluloses and lignin. Since the density (mass per unit volume) of these is identical (about 1.5 g cm^{-3} on an oven dry basis (Jozsa and Middleton 1994, Molteberg 2004), the solid wood substance is considered to be constant for all wood species, irrespective of their relative concentrations. Wood density provides a simple measure of the total amount of solid-wood substance per unit volume. Basic wood density, frequently measured as oven dry weight (kg) over wet or saturated volume (m^3), does not routinely correlate with cell wall dimensions because solid wood substance includes vessels and parenchyma, the latter which have thinner walls and wider lumens and hence reduce density (Sandercock et al. 1995, Philipson et al. 1971).

Wood density varies greatly within and between trees. Radially, wood density increases from pith to bark (as the cambium matures). The preoccupation with density as the major determinant of wood quality is warranted in two ways. Firstly it is a valid generalisation due its contribution to structure and secondly, it is relatively cheap and easy to measure and as such provides an excellent means of predicting end-use characteristics of wood such as pulp and paper making quality (Jozsa and Middleton 1994). The preferred range for wood density in pulp and paper industry is between 400-600 kg m^{-3} (Downes et al. 1997).

1.5.2.1 Growth rings

Wood density variation is often studied within the annual growth rings. *Eucalyptus grandis* is an example of a hardwood species that does not show distinct contrast between dark latewood bands and light coloured earlywood and thus does not visually have clearly defined growth rings (Downes et al. 2002, Naidoo et al. 2010). In most conifers, the light and dark bands which represent early- and latewood rings are clearly visible to the naked eye. Growth rings are the result of new growth in the vascular cambium and are synonymous with secondary growth. Visible rings result from the change in growth speed through the seasons of the year; one ring usually marks the growth of one year in the life of the tree. The rings are more visible in temperate zones, where the seasons differ more markedly (Jacobs and Drew 2001). According to Bhattacharyya et al. (1992), the lack of macro-visible growth rings in eucalypt wood is attributable to a lack of response of the cambium during seasonal variation in the climate seen at that level.

The usefulness of identifying growth rings to study wood formation was demonstrated by Greaves et al. (1997) in a study conducted to establish correlations and relationships between basic density and growth of *E. nitens*. This study identified and described the variability in density by:

- analysing density curves plotted from the pith to the bark
- establishing the relationships between wood density and trees planted at various spacings.

1.5.3 Fibre properties

1.5.3.1 Fibre tracheids

Although wood and paper are constituted of the same type of cells (fibres), they are arranged in different ways. In wood, most individual fibres are arranged longitudinally and are bound together by a thin lignin-rich layer known as the middle lamella. Chemical pulping separates these fibres by dissolving that lignin. In paper, pulp fibres (tracheid fibres and vessel elements) are then randomly oriented depending by the forming characteristics of the paper making machine, and bonded together by secondary chemical (intramolecular) bonds and mechanical forces. However, the most important constituent of wood for pulp and paper as end-use is the hardwood fibre tracheid. Main fibre properties for pulp and paper manufacture are fibre tracheid length, diameter and wall thickness. However, vessel elements have an influence, albeit negative, on paper quality. Fibre properties result in desirable pulp properties which make them suitable for fine paper production. *Eucalyptus*-fibres delignify (pulp) 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 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 close relationship between these two wood properties (Bhat et al. 1990, Naidoo et al. 2007, Zboňák et al. 2007). Fibre length, diameter and wall thickness of *E. grandis*, measured in India, increase with increasing distance from the pith, levelling off after about 8 to 15 years (Bhat et al. 1990). The cell wall volume and wall thickness of fibres increase with age as a result of the combined effects of an increase in fibre diameter and a decrease in lumen size (Malan 1991) which, according to Zamudio et al. (2002), probably accounts for most of the radial variation in wood density.

From a *Eucalyptus* tree breeding perspective, Malan (1988) cautioned that selection for increased growth rate may result in a decrease in wood density and fibre length. This may have a significant impact as both these properties are widely regarded as important indicators of wood quality and pulp yield predictors; any changes in these may have important influences on the direction in which breeding for optimized timber use is steered. In a study by Malan and Hoon (1992), related to the effect of initial spacing on wood properties in *E. grandis* it was reported that the less trees are suppressed (at wider spacing intervals), the higher the density and the thicker the fibre cell wall fibres.

1.5.3.2 Vessel elements

In the pulp and paper industry, the relative proportions of parenchyma cells and vessels are important because of the effect they have on pulp yield and paper quality. Vessel elements, combined in a complex transport system of plant sap and water in hardwoods, are a major problem in paper-making. Large quantities of vessel elements in particular have adverse effects on paper surface quality as the paper sheet tends to undergo lifting of the vessel from the surface (picking), causing high speed printers to clog up from vessel fragments. Since vessels are not fibrous, they are only held loosely on the paper surface. 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). It was suggested by Lundqvist (2002), when hardwoods 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.

In the tree, it is common for vessels to adjust their arrangements according to seasonal patterns, especially as water availability changes. There are at least two ways in which a tree may improve on its sap transport effectiveness; one is by producing more cross sectional xylem, and the other is by changing some anatomical features that affect conductivity such as vessel diameter, length and number of vessels. 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 (Malan 1991, Downes et al. 1997). It was also shown by Naidoo et al. (2007) that vessel diameter and frequency tend to be inversely proportional to wood density.

1.5.4 Wood chemical properties

Wood is composed of structural and extractive chemical components. The structural components are insoluble polymeric macromolecules namely cellulose, hemicelluloses and lignin. It is the variation in the relative amounts of these substances that also give rise to the wide variation in wood.

Cellulose is the main component of wood and the skeletal polysaccharide of cell walls. About 60% of this linear homopolymeric molecule with degree of polymerisation of *ca.* 10,000 is arranged in a crystalline structure known in wood as cellulose I. The principal source of fibre-to-fibre bonding in paper is created by the attraction between cellulose molecules present on fibre surfaces, known as van der Waals' forces (Pereira et al. 2003). Hemicelluloses, in contrast with cellulose, are polysaccharides with shorter chains. They are heteropolymers, containing different saccharides and are named referring to the main type of sugar residues present in the polymeric main molecule. In hardwoods, the predominant hemicelluloses are xylans (*O*-acetyl-4-*O*-methylglucuronoxylans) whereas glucomannans are present in lower amounts (Pereira et al. 2003).

Lignin is an aromatic polymer and often described as the 'glue' that holds the cellulose and hemicelluloses together; and provides rigidity to the cells. Lignin comprises 16-25% of hardwoods' chemistry (Fengel and Wegener 1984). Hardwoods have a complex lignin made up of syringyl (S), guaiacyl (G) and *p*-hydroxyphenyl (H) units (Pereira et al. 2003). It was shown by Nunes et al. (2010) that woods having high S/G ratios tend to deliver larger pulping yields and are easier to delignify during their conversion into chemical pulp. This important wood quality characteristic depends on factors like the origin of the tree, growth conditions, climate, species, etc. Initial planting density therefore influences lignin content.

Extractives give an indication of the amount of soluble substances that is removed from the wood in the pulping process. Extractives can be dissolved by neutral solvents such as water, alcohol, acetone, benzene, and ether (Fengel and Wegener 1984). High extractive content in wood tends to reduce pulp yield, lowers the brightness of unbleached pulp and increases chemical demand of pulping and bleaching chemicals (Fengel and Wegener 1984).

1.6 THE PULPING PROCESS

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).

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 and is advantageous since the yields are high (over 95%). However, the energy consumption from the mechanical process is high and the fibres are often damaged or cut. Also, since the lignin is retained in the pulp, papers produced from mechanical pulps have a tendency to yellow, these pulps are better suited for short-lifetime papers. With chemical pulping, lignin is degraded and dissolved away and cellulose and some hemicelluloses are left behind (Karlsson 2006).

There are two main types of chemical pulping processes, the (alkaline) or Kraft process and the (acidic) sulphite process. Worldwide, the Kraft process dominates and accounts for almost 70% of pulp production (Washusen and Clark 2005). The Kraft process minimizes fibre damage, preserves inherent fibre strength (Washusen and Clark 2005), and is also less demanding in terms of wood species, and tolerates bark in the pulping process (da Silva Perez and Fauchon 2003). *Eucalyptus* in SA are often chemically pulped using the Kraft pulping process. The advantage of this process is the production of a high strength pulp and a high chemical recovery, both of which make this process economically feasible (Karlsson 2006).

During chemical pulping, wood chips are treated at an elevated temperature in a solution of pulping chemicals until a certain degree of delignification is achieved (Karlsson 2006). This process is referred to as cooking. The pulping chemicals used in Kraft pulping are sodium hydroxide (NaOH) and sodium sulphide (Na_2S). The cooking process is performed in a pressurized system to ensure that the cooking liquor does not boil and generate vapour. The pulping chemicals are recovered after cooking. Unbleached Kraft pulp has a dark brown colour; however, bleaching processes can be used to bleach pulp for producing white papers. The yield of unbleached Kraft pulp is between 65-70%, the yield of bleachable pulp is approximately 47-50%, and the yield of bleached pulp is the lowest, 43-45% (Karlsson 2006). The length and dimensions of fibres is dependent on the process used to separate the fibres. Since chemical pulp is cooked, substances within the fibre other than cellulose are removed by dissolution resulting in a decrease in cell wall thickness, an increase in fibre collapsibility and increased paper strength (Karlsson 2006).

Another product from chemical pulping is dissolving pulp which is a chemically refined bleached pulp with a high cellulose yield. It is made from either a modified Kraft process or modified sulphite process for the purpose of producing fairly pure and uniform cellulose. Dissolving pulp is used to make products such as cellulose acetate, cellulose nitrate, rayon, and cellophane (Karlsson 2006).

1.7 PAPER PROPERTIES

A great deal of 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. 2002, Grzeskowiak and Turner 2000, Wimmer et al. 2008). If relationships exist, it would be valuable to industry to use the variability in wood to reduce costs and optimize product quality to meet market demand (Wimmer et al. 2002, Downes and Drew 2007).

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 raw 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 (du Plooy 1980, Malan 1991, Malan et al. 1994, Malan and Arbuthnot 1995). Wood with thick cell walls tends 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 upon with 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 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).

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).

1.8 PRODUCTIVITY AND ECONOMIC IMPORTANCE

The economics of the forestry, pulp and paper industry is driven by productivity. Although much is said about wood quality, little is known about what drives product (pulp) quality and how wood quality affects this (Downes et al. 1997). The importance of such a study is for foresters and Kraft pulp processors engaged with maximizing timber value in selecting the best management regime, initial stand density in this case, for a particular end-product. Knowledge of how management factors influence wood quality can assist in making a more effective management decision for optimal tree growth and production of high quality wood. This can then be re-enforced with more site-specific silvicultural operations.

The possibility of using site and stand parameters as predictors of pulp and paper properties has been shown by a number of research programmes (Malan and Hoon 1992, Greaves et al. 1997, Chantre et al. 2000, Downes et al. 2009). The ability to predict wood quality for a given site or management regime, stand density in this case, may have positive results on pulp and paper production and quality. Pulp and paper properties from a stand may be determined in advance using predictive models for the assessment of growth and yield, fibre morphology and density. Variability in the quality of wood supplied to the pulping process is a big challenge that the pulp and paper industry has to manage. The variability is mainly due to the interaction between genetics, environment and management variables.

End product characteristics are often the determinant of raw material quality and hence, fitness for use. This is also applicable to forestry; in this case wood produced from trees established at various planting densities defines the raw wood material quality which pulp and paper are produced from. A forestry company should have as one of its main objectives the optimization of timber profits (Pilbeam and Dutkowski 2004). The value of the throughput of a hypothetical Kraft pulp mill is described later in this dissertation with a technical and economical productivity indicator, adapted for cost of delivery of timber from various planting density treatments, to the mill. A Fibre Productivity Index at the mill is recommended where the delivered costs of pulpwood (R/c) are compared by a combination of tree plantation attributes, such as volume growth (m^3 ha^{-1} yr^{-1}), basic wood density (kg m^{-3}) and pulp yield (%) into a meaningful productivity index.

In a vertically integrated timber processing company, the value and productivity of the pulpwood plantation can be determined by the fibre productivity; the product of stem wood volume per hectare, basic wood density and pulp yield (Borralho et al. 1993). The product of these three components, defined as the Fibre Productivity Index is explained by the equation below:

$$\textit{Fibre Productivity Index} = Volume(MAI)\ x(Basic\ wood\ density)\ x(Pulp\ Yield)$$

$$= \frac{m^3}{ha} \cdot \frac{1}{year} * \frac{kg}{m^3} * \frac{kg_{pulp}}{kg_{wood}}$$

$$= kg\ pulp. ha^{-1}. year^{-1}$$

Forest resources should endeavour to achieve optimum levels of pulp production at the mill by optimising this relationship in a vertically aligned business model through focussed effort on tree breeding and forest management or silviculture (Pallett and Sale 2004). Research that focuses on the establishment of product property relationships and influence of the growing site and management practices on wood quality is required to establish the raw product, process and end-product relationships.

1.9 OBJECTIVES OF THIS STUDY

The need for a reliable decision support system to enhance precision silviculture was emphasized by Louw and Scholes (2002) and du Toit et al. (2010). In addition, a forestry decision support system can provide a basis for an effective wood quality improvement program. In evaluating a given site, a forest manager would not only want to predict with a reasonable degree of accuracy the yield but also the quality of wood that will come out of a given site or management regime. A more uniform mix of wood properties will in this way be delivered to the mill which will necessitates accurate planning but will allow the pulp mill to make a more uniform product.

This study endeavours to establish the relationships between forest management factors, wood quality parameters and end-product characteristics for a *Eucalyptus grandis* hybrid grown in the high elevation areas of Swaziland. It is, therefore, expected to make an important contribution to the decision support system for the forestry industry in designing site-specific management strategies for wood quality improvement and end product optimisation, especially under variable planting density regimes. The Nelder 1a trial design, as described by Nelder (1962), was used to grow trees under the same site and climatic regime, but at varied stand densities. The growth and yield, wood density, fibre properties and pulp and paper characteristics were studied. Anatomical and chemical properties of wood produced in a Nelder 1a trial design were determined. In the analyses, planting density (trees per hectare; TPH) was used as the independent variable while growth and yield, density and fibre properties, and pulp and paper characteristics were entered in the growth and yield models as dependent variables. The null hypothesis to be tested through analysis described in this research is that the afforestation at different planting densities, resulting in various stand densities at the time of clear felling, has no meaningful effect on wood properties, physical or chemical, pulp properties and its utilisation in downstream manufacturing of paper.

Therefore, the overall objective of the study was to develop an understanding of the resource and utilization opportunities of an *Eucalyptus grandis* half-sib clone (*E. grandis* x *E. grandis* of different families), planted in a Nelder 1a experiment; and to conduct a complete materials study with the aid of non-destructive, rapid assessment techniques and laboratory pulping to assist the establishment of relationships between planting density treatments and overall product quality. The sub-objectives conclude in a fibre productivity index which will be used to categorize timber plantations in terms of their contribution to the pulping process, and to set a method to determine a differential price structure for timber quality and not the purchasing of raw wood based solely on the bulk or mass properties.

1.9.1 Specific objectives and content

1.9.1.1 Chapter 2 and 3. Specific objective 1: Assessment techniques

- Develop techniques to assist in the knowledge gaining of the wood resource namely:
    - In **Chapter 2** a technique to measure growth rings in the wood resource is undertaken to form an understanding of the variability in wood density and possible prediction thereof.
    - In **Chapter 3,** a near infrared (NIR) spectroscopy calibration model will be developed to enable the prediction of wood and pulp chemical and where possibly physical properties of wood, pulp and paper.
- Furthermore, to investigate the rapid assessment techniques available to discriminate between effects of environment and planting density on the wood properties and pulp quality of a *Eucalyptus grandis* clone. Available microscope image analysis protocols will be used to describe bulk wood properties, fibre tracheid and vessel element morphology of both pulped and un-pulped fibres. Gamma-ray densitometry will be used to develop air dry wood density profiles representative of various planting density treatments.

1.9.1.2 Chapter 4. Specific objective 2: Growth and yield study

To investigate the effect of planting density on the growth and yield of a *Eucalyptus grandis* clone on the utilisable timber volume, on a single site with high rainfall (>1200 mm) and deep apedal soils (> 150 cm). Data sourced from a Nelder 1a spacing experiment in Swaziland Piggs Peak region, will be fitted with functions to describe survival/ mortality, dominant height and basal area development over time. The functions must be suitable for use in a growth model and comparisons will be made with an existing and suitable model, to test the predictive ability and behaviour of the model. It is expected that tree volume will be a key indicator to productivity throughput in the pulp mill, hence the functions are prepared to assist in a simulation of a forest enterprise.

1.9.1.3 Chapter 5. Specific objective 3: Establish the variation in wood density and cellular morphology of a Eucalyptus grandis clone as influenced by planting density

To conduct a materials investigation from the macro to micro level of wood structure to describe the effect of variable spacing levels on the physical properties of an *Eucalyptus grandis* clone. Wood structure will be investigated by describing bulk properties, e.g. wood density, morphological traits, e.g. fibre dimensions and vessel component properties in the radial plane.

1.9.1.4 Chapter 6. Specific objective 4: Establish the variation in pulp & paper properties of a Eucalyptus grandis clone as influenced by planting density

Use the Kraft chemical pulping process to produce pulp and paper from different planting density treatments for the analyses of pulp fibres in the liberated and in the handsheet form. Wet chemistry techniques will be used in a pilot scale laboratory experiment to establish the chemical properties describing the fibre properties contributing towards pulp yield and quality. The strength properties of paper (handsheets) will be evaluated making use of standard Tappi methods and will be correlated with the various planting density levels. Furthermore, existing NIR models will be tested to describe their suitability to predict chemical properties of pulpwood.

1.9.1.5 Chapter 7. Specific objective 5: Establish a productivity index suitable for measuring the value of the fibre resource

Develop a fibre productivity index which will describe the technical (volume, density and pulp yield) and economical factors, e.g. cost of delivery of timber, taking cognisance of the extent of the land required per planting density treatment to supply a hypothesized Kraft mill of commercial size. The index should be sensitive for relative contributions (economic weights) of technical elements of the forestry component of the value chain, identify key pulping indicators and be sensitive for the wide spread of planting densities tested in the Nelder 1a experiment. Furthermore, the index should be easy to apply in an integrated commercial forestry company with an opportunity to set a differential timber price for the value of the wood fibre in the Kraft process, and not just merely for purchasing bulk or mass of wood.

This dissertation presents a compilation of manuscripts where each chapter is an individual entity and some repetition between chapters, therefore, has been unavoidable.

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CHAPTER 2 : A technique to separate growth rings in a *Eucalyptus* clone with gamma-ray densitometry and radial increment data applied on a Nelder 1a spacing trial

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CHAPTER 2 : A technique to separate growth rings in a *Eucalyptus* clone with gamma-ray densitometry and radial increment data applied on a Nelder 1a spacing trial

Abstract

Recent advances in dendrochronological technology offer great opportunities to understand the relationships between climate, wood formation and its inherent variability. Although we realise that *Eucalyptus* wood in South Africa is a highly variable resource, there is limited research conducted to describe tree physiological processes. Identification of growth rings in hardwoods, especially in *Eucalyptus* is difficult where the occurrence of 'false' rings is common. False growth rings typically occur on sites which are subject to periodic seasonal events of water deficit.

A method was developed by Naidoo et al. (2010) which made use of bark-to-pith gamma-ray density profiles and annual measurements of diameter at breast height (DBH) to identify growth rings on wood density profiles of *Eucalyptus grandis* sourced from a permanent sample plot program. In this investigation, a similar approach was followed to identify growth rings of *E. grandis* taken from a spacing experiment. Using a Nelder 1a spacing trial dataset, it was possible to assess the annual pattern of stem diameter growth 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 at treatment level for each year and used to predict annual RI at an individual tree level. Data was corrected for bark thickness and predicted RI corresponded well with latewood density peaks. These separation points were considered a reliable guide to divide the density profile into annual increments. The results indicated that tree spacing at establishment as a management intervention does not influence the variability of wood density, but that it is influenced by the amount of juvenile wood in the stem and a micro-environmental function such as individual rainfall events, the intensity and spread, and thus available soil water.

Keywords: growth rings, wood density, gamma-ray densitometry, *Eucalyptus*

2.1 INTRODUCTION

Wood is one of our most important renewable resources and has been an objective of research for many years and also for as many reasons. The anatomical composition of wood is variable among species, between trees and within a tree. For example, high levels of variation for measured and derived wood properties were described between species (*E. globulus* and *E. camaldulensis*) and between and within trees (Oshima et al. 2005). Similar, variability of basic wood density in the local South African eucalypt source was described by Malan (2005).

It is important for optimal utilisation of wood to understand the nature and causes of the intra-specific variation in wood properties within trees and inter-specific variation between trees of the same species. This variation, despite the fairly accurate way of measurement, remains difficult to predict accurately. Although a large proportion of wood variability is under genetic control (Pot et al. 2002, Zamudio et al. 2002), the environment and silvicultural practices under which a tree is growing is also a major driver of variation (Pallett and Sale 2004).

Many *Eucalyptus* species do not have distinct annual growth rings due to a lack of response of cambial activity to the specific seasonal variation of a site (Sandercock et al. 1995). This makes it difficult in a number of *Eucalyptus* spp. to separate seasonal growth rings into annual increments for the purposes of studying wood properties (Malan 2005, Downes and Drew 2007, Downes et al. 2009) especially when the interpretation of climate and site is considered. Visually, the earlywood and latewood bands are poorly contrasted in *Eucalyptus grandis* and do not always correspond with the annual growing season (Downes et al. 2002). Wood sampling methodologies can have a major impact on how variability of wood properties is reported on and understood (Downes and Drew 2007).

Growth and yield relationships, describing the influence of initial stocking levels in a Nelder 1a trial were explained by du Plessis and Kotze (2011). It was shown that the volume growth rate between tree spacing treatments in the Nelder 1a trial, varying from 6809 to 161 trees per hectare (TPH,) differed significantly, mainly due to the available growing space which regulates access to water, nutrients and light. From the data analysed it was reported that smaller trees have a smaller rate of volume increment whereas the larger trees, grown wider apart, had a higher rate of increment. Similar inferences were described by du Toit et al. (2010) showing that volume gains associated with capturing the full potential of the site (stand density) averaged 14 % across all sites.

The research in this paper describes wood density profiles obtained on 7 year old *Eucalyptus* clonal material in the radial direction in a Nelder 1a spacing experiment of. Annual DBH measurements were combined with high resolution gamma-ray density measurements to predict latewood peaks in *E. grandis* wood and hence describing the variability of the resource by identifying growth rings.

2.2 MATERIALS AND METHODS

2.2.1 Sample origin

Data were obtained from a Nelder 1a spacing trial that was established in the Piggs Peak region of Swaziland, located at 743 m elevation and positioned on the coordinates 25º59’08.63”S; 31º17’45.76”E.

As part of an all inclusive site classification system for the South African forest industry, the summer rainfall areas have been classified by Smith et al. (2005) into broad mean annual precipitation (MAP) and mean annual temperature (MAT) classes. The experimental site is located in the WT9 climate zone (Smith et al. 2005) which places it in the 18-19 ºC MAT class, located within the warm temperate climatic zone. Rainfall, a variable positively related to forest productivity (Stape et al. 2004, Pallett and Sale 2004, du Toit et al. 2010), was considered high for the study site with a 30 year long term average of 1477 mm MAP recorded for the site. The average measured annual precipitation on the site for the seven year period of experimentation was 1432 mm.

2.2.2 Data collection

The Nelder 1a trial consisted of 17 stand density or spacing treatments represented by 48 individual tree plots arranged in a full circle with the most dense stocking treatments in the centre of the hub and widely spaced trees on the outer rim. All trees in the trial were re-measured at seven equally-spaced time intervals. For each measurement event, the age (years), stand density (trees per hectare, TPH), quadratic mean diameter (Dq in cm), dominant height (HD in m) and basal area (BA in m^2 ha^{-1}) were recorded or calculated. Four spacing treatments covering the range of the Nelder 1a experiment for which detailed density profiles were recorded, were chosen.

2.2.3 Measurement of air-dry wood density

Five trees each from treatments: 6809, 2336, 801 and 275 TPH with complete DBH data records (measured at 1.3m above ground level), were used in the wood analysis. Blocks were sawn through the centre of each disc taken from DBH (see Figure 2-1) of each standing tree in the trial. Care was taken to cut all blocks in the same original North-South orientation from the original position in the trial and no compensation was made for asymmetrical tree shape. The cores from each disc were stored at 23 ºC and 50 % RH to achieve an equilibrium moisture content of about 10 %. Strips of uniform thickness were cut along the radius of each block using a twin-blade saw. Samples were 12 mm longitudinal, 2.5 mm tangential; the radial dimension being determined by the diameter of the disc from which the strip was sampled. Scanning to determine the density profile of the wood strip was done from bark to pith with a custom built gamma-ray densitometer with an isotopic radiation source (Fe^{55}). Strips were mounted in a movable carriage using a stepping motor to propel it forward in accurate 0.5 mm intervals. Figure 2-1 explains the dimensions of the strip and scanning direction graphically. The use of gamma-ray densitometry was considered to be an accurate and reliable technique to determine wood density (Cown and Clement 1983, Malan 1991, Malan and Marais 1991) as demonstrated by Naidoo et al. (2006). Extractives were not removed prior to scanning consistent with standard procedures at the CSIR-FFP laboratory (Zboňák, 2002)

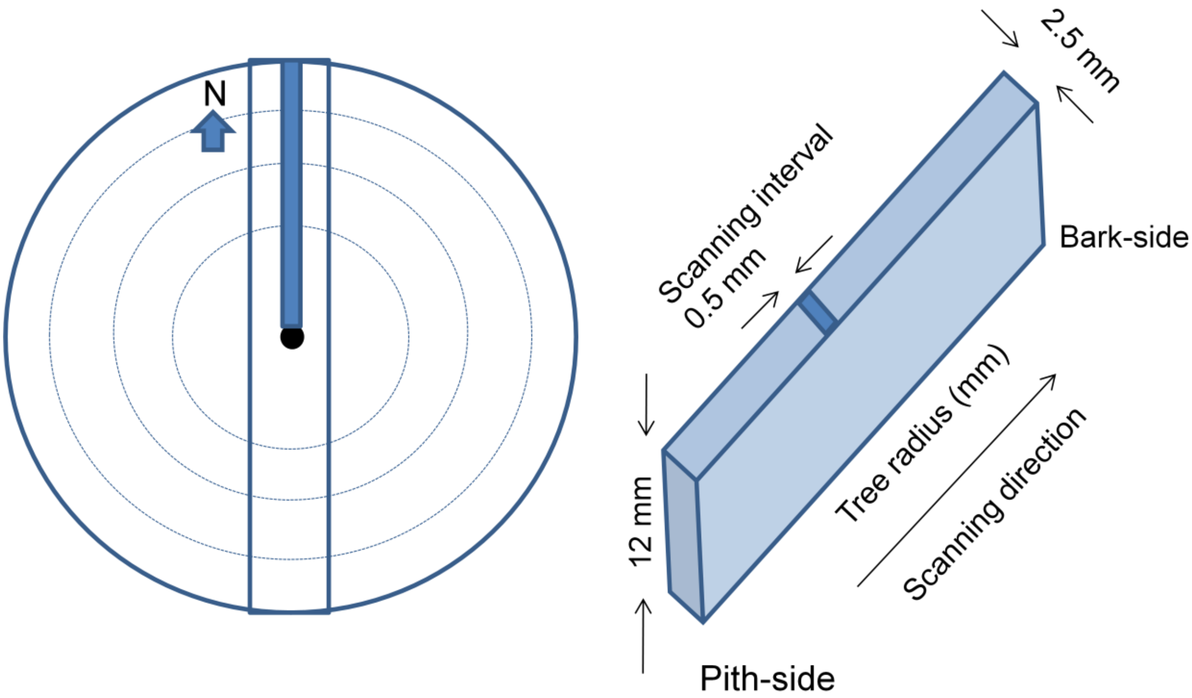

Figure 2-1: Pictogram showing wood disc, and block and strip dimensions with direction of scan.

2.2.4 Calculations of radial increment for treatments: 6809, 2336, 801 and 275 TPH

The compilation of the analysis dataset included the removal of individual trees from the calculations if any missing values were recorded. The diameter measurements were converted to radius measurements which defines radius at breast height - RBH in mm (1.3 m above ground).

The radial increment (RI) was defined as the difference in RBH between two consecutive years. The RI was calculated for each year of measurement from the bark to pith. This was done because the last measurement is a more defined point of reference, as opposed to the pith-end.

The RI was also expressed as a percentage of the radius (%RI). All %RI-values were calculated from the final DBH measurement from the bark-end towards the pith in annual increments. The first radial increment between year_f and year_{f-1} is shown in the equation below:

$$\%RI = \frac{RI_{f-1}}{R_f} \cdot \frac{100}{1} \qquad \text{(Equation 1)}$$

where

f = final year of measurement (closest to bark-end),

R_f = radius at the year f (mm) and

RI_{f-1} is the radial increment (mm) between year $_f$ and $_{f-1}$

The DBH observations from each treatment were combined and averaged for each year to derive an average value of radial growth over the period of assessment. The mean radial increment percentage (%MRI) was calculated by dividing the sum of %RI-values of each year by the number of trees measured. All the tree measurements of the Nelder, which consisted out of 48 individual tree plots, except for five trees per treatment kept separate to test the model, were used to calculate the %MRI for each spacing treatment. These calculated %MRI values were applied to the test set data of five trees per treatment, to predict annual radial increments.

2.2.5 Method of predicting radial increment

The calculated %MRI for each year was used to predict the annual RBH for the test data set (5 replicates per treatment). The RBH at the last point measurement (f) was used as the starting point, working backwards, predicting annual RBH-values towards the pith. Equations 2 and 3 show the calculations for predicted RBH-values for the first two measurements:

$$Predicted\ RBH_{f-1} = RBH_f - \left(RBH_f \cdot \left(\frac{\%\mathrm{MRI}_{f-1}}{100}\right)\right) \qquad \text{(Equation 2)}$$

$$Predicted\ RBH_{f-2} = RBH_{f-1} - \left(RBH_{f-1} \cdot \left(\frac{\%\mathrm{MRI}_{f-2}}{100}\right)\right) \qquad \text{(Equation 3)}$$

where

f	= final year of measurement (closest to the bark),
RBH_f	= radius at the year f (mm) and
$\%MRI_{f-1}$	= percentage mean radial increment for treatments: 6809 TPH, 2336 TPH, 801 TPH and 275 TPH between year f and f-1 (mm).

2.2.6 Matching wood density profiles with radial increment

Density profiles were constructed from the gamma-ray densitometry data for the test data set for each of the selected treatments: 6809 TPH, 2336 TPH, 801 TPH and 275 TPH. The predicted RI values (mm) were expressed as cumulative values from the bark-end towards the pith. The cumulative radial increment is a sum of the predicted radial increment values where RI_{f-1} was the first radial value closest to the bark-end.

The cumulative RI, for each of five single tree replications in each treatment, was superimposed onto the respective density profile.

2.3 RESULTS

Mean trial data at the final measurement age of 6.75 years was summarised for treatments 6809 TPH, 2336 TPH, 801 TPH and 275 TPH respectively (Table 2-1).

Table 2-1: Summary trial data at 6.75 years for selected treatments (planting density) included in the analysis.

Planting density (TPH)	Survial (%)	Volume i.b. (m^3 ha^{-1})	Basal Area (m^2 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	Dominant Height (m)	Quadratic Mean Diameter (cm)
6809	64.6	187.7	41.6	27.8	22.6	10.5
2336	89.6	216.5	31.8	32.1	24.5	13.5
801	93.8	204.6	23.0	30.3	27.2	19.3
275	100	154.1	15.4	22.8	28.7	26.6
48 trees per planting density treatment						

The flattening-off of RBH-increment between years 4 and 6.75 is illustrated in Figure 2-2, this is particularly visible for treatments 6809 and 2336 TPH. Treatment 6809 TPH was excluded from further analyses because no increment could be detected due to the extremely high stocking levels.

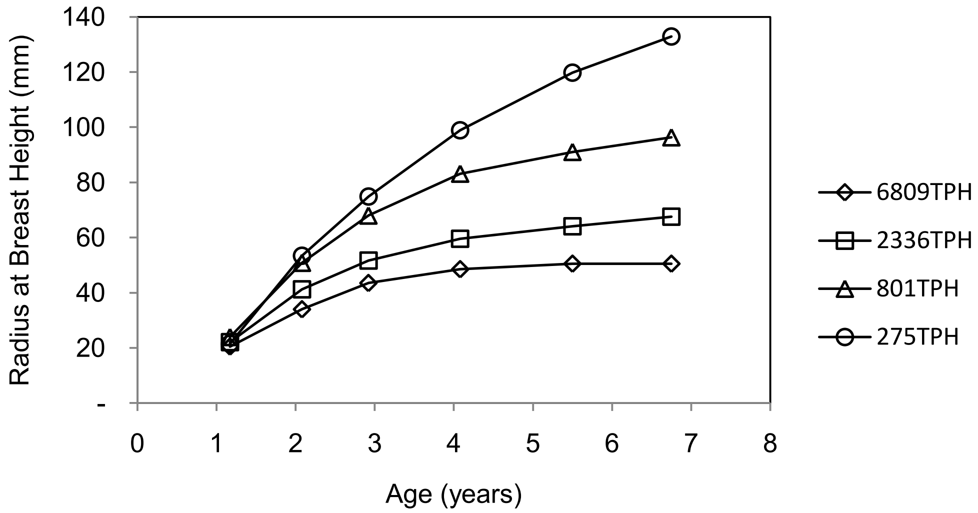

Figure 2-2: Radius Breast Height development by treatments 6809 TPH, 2336 TPH, 801 TPH and 275 TPH over time.

It is noted from Figure 2-3a, showing the measured RI-values for treatment 2336 TPH, that trees numbered T6, T8 and T10 followed a similar path of RI development while trees T7 and T9 had a comparatively lower rate of increase in radial increment in comparison. It was evident from the development curve that T7 and T9 had virtually no additional radial development from years 2003 to 2005. In contrast, T6, T8 and T10 showed a trend of consistent radial increment over the entire period of measurement. Figure 2-3 a, b and c were used to select one tree each per treatment to verify the methodology and were selected as follows: for treatment 2336 TPH; T6, for treatment 801 TPH; T13 and treatment 275 TPH; T17.

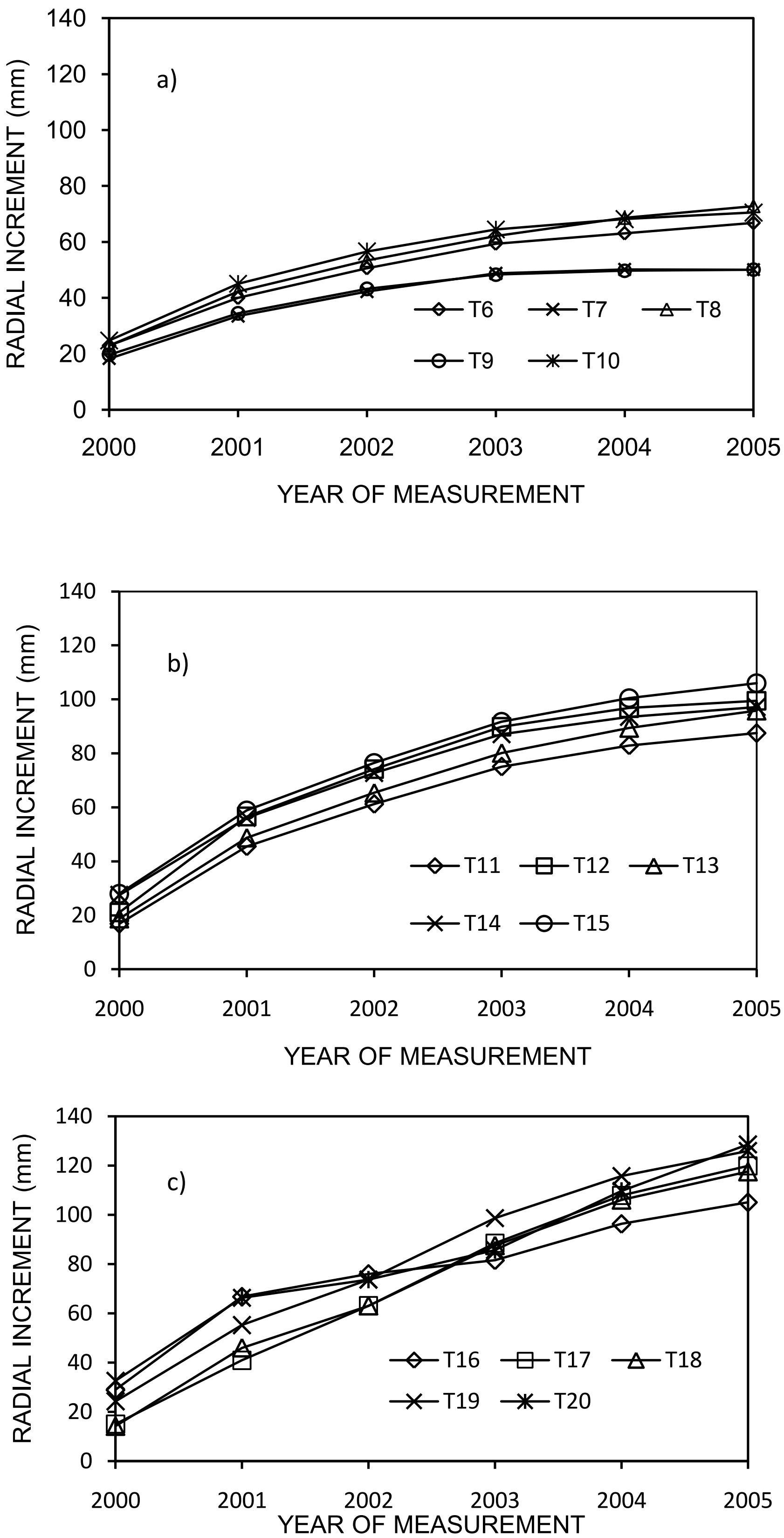

Figure 2-3: Cumulative Radial Increment (mm) of trees measured in a) treatment 2336 TPH (T6-T10), b) treatment 801 TPH (T11-T15) and c) treatment 275 TPH (T16-T20) used for comparison of RI among treatments and prediction of RBH.

The ability of the method to predict RBH was tested by comparing measured RBH with predicted RBH values for the three treatments included as shown in Figure 2-4. The same was done for predicted RI and measured RI as seen in Figure 2-5. All five test trees per treatment were included in the data. The linear relationships were highly significant as indicated in Figure 2-4 and Figure 2-5.

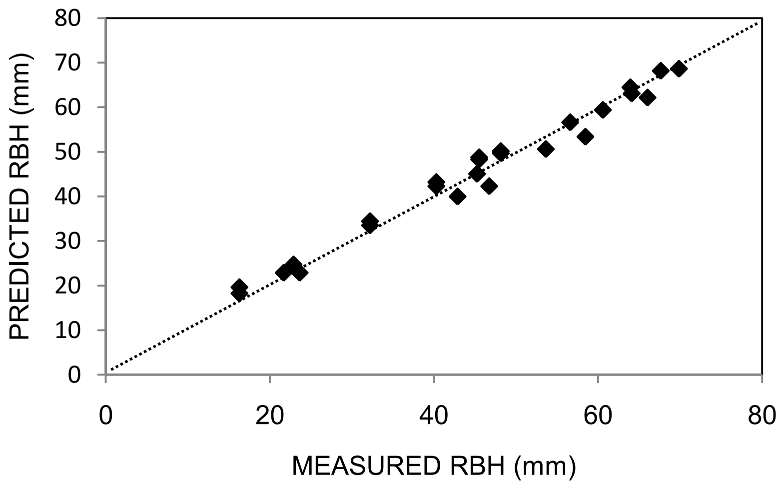

Figure 2-4: Relationship between predicted and measured RBH (treatment 2336 TPH).

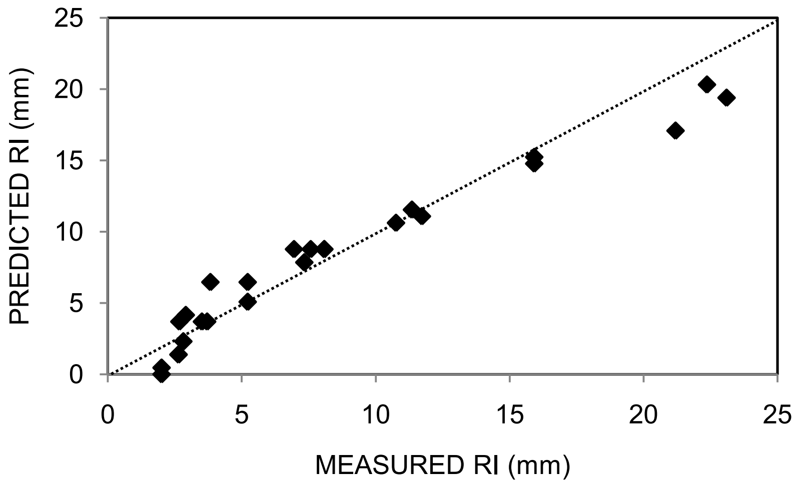

Figure 2-5: Relationship between predicted and measured RI (treatment 2336 TPH) with the linear fitted model.

Coefficients of determination (R^2) and p-values were calculated for the treatments included in the study. They are shown in Table 2-2.

Table 2-2: Regression parameters for RBH (mm) and RI (mm) for treatments: 2336 TPH, 801 TPH and 275 TPH.

	Radius at Breast Height (mm)					Radial Increment (mm)				
	β_0	β_1	R^2 (adj)	SE	p	β_0	β_1	R^2 (adj)	SE	p
2336TPH	3.6276	0.9231	0.9793	2.204	<0.001	-5.5158	1.1025	0.9465	1.528	<0.001
801TPH	-0.0977	1.0208	0.9889	2.754	<0.001	1.7211	0.8843	0.9740	1.825	<0.001
275TPH	7.2071	0.9175	0.9347	7.737	<0.001	8.7536	0.5894	0.5800	4.325	<0.001

A paired sample *t*-test was carried out to establish whether there were any differences in the treatments between the measured and predicted RI in each year of measurement. As seen in Table 2-3, no significant differences between measured and predicted values were found, apart for the year 2000, and as such, predicted values were used in subsequent data analysis.

Table 2-3: Results from paired sample t-test comparing measured and predicted RI, all treatments inclusive for each year of measurement. The significance of the t-test for each year ($p<0.05$) is shown.

Year	Mean (paired differences)	SD	MSE	*p*
All years	0.31	1.61	0.32	0.334
2000^{ns}	-2.34	1.53	0.68	0.0269
2001	0.16	0.57	0.26	0.5779
2002	0.93	0.75	0.33	0.0516
2003	0.06	1.58	0.71	0.9372
2004	-0.35	1.5	0.67	0.6291

The density profiles for selected trees of treatments 2336 TPH, 801 TPH and 275 TPH, were used to test how well the predicted RI related to the latewood peaks on the density profiles and are illustrated in Figure 2-6, Figure 2-7 and Figure 2-8, respectively.

Figure 2-6 shows the gamma-ray density profile for Tree 6 (2336 TPH) with Predicted and Measured RI. For this tree; the density between the lowest early wood and highest late wood peaks ranged from 0.352 to 0.720 g cm^{-3}, an average of 0.493 and standard deviation of 0.061 g cm^{-3}. In Figure 2-7 and Figure 2-8 the density profiles of tree no 13 (801 TPH) and tree no 17 (275 TPH) are shown. Their respective density profiles ranged for earlywood to latewood from 0.338 to 0.701; with an average 0.480 and SD of 0.065 g cm^{-3} for tree no 13 and 0.414 to 0.691; average 0.505 and SD of 0.053 g cm^{-3} for tree no 17.

In all three of the above test examples, the most prominent wood density peak (in 2004) was regarded to be a real latewood peak, as opposed to a false peak and was used to calibrate the curve. The predicted RI values developed for each treatment was applied to this starting point and latewood peaks for the years 2003 and earlier predicted from the bark towards the pith. It was noted from all the examples used to test the predictive ability that there was a lack of alignment and hence the predicted latewood peaks were out of cycle. A process of optimising the match, as described by Drew and Downes (2009) was used to rescale the RI predictions. The rescaling was defined by Drew and Downes (2009) as the overall bark thickness correction factor measured as a percentage adjustment of total growth over time ascribed to the growth of bark and phloem over the same period. It was reported by the authors that re-scaling at a local level is necessary to cancel out the unknown pattern of increment of the bark and phloem layers. Furthermore, it was reported by Drew and Downes (2009) that bark thickness, which is closely related to tree water status (Bouriaud 2005), can decline over time due to a seasonality effect and suggested correction may be done for bark thickness decline and shrinkage events. It was observed in the 6809 TPH treatment that tree DBH would decline between some consecutive years due to drought conditions and prevailing competition between trees. Moreover, the gamma-ray data did not include the bark, but the DBH measurement did; hence the need for the adjustment suggested by Drew and Downes (2009). This was possible on the Nelder 1a trial site, given the variability of the rainfall and the initial wet and later dry periods. The daily recorded rainfall for the trial site, summarised per month is shown in Figure 2-9. The rescaling of the data for Tree 6 was done through visual inspection revealing a constant amount of 3 mm the %MRI was out of cycle with the tree (e.g. Tree 6). Consequently, the pith to bark measurements were reduced by 3 mm. This was also done for Trees 13 and Tree 17. After these corrections were applied, the RI-predictions were in cycle and corresponded well with the observed latewood peaks (see Figure 2-6, Figure 2-7 and Figure 2-8). The correction applied could also have corrected any asymmetry of the tree stem which was not taken into account when measurements were done with a DBH-tape in this experiment.

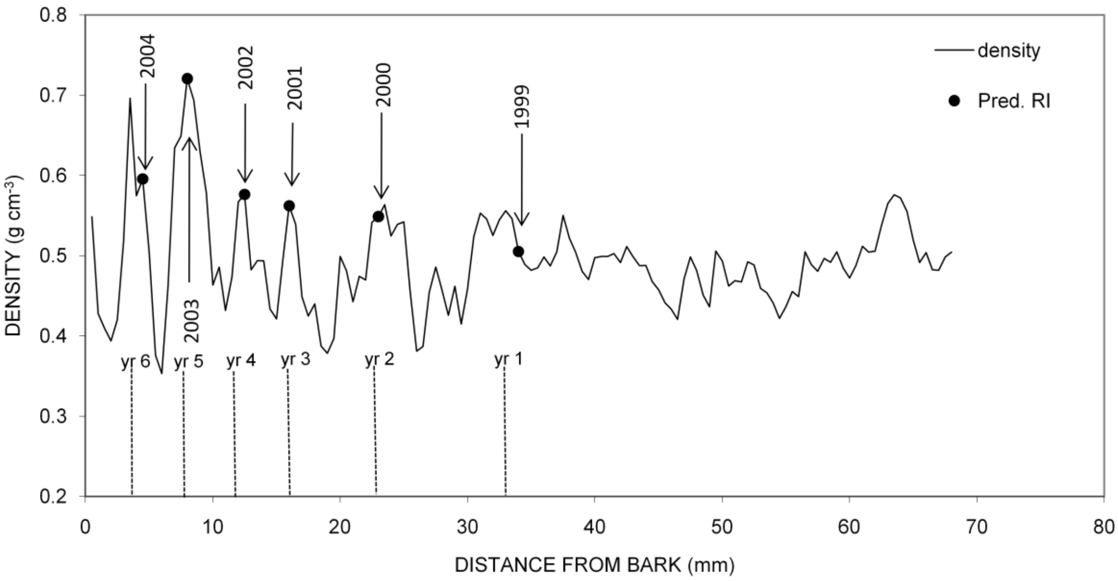

Figure 2-6: Density profile of T6 at DBH, calibrated at age five, showing predicted RI from bark to pith.

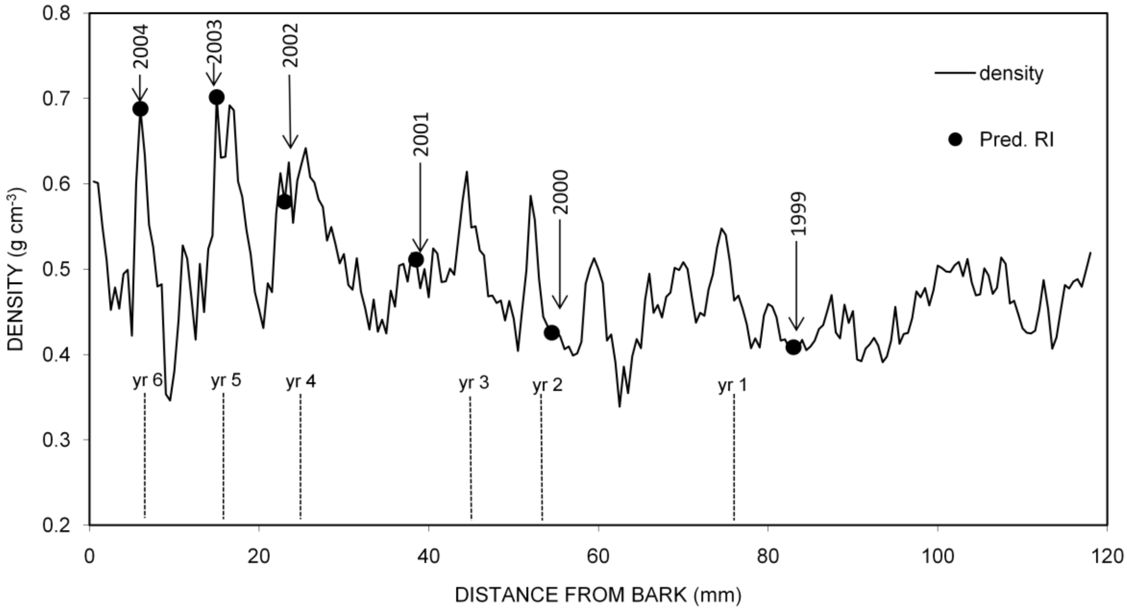

Figure 2-7: Density profile of T13 at DBH, calibrated at age five, showing predicted RI from bark to pith.

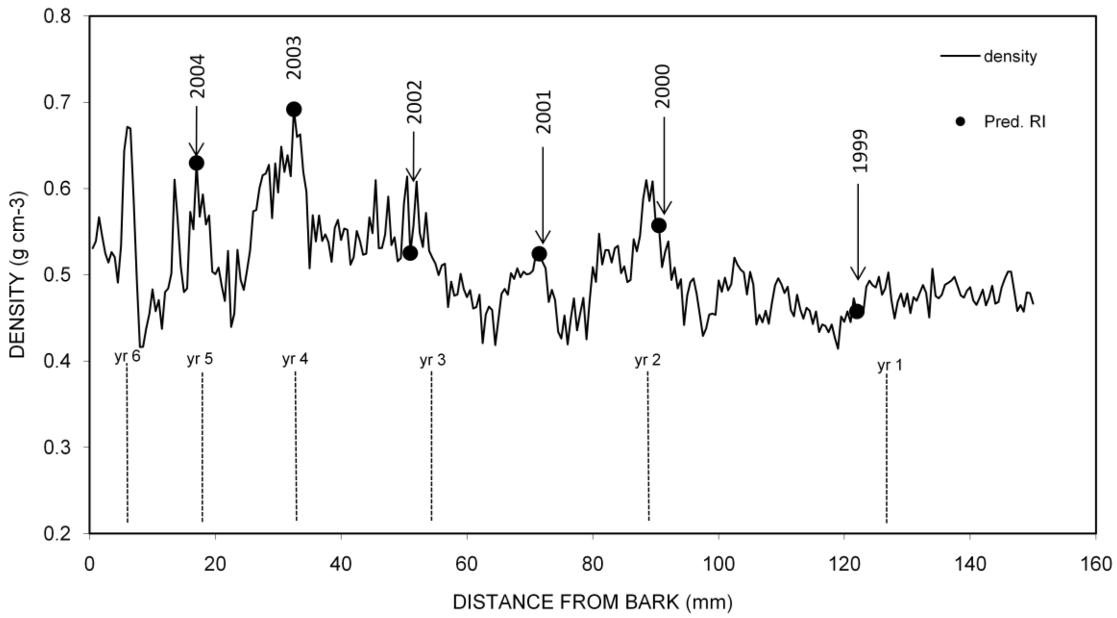

Figure 2-8: Density profile of T17 at DBH, calibrated at age five, showing predicted RI from bark to pith.

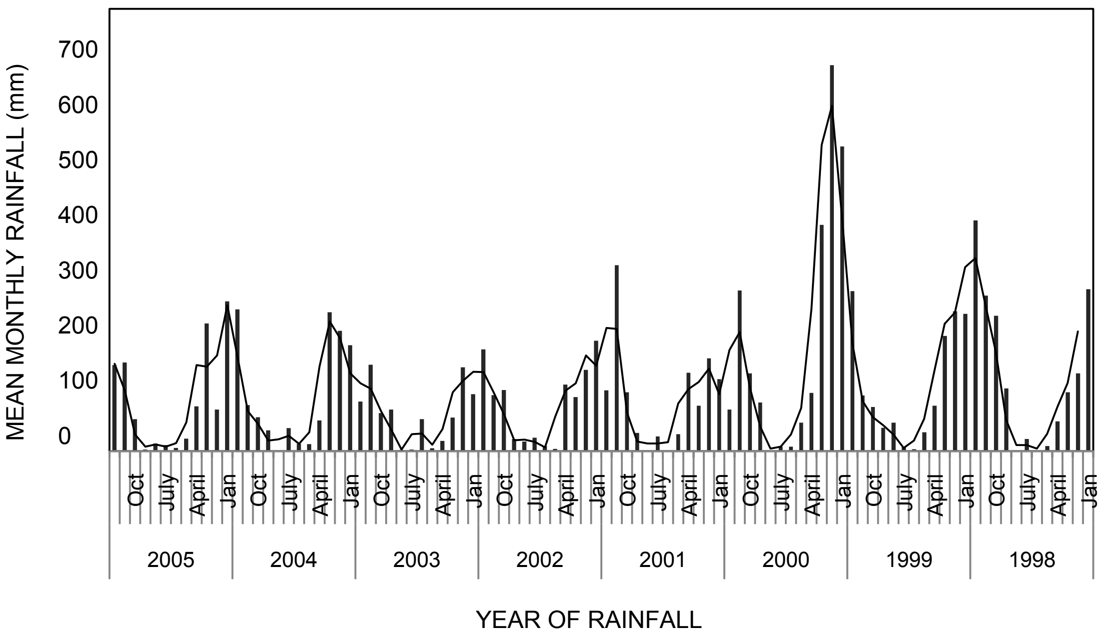

Figure 2-9: Mean monthly precipitation for the duration of the Nelder spacing experiment (1998 – 2005) with the moving average indicated by the solid line.

2.4 DISCUSSION

The development of wood density over time, when plotted from the bark to the pith, showed a high level of variability. This variation was characteristic due to the age of the wood and the stand density at which as stand was established. During the growing time, periods of water surplus and deficit caused a change in cell wall constituents.

Identification of annual growth rings in hardwoods, especially in *Eucalyptus* is difficult where the occurrence of 'false' rings is common (Bouriaud 2005). False growth rings typically occur on sites which are subjected to periodic seasonal events of water deficit. The effect of these intermittent drought periods is a reduction in fibre enlargement and an increase in the proportion of the S1 and S2 cell wall layers and hence, an untimely increase in wood density in the period when earlywood should have been formed (Bouriaud 2005). These are false growth rings and are visible (Figure 2-7 and Figure 2-8) in the density profiles and when the unpredictable distribution of rainfall is considered (Figure 2-9), the fluctuations of highs and lows in the wood density profile are explained. The relatively flat density curve in the first two years of the life of the trees is most probably attributable to high total rainfall of 1225 mm for 1999 and 2123 mm for 2000. In contrast, the numerous large false peaks in both T13 and T17 are visible.

When compared with other dendrological studies which often analyse long term data collected over 50 years or more (Wimmer and Downes 2003, Downes et al. 2009), this data represents a much shorter time period of six years of wood formation, of which the young trees might not have produced mature wood yet. In this study, mainly juvenile wood was assessed which does not show stable development patterns yet and is susceptible to environmental influences (Ilic et al. 2003). The seasonal periods of water surplus or deficit during the autumn and spring seasons may have had an effect on variability of the resource. Hence the false growth rings are rather seasonal growth rings than annual growth rings.

Treatment 2336 TPH exceeds the current commercial establishment practice of 1666 TPH by 40 %. The trees were small and mostly suppressed as can also be seen from Figure 2-3a, confirming the small diameter of T7; DBH of 14 cm at age 6 years. These suppressed trees have a less variable wood density profile and predicted late wood peaks coincide well with the observed seasonal growth rings. The large trees from treatments 801 TPH and 275 TPH, of which some trees exceeded 30 cm DBH, had a much more variable density profile, showing the direct response of cambial growth to micro-environmental influences, especially rainfall events.

The rescaling procedure was necessary at the individual tree level as the predicted RI-values were out of cycle. The method as suggested by Drew and Downes (2009) worked well when applied to the data, and the latewood peaks and predicted RI values coincided well for all three treatments.

2.5 CONCLUSION

The use of dendrometers to record detailed stem growth data can contribute to our understanding of plant physiological processes such as tree water usage, onset of drought stress and various measures of growth response, and subsequently contribute to the development of hybrid and process-based growth models.

Although we appreciate that *Eucalyptus* wood in South Africa is a highly variable resource, practitioners often refer to basic wood density as a single value. However, a reference to basic wood density should always include the variability of the resource, measured either as coefficient of variation (CV) or standard deviation (SD).

Demonstrated in this study is a technique to use radial increment data from a spacing experiment to construct wood density formation curves and make inferences with regards to environmental influences from site, spatial or management sources. While the technique worked well, it is of a low resolution and cannot be used for detailed dendrochronological research. However, by relating the pattern of variation of wood density to annual diameter measurements from this spacing trial, it was possible to support the visual estimation of annual growth rings on *E. grandis*, especially closer to the bark.

Tree spacing at establishment is a key silvicultural element of tree growing regimes, and as main effect of the experiment did not influence the variability of basic wood density. Although we know that average basic wood density is under strict genetic control, variability in basic wood density in this experiment can be attributed to the micro-environmental function of individual rainfall events, the intensity and spread, and thus available soil water and the proportion of juvenile wood in the stem. It is therefore almost impossible to manage the variability in basic density in *E. grandis* clones from a management intervention perspective only.

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CHAPTER 3 : Near infrared analysis of *Eucalyptus grandis* ground wood and Kraft pulp

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CHAPTER 3 : Near infrared analysis of *Eucalyptus grandis* ground wood and Kraft pulp

Abstract

A set of NIR calibration and validation models to predict wood properties, pulp physical and pulp chemical properties were developed using 60 samples from a Nelder 1a spacing experiment planted with a *Eucalyptus grandis* clone in Swaziland. The modelling procedure involved external validation with 30 % of samples that were from the original data set but kept out of the calibration. The NIR validation models for *air dry* wood density (R^2 = 0.77, RMSEP = 34.2), total pulp yield (R^2 = 0.75, RMSEP = 0.56), kappa number (R^2 = 0.77, RMSEP = 1.82) and insoluble lignin (R^2 = 0.82, RMSEP = 0.22) returned good values. A separate prediction testing of the models was completed on an *E. grandis* breeding population which had chemical data available and when the measured data set was compared with the NIR prediction data set, a *t*-test revealed that there were no meaningful differences between the two data sets. Regression analyses were carried out with the measured and NIR-predicted variables as dependent and independent variables respectively. The coefficients of determination for total pulp yield (R^2 = 0.73) and kappa number (R^2 = 0.76) were high and all models were significant at the 95 % level.

Keywords: Near infrared, NIR, *Eucalyptus grandis*, calibration, validation, wood density, cellulose, total pulp yield, kappa number

3.1 INTRODUCTION

The implementation of near infrared (NIR) and multivariate data analysis in an agriculture and industrial environment include a wide array of applications of which the non-destructive quality grading of agriculture fibres (Kelley et al. 2004), predicting of sugar content of peaches (Carlomango et al. 2004) and on-line control and monitoring of pulpwood chip properties, e.g. density and moisture content (Bharati et al. 2004, Jonnson et al. 2004, Schimleck et al. 2010), are a few. The technology proved to be suited to determine the chemical composition of agricultural biomass more rapidly than traditional wet chemistry methods.

It was reported by Meder et al. (2010) that the first forestry applications for NIR were nearly two decades ago for the prediction of wood cellulose, pulp yield and lignin content. NIR spectroscopy is a tool that is being used increasingly in the pulp and paper industry to rapidly estimate a variety of wood and pulp properties. One possible use of considerable interest is the measurement of the carbohydrate composition of pulp (Bharati et al. 2004, Tyson et al. 2010) but it has numerous other applications as the technology is also used in the research environment to speed up tree breeding programs, e.g. to characterize fibre components of woody plants, to rapidly predict wood lignin content and recently for the rapid analysis of properties of transgenic trees (Schimleck and Michell 1997, Sefara et al. 2000, Tokoyama et al. 2002, So et al. 2002, So et al. 2004, Yamada et al. 2005, Yeh et al. 2004, Yeh et al. 2005, Chang and Li 2005, Downes et al. 2010, Schimleck et al. 2010).

In the processing environment, NIR has been successfully used to determine the concentrations of NaOH, Na_2S and Na_2CO_3 in white and green liquors as part of the Kraft pulping process (Hodges et al. 1999) and to determine process parameters, e.g. kappa number which is representative of the residual lignin in unbleached pulp (Gellerstedt and Li 1996) and residual effective alkali (EAr) on-line (Easty et al. 1990, Antti et al. 2000, Sefara et al. 2000a, Sefara et al. 2000b, Fardim et al. 2002).

3.1.1 Near infrared technology

Near infrared light extends from 780 - 2500 nanometres (nm). The ability of this spectrum to penetrate is used to analyse animal or plant tissue with light. Light is absorbed by woody material and converted to energy in materials with characteristic functional groups, typically: C-H, O-H, N-H and C=O. Response from the vibration is transmitted or reflected to a probe or detector and displayed as a NIR spectrum by the application of suitable software (Swierenga et al. 2000).

The NIR spectrum of a substance contains information on the chemical bonds and their concentration. Spectral "fingerprints" provide a basis for the establishment of a known cause-and-effect relationship between the spectra and reference (analytical) data (e.g. pulp yield from a trial series or breeding population). When performing multivariate calibrations, analytical calibration models require a known relationship between X and Y, where X is the instrument's response spectrum and Y the reference data. The use of probability alone, tells us only if X and Y are related and not if a true cause-effect relationship exists. However, with reference to known relationships, e.g. the relationship between the light spectra and pure cellulose, the technology can be used for prediction modelling in scientific or industrial decision making. A series of training samples are used to calibrate spectrophotometers (NIR-equipment) for each specific NIR application, e.g. the detection of lignin in pulp samples. These testing sets must be representative of the variation in the sample population, instrument identity and measurement conditions (Swierenga et al. 2000).

Although there are numerous advantages of NIR spectrometry such as its non-destructive approach, that it is a simple procedure with minimal sample preparation, provides rapid results and offers potential application in process monitoring, there are also some draw backs of the technology. There is a clear sensitivity for the matrix effects of the algorithm to ensure predictability between absorbance or reflectance and the concentration of the variable of interest caused by light scattering, the spectral complexity caused by the overlapping of peaks, the substantial effect of abundant moisture, and the specific calibration requirement. However, if used within these limitations and accurately calibrated, NIR is well suited to study samples of woody biomass both for chemical, and physical properties such as particle size and packing density (Downes et al. 2010 and Schimleck et al. 2010).

3.1.2 Application of NIR in a Tree Breeding Program

Until recently, it has been standard practice to determine the chemical properties of wood, fibre and pulp by means of analytical chemistry with a laboratory scale pulping-digesting vessel and standard analytical chemistry techniques. For tree breeding programs, there has been a move away from selecting tree specific phenotypic traits such as stem straightness, canopy dynamics, and size and arrangement of knots, towards investigating morphological (anatomical), physical and chemical properties of pulp wood (Chang and Li 2005). Therefore, there has been a need to develop micro-scale analytical methods to measure various wood characteristics such as the chemical composition of wood, e.g. lignin (syringyl/guaiacyl (S/G) ratio, soluble and insoluble components), cellulose components (α, β, and γ-cellulose), hemicelluloses, and bulk properties such as wood density and fibre coarseness.

Significant progress on the micro-scale has been made at the Tree Improvement group of North Carolina State University (NCSU) by applying transmittance NIR. To determine key wood properties, the technology requires less than 100 mg of sample material as a wood meal or in a wafer format cut from increment cores. Successful correlations have been shown between individual growth rings and wood physical (density), anatomical (early- and latewood ratio) and wood chemical (lignin content (%); R^2 = 0.98; RMSEP = 0.45, S/G ratio; R^2 = 0.96; RMSEP = 1.34, cellulose content (%); R^2 = 0.96; RMSEP = 0.94, xylose content (%); R^2 = 0.83; RMSEP 1.12) properties (Chang and Li 2005). It is clear from the experimental work that these characteristics can be determined rapidly through NIR spectrometry and used in forestry and pulp research programs.

The application of NIR in tree breeding programs will improve the ability to select for product characteristics such as wood density, pulp yield, kappa number, cellulose and extractives content. The main advantage is the relative inexpensive data collection procedure and the ability to measure multiple properties simultaneously. The technology makes use of only a few grams of wood meal to determine selected wood and fibre properties, and is therefore suited for non-destructive sampling when trees are mid-rotation age or even younger. Large numbers of samples can be screened in this way and thereby realizing the benefits of desirable characteristics in trees for the production of pulp wood sooner.

3.1.3 Purpose of this study

The aim of this study was to evaluate NIR as a tool for measuring the wood characteristics of an *Eucalyptus grandis* clone with the purpose to replace wet chemistry methods in tree breeding and certain aspects of quality control in Mondi SA Division.

Therefore, the specific objectives of this study were to:

- Develop calibrations for those **physical properties** of *E. grandis* clonal wood meal, e.g. wood density and fibre dimensional properties, e.g. Muhlsteph-ratio, that are important in considering the quality and performance of wood under processing conditions. These are characteristics that are deemed important in the end-use of the paper manufactured.
- Develop calibrations for characteristics associated with the **Kraft pulping process** of this *E. grandis* clonal wood. These include pulp yield and kappa number, and also characteristics that supply more information about the process, e.g. residual effective alkali after the cook as an efficiency parameter.
- Develop calibrations for **chemical properties** of wood which include amount of cellulose, hemicelluloses, lignin (acid insoluble, soluble, and total) and individual monosaccharides (arabinose, galactose, glucose, mannose and xylose).

- Test these calibrations by estimating the wood physical, process and chemical composition of wood meal from another *E. grandis* breeding population based on NIR spectra.

3.2 MATERIAL AND METHODS

3.2.1 Tree sampling

The wood material described in this study was obtained from a Nelder 1a spacing trial established by Mondi SA in Swaziland with a *Eucalyptus grandis* clone which was commercially available in the planting season of 1998 and was sampled for the construction and evaluation of the NIR-model. There were 17 arcs (spacing treatments) of which the most inner and outer treatments were treated as guard rows. Each treatment was replicated in 48 single tree plots, which provided a sample of 48 trees per spacing treatment. The trees were measured for diameter and height annually for a seven year period and described by du Plessis and Kotze (2011). Growth and yield values of the treatments selected for this study are shown in Table 3-1.

Table 3-1: Growth and yield results of trees selected for NIR model development.

Tree planting density(TPH)	Survival (%)	Volume i.b. (m^3 ha^{-1})	Basal Area (m^2 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	Dominant Height (m)	Quadratic Mean Diameter (cm)
6809	64.6	187.7	41.6	27.8	22.6	10.5
2336	89.6	216.5	31.8	32.1	24.5	13.5
801	93.8	204.6	23.0	30.3	27.2	19.3
275	100	154.1	15.4	22.8	28.7	26.6
Mean of 48 trees per spacing treatment; i.b. = inside bark volume						

In total, twenty trees were selected for intensive material analyses. These represented five defect free individual trees from four treatments: 6809 TPH, 3052 TPH, 801 TPH and 275 TPH.

3.2.2 Wood sampling

Each tree was destructively sampled as shown in Figure 3-1.

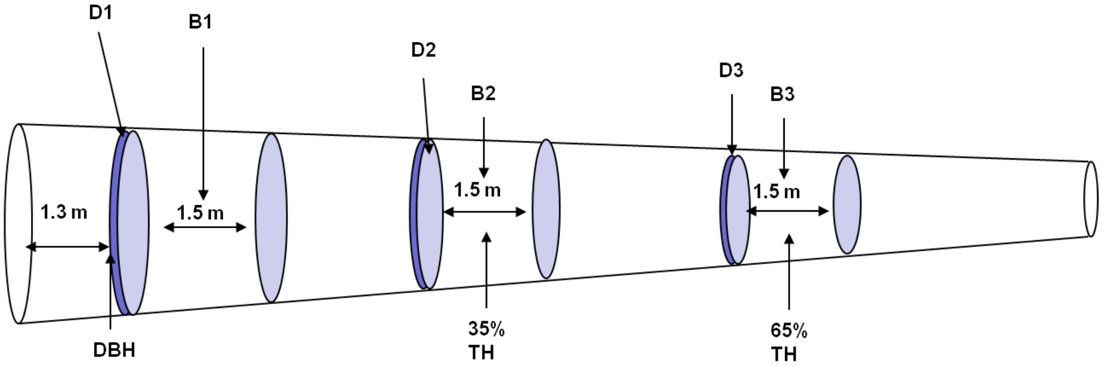

Figure 3-1: Schematic illustration of sampling for wood, pulp and paper studies (collecting discs D_i and logs B_i from various tree heights, TH).

3.2.2.1 Wood analysis

Discs numbered D1, D2 and D3 were used to cut pith to bark strips to determine air dry wood density. In addition, discs were also removed below and above each log for anatomical studies. A rectangular wooden block was sawn through the centre of each disc, all in the same direction relative to the orientation of each tree in the trial (see Figure 3-2). The wooden blocks from each disc were stored at 23 ºC and 50 % RH to achieve an equilibrium moisture content (EMC) of about 10 %. Strips of uniform thickness were cut along the radius using a twin-blade saw. As illustrated in Figure 3-2, the sample dimensions were 12 mm in the longitudinal and 2.5 mm in the tangential direction along the entire length of the core determined by the radius of each individual disc. Figure 3-2 also illustrates the scanning direction of the sample. To measure radial, air-dry wood density profiles from bark to pith, strips were scanned at 0.5 mm intervals using a gamma-ray densitometer with a Fe^{55} radiation source. The data acquisition was computer controlled with a stepper motor drive that ensured exact 0.5 mm incremental moves at a time. The use of gamma-ray densitometry was considered to be an accurate and reliable technique to determine wood density (Malan and Marais 1991, Kang et al. 2004). The weighted mean density of the entire disc was calculated from the density profile.

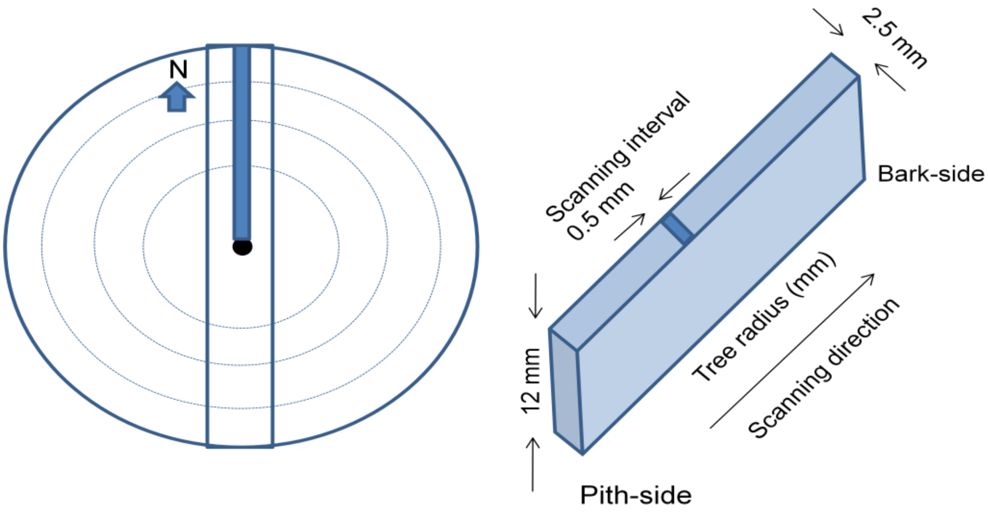

Figure 3-2: Wood sampling protocol from discs indicating block taken through the centre and strip sawn.

3.2.2.2 Pulping and pulp analysis

Logs (B1 - 3) were labelled and chipped individually with a 38" diameter horizontal feed disc chipper (Precision Husky Corporation, Alabama, USA) at the CSIR - FFP laboratory in Durban, South Africa. Chips were bagged and kept for pulping at the Mondi Richards' Bay Pulp Research laboratory. Three batches of chips per tree (B1, 2 and 3) were pulped in an Aurora recirculating mini digester subjected to standard cooking conditions normally used by the Mondi research laboratory, controlling the kappa number around *c.* 20. The following pulping protocol was used:

- 1000 g oven dry wood chips loaded per cook
- 15 % active alkali as Na_2O
- white cooking liquor added; NaOH (15 %) added as Na_2O + Na_2S
- 25 % sulphidity (added as SO_2)
- 4.6:1 liquor to wood ratio
- ambient to 170 °C in 90 minutes
- *h*-factor of *c.* 900
- degassing at 90 °C and 110 °C.

The pulp was disintegrated before being sieved through a Packer screen to remove all reject material including shives and uncooked knots.

The screened pulp yield, rejects and total pulp yield (TPY) were determined after the cook according to Tappi methods. The kappa number was determined as the volume (ml) of 0.1 N potassium permanganate solution consumed by one gram of moisture-free pulp under the condition that the screened pulp yield was below 70 % as per Tappi standard method (T236). Residual effective alkali which is an indication of the unspent cooking liquor in the Kraft cook, also referred to as the residual effective alkali (EAr) was determined making use of titration methods as described by Tappi method (T625 cm-85).

The coarseness of fibres, defined as weight per unit length measured in mg.100m^{-1}, was calculated from a sub sample of individual fibres after pulping, measured using a Metso Kajaani Fibrelab. Coarseness is a useful parameter used by papermakers to control paper strength; as the number of fibres per gram of pulp increases so does paper strength due to greater bonding area in the paper sheet (Arbuthnot 1991).

A physical tracheid fibre parameter often considered by paper makers is Muhlsteph-ratio which is defined as the relationship between fibre cell wall area (µm^2) and fibre cross sectional area (µm^2), has a size order of 0 - 1 and was calculated from the image analysis data. The Muhlsteph-ratio is widely seen as a measure to characterize wood density indicating that fibres with high Muhlsteph-ratio are less desirable for paper making (Jang and Seth 1998).

3.2.2.3 Chemical data obtained with HPLC

Samples of the pulp produced from logs 1 - 3 were analysed with high performance liquid chromatography (HPLC). Extractives were not removed prior to scanning. The solution of individual fibres was filtered in a regenerated cellulose membrane with pore size 0.45 µm and analysed with a Shimadzu CBM-10A HPLC apparatus equipped with a reverse phase analytical column. The column temperature was kept at 40 °C and mobile phase flow of 1.5 mL min^{-1} was used. Using this method it was possible to measure the amount of cellulose and xylose in the wood and sugars such as glucose, galactose, mannose and arabinose in the pulp samples according to the method described by Fardim and Duran (1999). Mannose and arabinose fractions were undetected in the pulp samples, most probably due to the harshness of the cooking liquor in the initial cook, also described by Kleen et al. (1993).

The lignin was determined as the insoluble portion and acid soluble portion. Total lignin is the sum of the two.

Hexuronic acids (HexA) are important in the Kraft pulping process. They are formed by the conversion of 4-O-methyl-glucoronic acid groups in the strong alkali conditions. If they are not removed from the pulp through an acid hydrolysis stage during the bleaching of pulp, they remain part of the pulp and cause a false and exacerbated kappa number (Andrew et al. 2008). The result of excessive hexuronic acid in unbleached pulp leads to increased use of chlorine dioxide and hence a potentially uneconomical bleaching process. Hexuronic acid (HexA) amount in pulp samples was measured by HPLC as described by Andrew et al. (2008).

Table 3-2 provides a list of wood, pulping and pulp properties evaluated.

Table 3-2: List of characteristics measured on wood and pulp materials and pulping process.

Product/Process	**Property**	**Unit**
Wood	Basic wood density	g cm^{-3}
	Muhlsteph-ratio	number
Pulping process (Digester)	Total Pulp Yield	%
	Kappa number	number
	Residual effective alkali	g_{NaOH} ml^{-1}
Pulp physics	Coarseness	mg $100m^{-1}$
Pulp chemistry (HPLC)	Glucose	%
	Cellulose	%
	Xylose	%
	Total polysaccharides	%
	Galactose	%
	Insoluble lignin	%
	Acid soluble lignin	%
	Total lignin	%
	HexA	µ mol g^{-1}

3.2.3 NIR analysis

3.2.3.1 Sample preparation

Wood meal was prepared for each of the 60 samples that were available for the NIR model calibration. A wedge (approximately 15 ° to 20 °) from discs D1, D2 and D3 from each of the twenty trees was removed. The wood was regarded as mostly juvenile. The wedges were reduced to smaller pieces and ground in a Wiley mill and passed through a 1 mm screen. Flat bottom glass vials with 22 mm outer diameter and 12 ml capacity were filled with the wood meal.

3.2.3.2 NIR scanning

For spectral acquisition, a Bruker MPA-R spectrometer was used equipped with software Opus version 6.5. This equipment uses the Fourier transformation and has an integrating sphere. Spectral acquisition was conducted in the 12,000 to 3,781 cm^{-1} range in absorbance mode at a resolution of 4 cm^{-1}. NIR scans of the wood meal in vials for each of the 60 samples (4 planting density treatments x 5 trees ea. x 3 logs each) were taken in triplicate for each sample, agitating the sample between scans. Of the 180 total scans generated, the software was used to assign 70 % to the calibration and 30 % to the validation procedures.

3.2.3.3 Multivariate data analysis

Multivariate calibration combines a large amount of spectral information with the corresponding reference values of the sample. Partial Least Squares (PLS) that combines features from principal component analysis (PCA) and multiple linear regression, is the most common statistical chemometrical method used for multivariate calibration in analytical chemistry, and spectroscopy in particular (Nadler and Coifman 2005). In the typical setting, given a finite training set with n samples (x_i, y_i), PLS builds a linear relationship between a set of predictor (independent) variables, the x's and a set of response (dependent) variables, the *y's* which is then used for prediction of y for new data x. The main assumption of PLS is that the data x, although possibly residing in a high-dimensional space, depend linearly on only a small number of principal components. PLS estimates these principal components as projections of the original input variables of x and uses them to construct the regression vector relating x to y (Nadler and Coifman 2005).

3.2.3.4 Calibration

The data set used for the prediction of properties with the newly developed NIR-models and comparison with wet analytical chemistry methods, was that of an advanced *E. grandis* breeding population that forms part of Mondi's tree improvement research program.

The Quant II software supplied as part of Opus 6.5 was used as a calibration tool. Models were fitted using the partial least squares (PLS) regression method with a limit of 10 latent variables. The exact number of latent variables that described the most variation for each model was suggested by the statistical program. Calibrations models were developed from 70 % (c.126 scans from 42 wood samples) of the complete data set while the validation method used in this work was 30 % (c. 54 scans from 18 samples) of the complete data set which were not included in the calibration. The validation strategy was that of "external validation"; i.e. validation samples were only used to validate the model. Optimization was done by evaluating coefficient of determination (R^2) and comparing the Root Mean Square Error of Calibration (RMSEC) and Root Mean Square Error of Prediction (RMSEP). The predictive ability of the model was evaluated by considering the Residual Predictive Deviation (RPD). RPD is calculated as the quotient of standard deviation (SD) of the reference values of the validation set and the bias corrected standard error of prediction (SEP); a larger RPD is indicative of a better prediction model. The bias, which is the systematic averaged deviation between the data set of the true and the predicted values, was also calculated.

Outliers were detected by calculating the residuum which is the difference between the real data and data reconstructed through factorization. Data points with exceptional high F - values are deemed outliers and removed by the software (QuantII) as described in Conzen (2006).
Selection of the best model was based on the application of the following sequential criteria:

- highest correlation coefficient of determination (R^2)
- lowest Root Mean Square Error of Prediction (RMSEP); the quantitative measure for the preciseness of the analysis of test samples
- highest ratio of Residual Predictive Deviation (RPD)
- lowest number of latent variables (factors) used in calibration.

3.2.4 Independent test data

Wood meal from an independent *E. grandis* breeding population from the proprietary breeding program of *Eucalyptus* in Mondi SAD, was sourced in a similar way as described above and was selected to test the calibrations. Glass vials were filled with wood meal constituting of 38 independent and random samples and were scanned using NIR. Wood density, total pulp yield, kappa number and cellulose content were predicted with NIR spectroscopy for the Nelder samples using the calibrations developed in this study. Laboratory measured data for the four selected variables were available for the 38 samples. A paired sample *t*-test was carried out to establish whether there were any differences in the data sets between the measured and predicted values. The accuracy of the newly developed calibrations was assessed.

3.3 RESULTS AND DISCUSSION

It is well known that properties of wood and the processed pulp are strongly affected by growing and processing (pulping) conditions. Variation in properties is ever present within a tree and between trees. Knowledgeable selection of trees and the sampling of wood from these trees can ensure that enough variation of the wood material is considered in an implementation of a NIR evaluation.

3.3.1 Descriptive statistics of wood, fibre, pulping and pulp results

Descriptive statistics of the wood, pulp and pulping process properties are listed in Table 3-3.

Table 3-3: List of properties measured on wood and pulp materials and pulping process.

Product	Property	Unit	Means for trial	SD	Min	Max	CV
Wood/ Fibre	Wood density (Gamma-ray; non-extracted air dry density)	g cm^{-3}	0.468	0.057	0.343	0.578	12.10
	Muhlsteph-ratio	number	0.514	0.023	0.464	0.603	4.47
Pulp Process (Digester)	Total Pulp Yield	%	53.61	1.42	50.52	56.69	2.66
	Kappa number	number	21.82	3.58	16.46	32.40	16.42
	Residual effective alkali	g_{NaOH} ml^{-1}	9.36	1.08	4.68	11.62	11.53
Pulp physics	Coarseness	mg $100m^{-1}$	7.13	0.633	6.00	10.30	8.87
Pulp chemistry (HPLC)	Glucose	%	80.14	2.36	74.44	85.63	2.95
	Cellulose	%	48.46	4.45	43.53	58.45	9.18
	Xylose	%	11.54	1.56	7.98	14.87	13.50
	Total polysaccharides	%	92.00	1.38	87.72	94.72	1.50
	Galactose	%	0.206	0.065	0.00	0.340	31.57
	Insoluble lignin	%	4.51	1.28	2.86	8.46	28.47
	Acid soluble lignin	%	3.16	0.29	2.38	3.90	9.25
	Total lignin	%	7.67	1.42	5.26	11.92	18.53
	HexA	µ mol g^{-1}	46.39	6.43	30.80	59.00	13.86

In Table 3-3 the means, SD, range and coefficient of variation (CV) are shown. Noticeable is the high pulp yield (53.6 %) and low CV in the data. When comparing cellulose content and pulp yield, it is observed that the pulp yield is 5.2 percentage points higher which is an indication of residual lignin and possibly extractives left in the pulp. The kappa number as can be expected, is close to 20 which is a process control parameter and was set before the pulping commenced. The coarseness with mean of 7.13 mg 100 m^{-1} is similar to those found for *E. globulus* and *E. nitens* as described by Muneri and Raymond (2001). Since the samples that were used in the HPLC were from the pulp, the total lignin reflects that of pulped fibres and not raw wood. Galactose was, due to the cooking process, almost undetected in the pulp sample and cannot as such be used in a calibration of a NIR model.

Shown in Figure 3-3 is a graphical representation of the NIR spectral data used in the calibration data set.

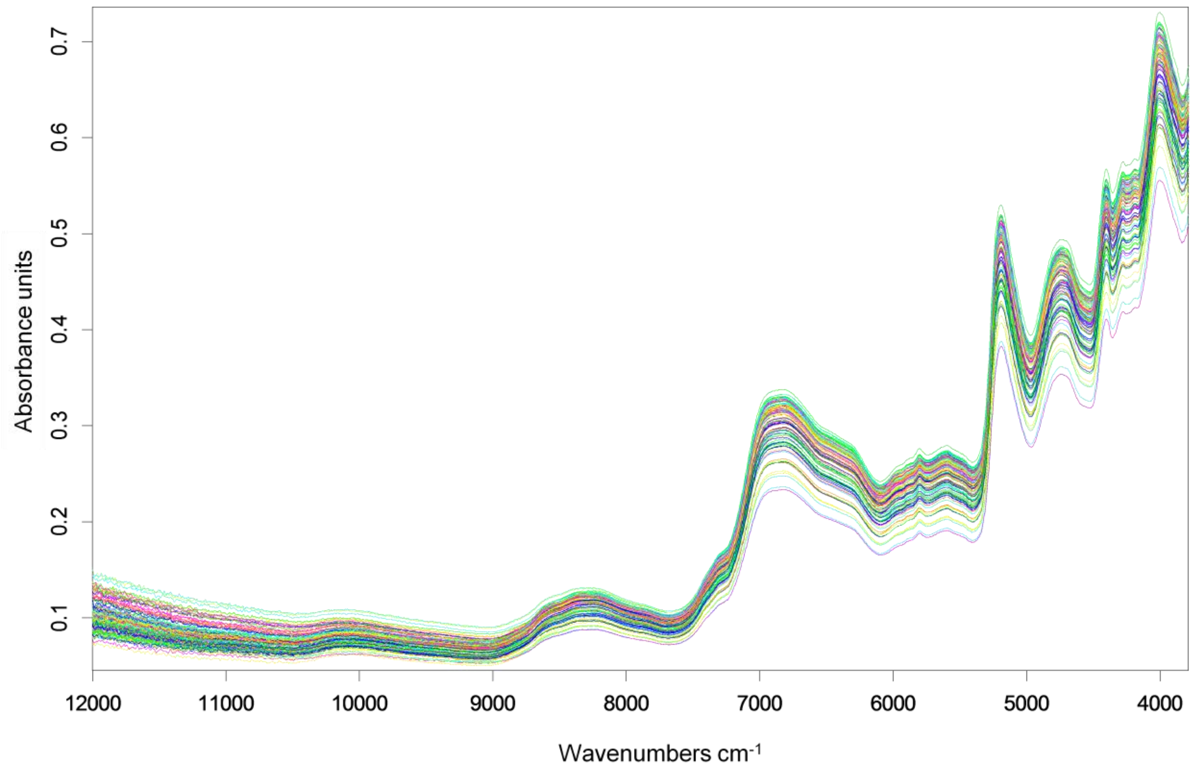

Figure 3-3: NIR unprocessed reflectance spectral data used as the calibration data set.

3.3.2 Calibration and validation

3.3.2.1 Wood and Fibre

Calibration statistics were developed for the two solid wood and one physical pulp properties as indicated in Table 3-4. The calibration statistics based on NIR scanning of wood meal demonstrated that good calibrations were obtained for physical (non-chemical) properties examined. The number of factors refers to the number of individual principal components developed by the PLS procedure to explain the variance in the population.

For air dry *wood density*, the RMSEP results for the validation were similar to the RMSEC results, indicating that calibrations based on NIR spectra of ground wood samples as suggested by Fardim (2002), can be used to rapidly predict air dry wood density in a prediction set. From Table 3-4 it is also noted that the PLS procedure used three different pre-processing algorithms to find optimum calibration. The coarseness and Muhlsteph-ratio calibrations were low considering the R^2 values. Sample outliers, if identified by the software, were removed from the calibration.

Table 3-4: Summary statistics of calibrations developed for *E. grandis* clone wood properties.

Parameter	Pre-processing algorithm	No. of factors	Calibration		Validation			
			R^2	RMSEC	R^2	RMSEP	Bias	RPD
Wood density (kg m^{-3})	Min-max normalization	4	0.81	23.30	0.77	34.2	–2.66	2.3
Muhlsteph-ratio	1st derivative	5	0.43	0.016	0.36	0.016	–0.003	1.3
Coarseness (g 100m^{-1})	Constant offset elimination	6	0.63	0.341	0.47	0.410	0.010	1.4

RMSEC: root means square error of calibration, RMSEP: root mean square error of prediction. RPD: residual prediction deviation.

The validation plots for measured and NIR modelled wood density, Muhlsteph-ratio and fibre coarseness are shown in Figure 3-4, Figure 3-5 and Figure 3-6.

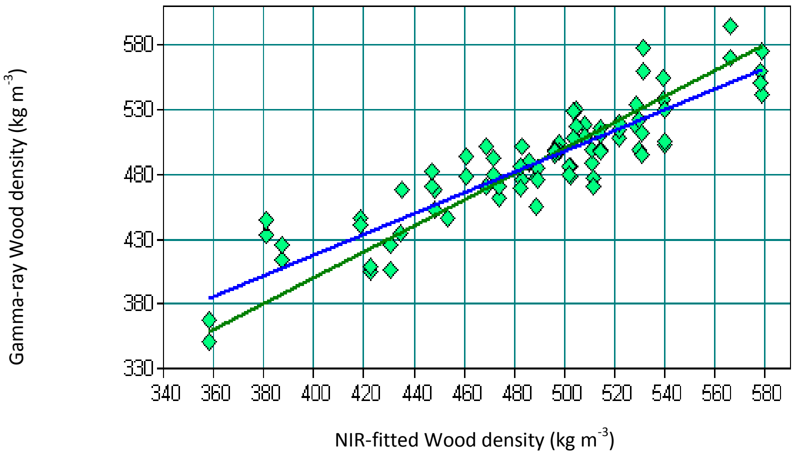

Figure 3-4: Relationship between gamma-ray density and NIR-fitted density for validation data set. Blue line represents the regression and the green line represents the 1:1 slope.

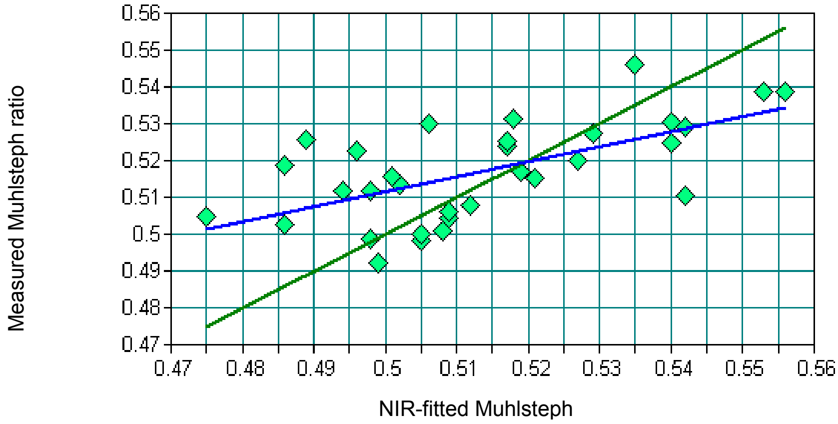

Figure 3-5: Relationship between measured and NIR-fitted Muhlsteph-ratio for the validation set.

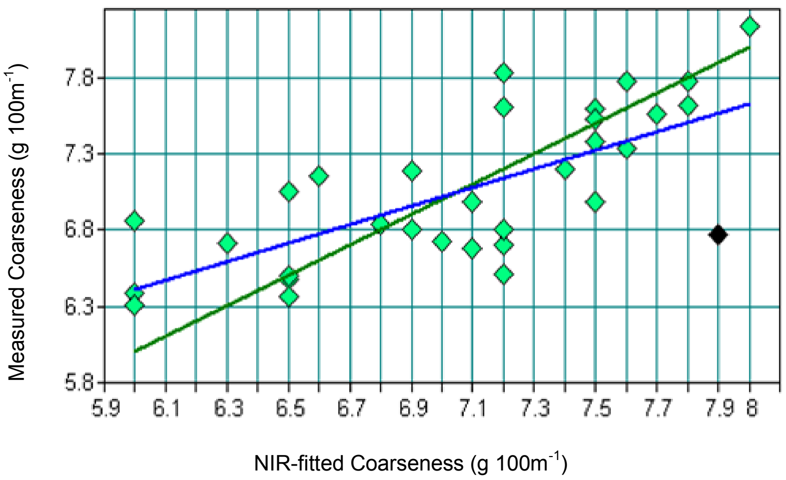

Figure 3-6: Relationship between measured and NIR-fitted fibre coarseness for the validation data set. Black diamonds are outliers excluded from the final fit.

When bulk wood properties were considered, a good fit was achieved for wood density. A weaker measured versus validation model relationship for Muhlsteph-ratio (Figure 3-5) and fibre coarseness (Figure 3-6) were observed. Little bias was evident in all three models, considering the green line in each of Figures 3-4, 3-5 and 3-6 that represents the slope of 1:1 and the blue line, the regression line. Underestimation occurs in all three fitted parameters; in the case of wood density a validation bias of –2.66 kg m^{-3} is evident at values below 440 kg m^{-3} and overestimation above 540 kg m^{-3}. The average wood density of 468 kg m^{-3} fits into the zone where little bias is measured.

The wood density model ($R^2_{cal.}$ = 0.81 and $R^2_{val.}$ = 0.77) with a Residual Prediction Deviation (RPD) as first described by Williams (1987) with a value of 2.3, is suitable to be used for screening of material. It was reported by Schimleck et al. (2003) that a RPD value of higher than 1.5 is considered satisfactory for preliminary readings and predictions for tree selection in forest tree improvement programs. The R^2 and RPD-value should improve with more samples added to the model to allow for bias of the RMSEP to decrease for the same variance (SD). RPD values greater than five can be applied for quality control and analytical procedures Williams (1987).

The wood density prediction model can be used for preliminary screening of trees especially where the knowledge about this property is important in, e.g. tree breeding, Kraft pulping or the manufacturing of paper.

3.3.2.2 Pulping process

Significant relationships were described when the NIR models of total pulp yield (TPY) and kappa number were fitted with measured data. TPY with 6 latent variables (PLS components) was well correlated; $R^2_{cal.}$ = 0.80, RMSEC = 0.549 and RPD = 3.2. RPD was in all cases calculated from the validation data. In the kappa number model, the following calibration statistics were returned; 3 latent variables, $R^2_{cal.}$ = 0.95, RMSEC = 0.831 and RPD = 4.6. According to Williams (1987) and Schimleck et al. (2003) the RPD values of 3.2 and 4.6 for pulp yield and kappa number respectively, (Table 3-5), position these predictions in the category of "quality control". Schimleck et al. (1998) further suggested that calibrations with these RPD-values can be used in the tree breeding programs to identify individual trees with high TPY and low kappa numbers given a specific set of cooking conditions. Summary statistics are shown in Table 3-5. Note that no spectral data pre-processing was necessary in the case of TPY and EAr. It was necessary to process kappa data by means of the constant offset elimination method to get the most suitable PLS calibration set.

Table 3-5: Summary statistics for the NIR spectra fit with measured data for the pulping process.

Parameter	Pre-processing algorithm	No. of factors	Calibration		Validation			
			R^2	RMSEC	R^2	RMSEP	Bias	RPD
Total Pulp Yield	No spectral data pre-processing	6	0.80	0.549	0.75	0.556	0.124	3.2
Kappa number	Constant offset elimination	3	0.95	0.831	0.77	1.82	–0.048	4.6
Residual Effective Alkali (g_{NaOH} ml^{-1})	No spectral data pre-processing	5	0.36	0.765	0.19	0.821	–0.042	1.2

RMSEC: root means square error of calibration, RMSEP: root mean square error of prediction. RPD: Residual Prediction Deviation.

The $R^2_{val.}$ for TPY and kappa number was 0.75 and 0.77 respectively, adding to the usefulness of these two calibrations to be used routinely. The residual effective alkali (EAr) returned low relationships between measured and spectral data. The EAr-model is not good for screening; however, residual effective alkali remains an important process parameter to establish the completeness of the cook.

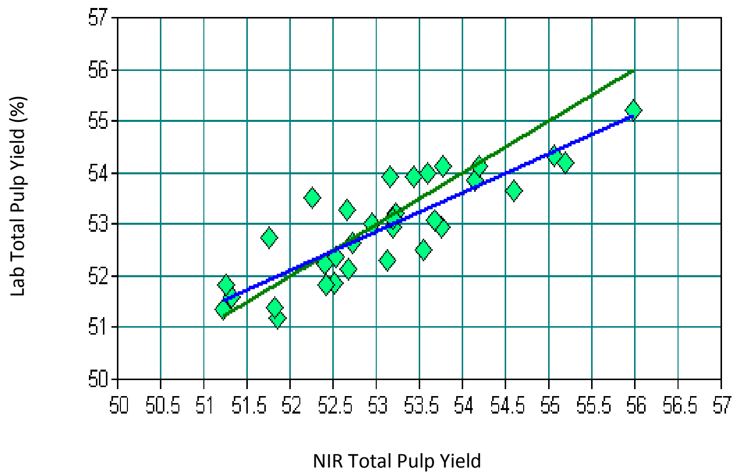

Figure 3-7: Relationship between total pulp yield and NIR-fitted TPY for validation data set.

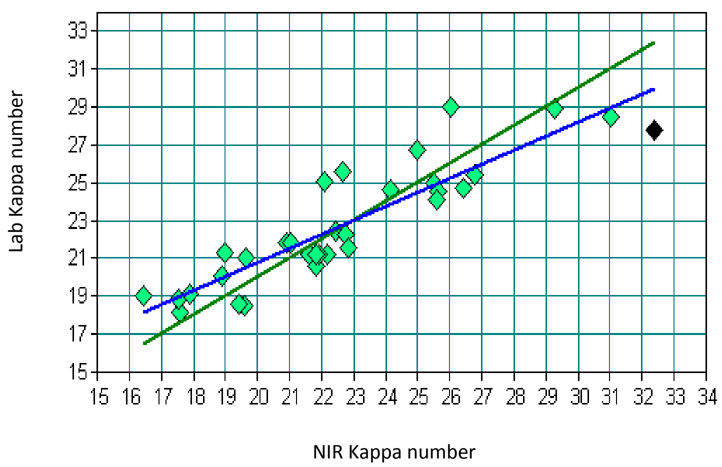

Figure 3-8: Relationship between measured and NIR- fitted kappa number for validation data set.

Visual representations of the TPY and kappa number validation model fits are given in Figure 3-7 and Figure 3-8. The regression lines (blue line) are noticeably close to the slope line where a slope of 1:1 is represented by the green line. Furthermore, the RMSEC and RMSEP values for all properties are similar which is an indication of good predictive ability (Fardim et al. 2002) when unrelated samples are scanned and predicted by means of these models. The benefit in especially breeding programs is substantial when non-destructive sampling of increment cores are used. Core samples can now, instead of pulping, be used to prepare wood meal and scanned to predict TPY or kappa number; also reported by Raymond et al. (2001). The bias reported for both TPY and kappa number in this Nelder planting density-study were small, *c.* 0.1 %, emphasising the need for experimental design to include the entire range of variation when the models are calibrated.

3.3.2.3 Pulp chemistry

Summary NIR statistics for pulp chemistry are shown in Table 3-6.

Table 3-6: Summary statistics for the NIR spectra fit with measured data from the HPLC, for wood and pulp chemistry.

Parameter	Pre-processing algorithm	No. of factors	Calibration		Validation			
			R^2	RMSEC	R^2	RMSEP	Bias	RPD
Glucose	1st derivative	5	0.53	1.87	0.39	2.10	0.349	1.46
Cellulose	No spectral pre-processing	9	0.70	1.53	0.43	2.48	0.312	1.84
Xylose	2nd derivative	6	0.60	1.11	0.29	1.45	–0.351	1.57
Total polysaccharides	1st derivative	4	0.45	1.09	0.41	1.17	–0.040	1.35
Insoluble lignin	1st derivative	7	0.82	0.22	0.66	1.09	0.054	1.63
Total Lignin	1st derivative + MSC	4	0.45	1.11	0.37	1.24	0.069	1.34
HexA	Straight line subtraction	6	0.50	4.78	0.25	5.83	–0.931	1.42

Good calibrations were developed for predicting amounts of cellulose and insoluble lignin, and moderately good for xylose from pulp samples analysed by HPLC as indicated in Table 3-6. A high $R^2_{cal.}$ value of 0.82 and a low RMSEC of 0.22 were obtained for the calibration for insoluble lignin content using measurements from *c.* 42 samples (70 % of the data set) scanned in triplicate. Hexuronic acid (HexA) showed moderate calibration ($R^2_{cal.}$ = 0.50) but high RMSEC of 4.78. Xylose calibrated moderately good with an $R^2_{cal.}$ = 0.60 and RMSEC = 1.11. Similarly, cellulose had a good $R^2_{cal.}$ = 0.70 and RMSEC = 1.53 but with a low RPD value of 1.84 that indicates low application value. No meaningful calibration was found for galactose, returning negative coefficients of determination (not shown).

The wood and pulp chemistry validation sets were poorly correlated. Validations developed from *c.* 18 samples (30 % of the data set) for insoluble lignin returned $R^2_{val.}$ of 0.66, and RMSEP of 1.09. The R^2-values in the validation data set was generally much lower than for the calibration data set and hence, when considering the R^2-values and evaluating RPD simultaneously, it is evident that wood and pulp chemistry of the *E. grandis* material used, can at this stage not be predicted accurately with the NIR-models.

3.3.3 Independent test data validation

Based on the prediction models developed for wood and fibre (Table 3-4), pulp and process (Table 3-5), and chemical parameters (Table 3-6), an independent data set with known laboratory measured values was tested with predicted values from the newly constructed NIR-models. The data set used for the validation of the newly developed NIR-models and comparison with wet analytical chemistry methods, was that of an advanced *E. grandis* breeding population that forms part of Mondi's proprietary tree improvement research program. The selection of properties entered in the independent test was based on significance of the coefficients returned from the validations, but also on the potential use of these properties to develop a fibre optimization index to describe potential productivity throughput in a vertically integrated pulp mill such as Mondi Kraft at Richard's Bay.

The variables selected for the evaluation of the test data set had high R^2 and low RMSEP values and are listed:

- Wood Density ($R^2_{val.}$ = 0.77, RMSEP = 34.2)
- TPY ($R^2_{val.}$ = 0.75, RMSEP = 0.56)
- Kappa number ($R^2_{val.}$ = 0.77, RMSEP = 1.82)
- Cellulose ($R^2_{val.}$ = 0.43, RMSEP = 2.48).

The paired *t*-test assumes that the differences between pairs are normally distributed; as seen in Table 3-7 evaluating the p-values, no significant differences between NIR predicted and measured paired data sets were found. The data was normally distributed and deemed fit to test the calibrations on.

Table 3-7: Statistics from pair wise *t*-test returned for NIR predicted and measured variables.

Property	Mean of the difference	SD	Standard Error	*t* – value	Pr > |*t*|
Wood density	6.388	45.97	7.458	0.86	0.397
Pulp Yield	–0.075	0.62	0.142	–0.68	0.604
Kappa number	0.567	1.87	0.304	1.86	0.072
Cellulose	1.180	2.28	0.554	2.31	0.059

Linear regressions were fitted to the data with the measured and NIR-predicted variables respectively as dependent and independent variables. The statistics are given in Table 3-8. The coefficient of determination for total pulp yield (TPY) and kappa number were high; all models were significant at the 95% level.

Table 3-8: Regression statistics for NIR-predicted and measured variables (n=38).

Variable	Coefficients		MSE	F-value	R^2_{adj}	p
	β_0	β_1				
Wood density = $\beta_0+\beta_1 \cdot$NIR(Wood density)	114.877	0.770	38.176	22.73	0.39	<0.0001
Pulp Yield = $\beta_0+\beta_1 \cdot$ NIR(Pulp yield)	8.561	0.824	0.741	93.88	0.73	<0.0001
Kappa number = $\beta_0+\beta_1 \cdot$ NIR(Kappa number)	–1.519	1.108	0.964	77.77	0.76	<0.0001
Cellulose = $\beta_0+\beta_1 \cdot$ NIR(Cellulose)	1.332	0.996	2.534	5.59	0.24	0.0343

The regression equations were plotted with observed values and displayed in Figure 3-9.

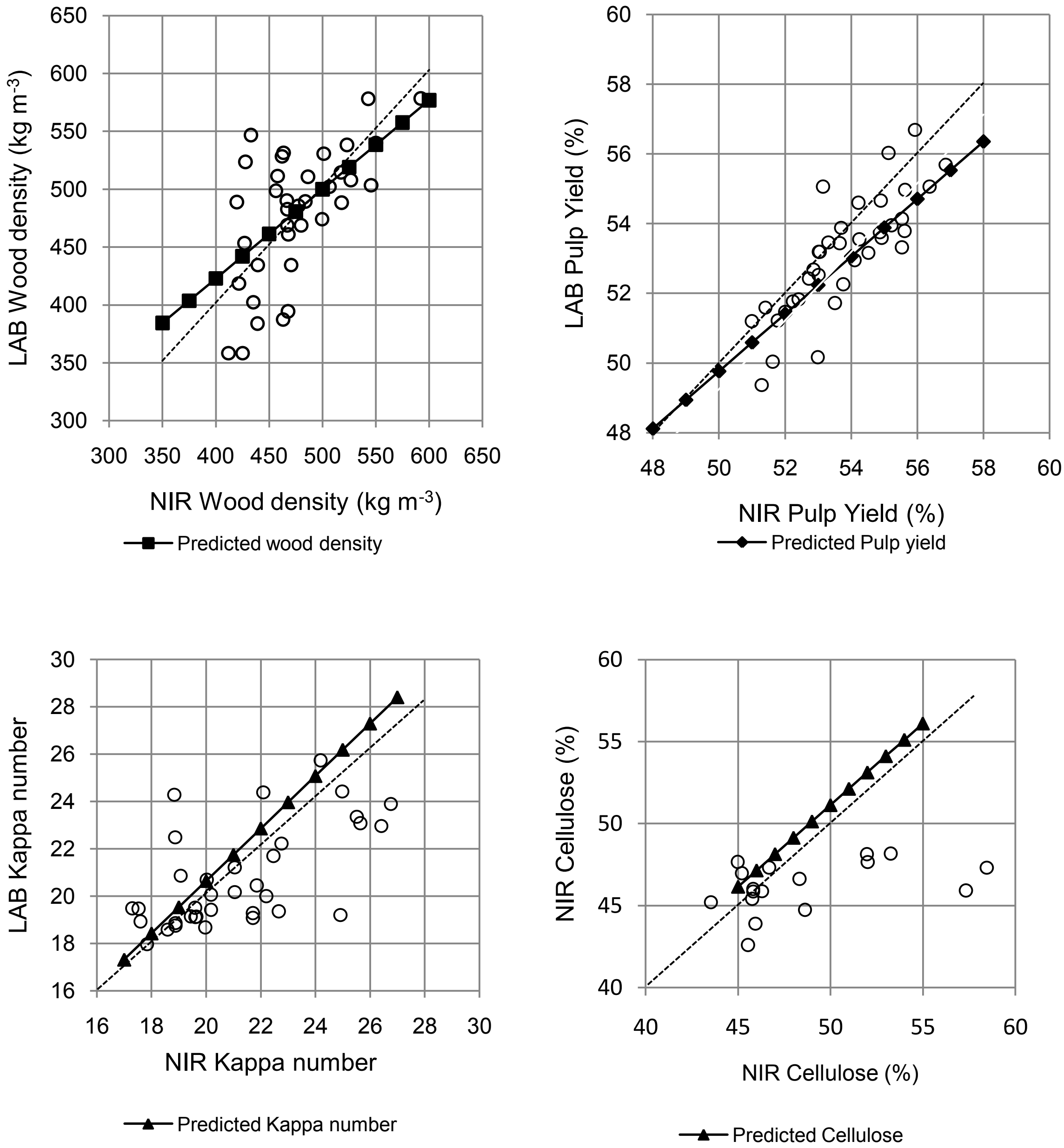

Figure 3-9: Graphical representation of calibration model for NIR vs. Measured data with observed data points on each curve for wood density, pulp yield, kappa number and cellulose. Dashed lines with a slope of 1:1 represent a perfect fit. Regression coefficients

When validating calibration models with an independent dataset the **wood density** of NIR predicted and laboratory measured samples were poorly correlated at $R^2 = 0.39$ (Table 3-8). The wood density model in Figure 3-9 displays an under-prediction at levels below 500 kg m^{-3} and an over-prediction for values greater than 500 kg m^{-3}. The NIR calibration for the wood density model as indicated worked well Table 3-4: $R^2_{cal.} = 0.81$ and $R^2_{val.} = 0.77$), however the sample range of the test data set was limited (400 < kg m^{-3} < 550) and could cause low regression fit. The high RMSEC for wood density calibration (RMSEC = 23.3) and validation (RMSEP = 34.2) indicates high error in the calibration procedure. The underlying problem can be with laboratory techniques; the NIR calibration used air-dry gamma-ray density data to develop the calibration and the test data set was developed with gravimetrical methods (basic wood density). Basic wood density is usually 10 % lower than gamma-ray density and well correlated (Grundelius 1990, Zboňák 2002). The predictions within the regression model were found to have low bias as described by Poke and Raymond 2006, based on the X-multiplying factor (β_1 coefficient) of 0.770, see Table 3-8 and Figure 3-9.

Total pulp yield (TPY) was highly correlated between NIR prediction and laboratory measured data ($R^2 = 0.73$). Methods of laboratory pulp cooking are well described and understood, resulting in consistent, good data for regression coefficients. The β_1 coefficient in the regression equation (Table 3-8) of 0.824 indicated high prediction potential; the NIR calibration was also successful ($R^2_{cal.} = 0.80$; RMSEC = 0.549 and $R^2_{val.} = 0.75$; RMSEP = 0.124) as seen from Table 3-5.

The NIR-prediction for **kappa number** was well correlated with the test data from the laboratory determined kappa number ($R^2 = 0.76$) and the β_1 coefficient of 1.108 indicating a sufficient predictive ability without major bias. The model, as suggested by the β_1 coefficient, over-predicts by *c.* 10 % for the entire range of data samples. This will adjust when more samples are calibrated by PLS-analysis of spectral and analytical data on the NIR spectrometer.

It is recommended from this information that wood density and cellulose models are used for crude screening and ranking procedures. Although regression equations indicated that these predictions did not have high accuracy overall, the majority of predictions were close to laboratory analytical values and wood meal NIR calibrations may be useful to approximate values for these traits (See also Poke and Raymond 2006).

The pulp yield and kappa models are recommended for the prediction of values from new samples. If these calibrations are used in scenario modelling such as fibre productivity and optimisation modelling, the prediction model will return unbiased figures.

Similarly for **cellulose**, from Table 3-8 and Figure 3-9 it is clear that the regression coefficients were unsatisfactorily low ($R^2 = 0.24$), indicating a low precision, but the prediction bias of the regression model ($\beta_1 = 0.996$) of determining Y was low, indicating potential for better calibration success if more samples are added to the calibration and validation data sets, which is already satisfactorily ($R^2_{cal.} = 0.70$ and $R^2_{val.} = 0.43$). The cellulose model is consistently over-predicting by *c*. 2 % and may be a factor of the data range of the samples in the test data.

From the chemical data set (Table 3-8) and subsequent calibration with NIR spectra, only insoluble lignin returned satisfactorily results ($R^2_{cal.} = 0.82$ and a low calibration error of 0.22; $R^2_{val.} = 0.66$ and a low error of prediction of 1.09). Analytical chemistry data for insoluble lignin were not available for the test data set and it was postulated that kappa number, showing high calibration statistics and returning good results from independent tests, can be used in further screening and analysis when lignin in the wood or process is considered.

3.4 CONCLUSION

NIR calibrations can be conducted successfully on ground wood prepared from increment core samples, facilitating the non-destructive sampling of standing trees. The results from this study suggested that, given a suitable set of samples from a wood resource, a single set of NIR spectra could be used (after appropriate calibration) for the prediction of many wood, fibre and product properties. The calibrations developed in this study have demonstrated that NIR spectroscopy has the potential to predict a range of wood, fibre and pulp properties of *E. grandis*. The method offers an alternative to traditional methods of wet chemistry laboratory analysis. In the light of these results and prior literature reports, it appears that NIR spectroscopy can be used to predict a wide range of chemical and physical properties of wood, fibre and pulp.

A few aspects of the study impacted negatively on results and are highlighted as follows:

- The calibration with HPLC derived chemical data was unsatisfactory and suggested that analytical chemistry data, rather than indirect data acquisition methods such as HPLC should be used for clear calibration sets with wood meal.
- Better calibration, validation and independent test results were expected when consistent sample preparation techniques are followed throughout the process, e.g. samples for kappa number were consistently prepared by using Tappi method (T236). To the contrary, wood density calibration data was sourced from gamma-ray densitometry (which gives air-dried density) whereas the test data set was measured gravimetrically as basic wood density. It was shown that the wood density data contained a large error.

However, NIR spectroscopy and multivariate data analysis can be used satisfactorily as a means for rapid and cheap evaluation of chemical properties of wood, fibre and pulp properties for *Eucalyptus grandis* clones. This will facilitate the ranking of populations for tree breeding; determine response of wood property development to site factors or developing key indicators for the establishment of a fibre productivity index.

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CHAPTER 4 : Growth and yield models for *Eucalyptus grandis* grown in Swaziland

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CHAPTER 4 : Growth and yield models for *Eucalyptus grandis* grown in Swaziland

Abstract

The aim of this study was to develop a stand-level growth and yield model for short-rotation *Eucalyptus grandis* trees grown for pulp wood production at Piggs Peak in Swaziland. The data were collected from a Nelder 1a spacing trial established with *E. grandis* clonal cuttings in 1998 and terminated in 2005. Stand density ranged from almost free growing trees established at 161 trees per hectare to extremely dense stands at 6809 trees per hectare. Functions were fitted to describe stand density, dominant height and basal area development over time. The survival, height and basal area functions performed well when scrutinized for their goodness of fit. They were also found to be consistent with forest growth theory when their logical behaviour was tested over the range of planting densities. High predictive ability was observed when the Nelder models were compared with the Langepan model. The model forecasts an accurate growth and yield scenario for trees of variable stand densities that can be used in a fibre productivity index. The work presented in this chapter represents the quantitative forestry related component of a fibre productivity index designed to measure effectiveness of an integrated forestry enterprise and that also takes into account the quality of the pulping process, and the pulp and paper produced.

Keywords: *Eucalyptus grandis*, Nelder 1a spacing trial, stand-level growth and yield model, stand density, height, basal area, Piggs Peak, Swaziland

4.1 INTRODUCTION

The introduction of the genus *Eucalyptus* into South Africa occurred as far back as 1886 when Sir Lowry Cole introduced nine seedlings from Mauritius to Cape Town (Poynton 1979). In South Africa the *Eucalyptus* genus has received much attention with regard to tree breeding (Pallett and Sale 2004, Retief and Stanger 2009a, Verryn et al. 2009) and its interaction with site, management and environment has been studied intensively (Malan 2005, Retief and Stanger 2009b). Today, the genus *Eucalyptus* forms the backbone of the short-fibre kraft pulp industry in South Africa. In 2008 no less than 600,000 hectares had been planted to *Eucalyptus* spp. while the delivered volume was 11.3 million m^3 of which 85 % was processed in Kraft pulp mills (FSA 2009).

To optimize land use, managers need to know what the effect of different silvicultural regimes, such as genotype, stand density, fertilization and vegetation management will be on timber yield and also on wood, fibre, pulp and paper quality. A fibre productivity index, envisaged as part of this study, has quantity and quality components; the purpose of this growth and yield study was to describe quantity in terms of forestry factors namely survival, height and basal area development measured over a series of planting densities and time. Mondi Forests has the need to predict wood properties from stand-level data. The pulp processing component has set specifications for pulp wood quality and an indicator to measure conformance is required.

Stand density is one of the main intensive forestry management interventions used by foresters to manipulate vital resources required for tree growth. Spacing experiments are often used for growth and yield studies with the aim of capturing response of tree growth to varied planting densities (Shiver and Brister 1992, Mabvurira and Miina 2002, Malan 2005, Stape and Binkley 2010).

A Nelder 1a spacing trial, planted with *E. grandis* clonal cuttings, at Piggs Peak in Swaziland, became available to test the procedures to develop the underlying models required to predict growth as a function of age and stand density and to use this as a platform to predict wood properties as a function of the stand-level properties.

The objective of this paper was to develop a stand-level model with survival, dominant height and basal area as components to describe the growth of *E. grandis* over time as a function of stand density. Planting densities ranged from 6809 trees per hectare (TPH), grown under conditions of extremely limited resources to almost free growing trees planted at 161 TPH where resources were abundant. Mathematical functions were fitted to experimental data to describe the development of survival, dominant height and basal area over time, as a function of stand density.

4.2 MATERIALS AND METHODS

4.2.1 Sample origin

The Nelder 1a spacing trial was established in the Piggs Peak region of Swaziland in 1998 and located at an elevation of 743 m, positioned on the coordinates 25º59’08.63”S; 31º17’45.76”E. From results of tree breeding trials, the genetic material used were cuttings from a specific *E. grandis* clone, selected from the proprietary in-house tree improvement program of Mondi Forests and which were found most suitable for this area. The *E. grandis* clones used in 1998, when this trial was established, have since been replaced with superior hybrid-clones.

Temperature and rainfall together with the soil are major factors determining species choice and productivity in commercial forests in South Africa (Swain and Gardner 2003, Smith et al. 2005a, Smith et al. 2005b). The niche which a species typically occupies is determined by a range of factors which are often related to risk, e.g. pests and disease occurrence, drought tolerance and other climatic factors such as resistance to withstand frost, snow and cold and hot spells. Many of these factors are related to micro temperature regimes of a given area that is most frequently a function of the topography of the area, as well as the elevation above sea level. As part of an all inclusive site classification system for the South African forest industry (Smith et al. 2005b), the summer rainfall areas have been classified into broad mean annual precipitation (MAP) and mean annual temperature (MAT) classes.

The experimental site was located in the WT9 climate zone (Smith et al. 2005b) which placed it in the 18-19 ºC MAT class located within the warm temperate climatic zone. The rainfall, which is closely related to forest productivity, was regarded to be high with a 30 year long term average of 1477 mm mean annual precipitation (MAP) recorded for the site. The average measured MAP on the site for the seven year period of experimentation was 1432 mm.

4.2.2 The Nelder trial design

In contrast with the larger Randomized Complete Blocks (RCB) design used by Bredenkamp (1990), Buford (1991), Coetzee (1994) and Coetzee et al. (1996), the Nelder design which was first described by Nelder (1962) and later implemented by growth and yield modellers such as Faber (1990), Mabvurira and Miina (2002), Stape and Binkley (2010), is a compact systematic experimental design.

The design is known to be suitable for plantation spacing experiments and the statistical analysis is conducted accordingly (Mark 1983). It comprises a number of arcs in which the growing space or rectangularity, or both, could be varied in a continuous and systematic way in the experiment.

This trial was established as a Nelder 1a design in which there were 17 arcs (stand density treatments) of which the inner 15 treatments were analysed. There were 48 rays, which provide a sample of 48 trees per spacing treatment. Figure 4-1 illustrates a quarter of a Nelder 1a and visualizes the terminology used for this study. Table 4-1 provides the design parameters for the Nelder 1a spacing trial.

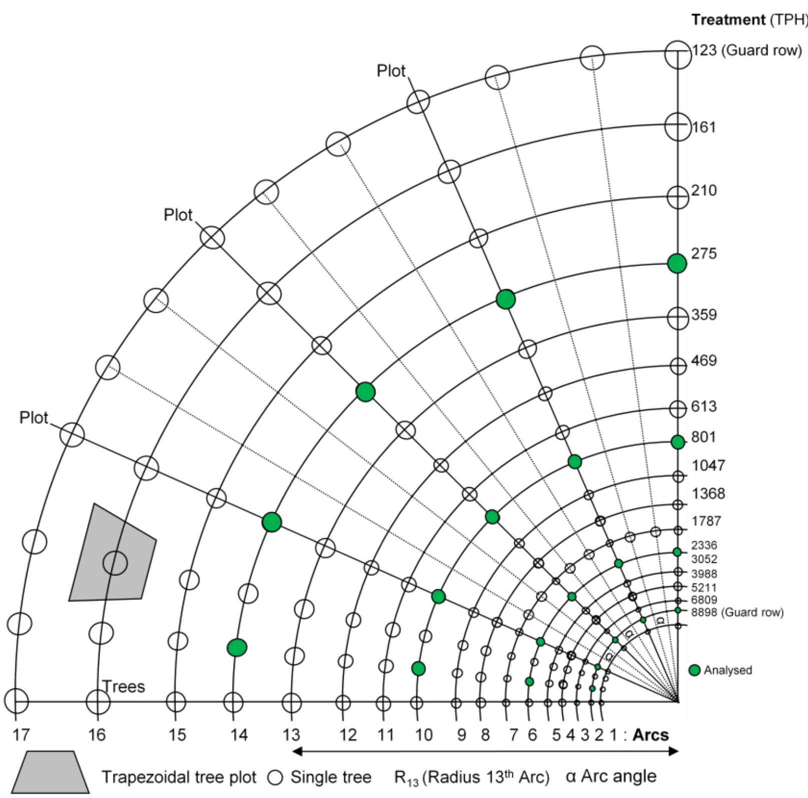

Figure 4-1: An illustration of a quarter of the Nelder 1a experimental design used in this study.

Table 4-1: Design parameters of the Nelder 1a spacing trial.

Arc no.	Treatment (TPH_0)	Radius (m)	Arc distance (m)	Area/tree (m^2)
1 (Guard row)	8898	8.00	1.05	1.12
2	6809	9.14	1.20	1.47
3	5211	10.45	1.37	1.92
4	3988	11.95	1.56	2.51
5	3052	13.66	1.79	3.28
6	2336	15.61	2.04	4.28
7	1787	17.85	2.34	5.59
8	1368	20.40	2.67	7.31
9	1047	23.32	3.05	9.55
10	801	26.66	3.49	12.48
11	613	30.48	3.99	16.31
12	469	34.84	4.56	21.31
13	359	39.82	5.21	27.85
14	275	45.52	5.96	36.39
15	210	52.04	6.81	47.56
16	161	59.49	7.79	62.14
17 (Guard row)	123	68.00	8.90	81.20
Rays	48 trees per spacing treatment			
Shape	1a; Circular (full wagon wheel)			

4.2.3 Modelling strategy and functions

Stand-level growth and yield were described by three independent variables namely tree survival, dominant height and basal area per hectare. Existing mathematical functions, that proved to be useful in the past, and are currently used in growth and yield simulators in forestry companies in South Africa, were selected. Stand density development over time was modelled with the function presented by Clutter and Jones (1980), hereafter referred to as the NS2CLJ survival function. Dominant height was modelled by a three-parameter Chapman-Richards-type function as described by Pienaar and Turnbull (1973) and later by Clutter et al. (1983). The guide curve form of the function is referred to as the HT1CR3 function and the difference form as HT2CR3. Basal area per hectare was modelled making use of a multiple regression approach with basal area expressed as a function of age, stand density and dominant height. This is a commonly used approach as published by Pienaar and Harrison (1989). The guide curve form of the function is referred to as the BA1MR1 function and the difference form as BA2MR1. The mathematical forms of these functions are shown in Table 4-2. The Max and Burkhart (1976) segmented polynomial taper function, as parameterised by Kotze et al. (2000), was selected to estimate volumes in this study. These functions can be directly incorporated in most forest growth and yield simulators and forest planning systems in South Africa.

The DBH and height of each individual tree in the trial were measured at seven equally-spaced intervals. For each spacing treatment and measurement age, the stand density Trees Per Hectare (TPH), quadratic mean diameter (D_q in cm), dominant height (HD in m), mean tree height (H_q in m) and basal area (BA in m^2 ha^{-1}) were determined.

Table 4-2: List of mathematical forms of growth and yield functions used in the modelling exercise (Kotze et al. 2000).

Model	**Name**	**Function**	**Comment**
The survival model	NS2CLJ	$$TPH_2 = \left[TPH_1^{\beta_1} + \beta_2 \cdot \left[\left(\frac{AGE_2}{100} \right)^{\beta_3} - \left(\frac{AGE_1}{100} \right)^{\beta_3} \right] \right]^{\frac{1}{\beta_1}}$$	Difference form where: TPH_1 is the stems per hectare at Age_1, the calibration age, TPH_2 is stems per hectare at Age_2; ß$_1$ to ß$_3$ are parameters to be estimated
The dominant height model	HT1CR3	$$HD_1 = \beta_0 \cdot \left[1 - e^{(\beta_1 \, (Age_1 + t_0))} \right]^{\beta_2}$$	HD_1 is the dominant height (m) at Age_1, t_0 was set at 0.4 years, the onset of height growth, ß$_1$ to ß$_2$ are parameters to be estimated
	HT2CR3	$$HD_2 = HD_1 \cdot \left[\frac{\left(1 - e^{(\beta_1 \times (Age_2 + t_0))}\right)}{\left(1 - e^{(\beta_1 \times (Age_1 + t_0))}\right)} \right]^{\beta_2}$$	Difference form where: HD_2 is the projected height (m) at Age_2
Basal area model	BA1MR1	$$\ln(BA_1) = \beta_0 + \frac{\beta_1}{Age_1} + \beta_2 . \ln(TPH) + \beta_3 . \ln(HD_1) + \beta_4 . \frac{\ln(TPH_1)}{Age_1} + \beta_5 . \frac{\ln(HD_1)}{Age_1}$$	BA_1 is the predicted basal area per hectare (m^2 ha^{-1}) at Age_1, the calibration age, HD_1 is the predicted dominant height (m) at Age_1 ß$_1$ to ß$_5$ are parameters to be estimated
	BA2MR1	$$\ln(BA_2) = \ln(BA_1) + \beta_1 . \left[\frac{1}{Age_2} - \frac{1}{Age_1} \right] + \beta_2 . \left[\ln(TPH_2) - \ln(TPH_1) \right]$$ $$+ \beta_3 . \left[\ln(HD_2) - \ln(HD_1) \right] + \beta_4 . \left[\frac{\ln(TPH_2)}{Age_2} - \frac{\ln(TPH_1)}{Age_1} \right]$$ $$+ \beta_5 . \left[\frac{\ln(HD_2)}{Age_2} - \frac{\ln(HD_1)}{Age_1} \right]$$	Difference form where: BA_2 is the projected BA (m^2 ha^{-1}) at Age_2

4.2.4 Testing the predictive ability of models

The evaluation of growth models is an essential part of model construction and careful examination of the model components should be done at every stage of the design, fitting and implementation (Vanclay and Skovsgaard 1997). The objective of evaluating the growth model is to assess the consistent reliability of predictions from the model and to assess the model's potential for its intended end-use (Schmidt et al. 2006). The predictive ability of the derived models was tested by applying the difference equation form to the measurement intervals.

The predictive ability of the models was evaluated with three statistics, or combinations thereof, namely: Mean bias ($\bar{B}$), Standard deviation of differences (S_D) and Total squared error (TSE), as defined by Perez et al. (1990), as follows:

Mean bias: $$\bar{B} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)$$

Standard deviation of differences: $$S_D = \sqrt{\frac{1}{n-1} \cdot \left[\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 - \frac{\left(\sum_{i=1}^{n}(y_i - \hat{y}_i)\right)^2}{n}\right]}$$

Total Squared Error: $TSE = (\bar{B})^2 + (S_D)^2$

where: y_i = observed,

$\hat{y}_i$ = predicted,

n = number of observations

The Mean bias statistic is an indication of how far the prediction deviates from the actual on the average. The standard deviation of differences is an indication of the precision of prediction. High accuracy is obtained by low mean bias and high precision. Total squared error gives a combined value for mean bias and standard deviation of differences and can be used to compare the predictive ability of different models against the same dataset.

4.2.5 Fitting of mathematical functions

The SAS system (SAS Institute Inc. 2006) was used for fitting all the functions. The NS2CLJ survival function is a difference form function and was fitted with Proc Nlin in SAS using the INTERVAL data set.

To model the development of dominant height over time, a two-stage model fitting exercise was adopted. In stage one, the height function (HT1CR3) was fitted as a guide curve to each of the stand density treatments using the 'POINT data set', after which the results were explored to determine whether parameters could be expressed as functions of stand density. The t_0-parameter represents the anchor point for the onset of height growth on the X-axis (X-axis intercept) and was set to a fixed value of 0.4 years, based on local experience. In stage two, an appropriate function was fitted to describe each parameter as a function of stand density.

To model basal area, the guide curve function (BA1MR1) and difference form function (BA2MR1) were fitted simultaneously as a system of compatible prediction and projection equations with a mutual set of parameter estimates with Proc Model in SAS. The 'POINT' and 'INTERVAL' data sets were combined for this purpose.

4.3 RESULTS

4.3.1 Description of the data

In Table 4-3 an excerpt of the trial data, summarised by treatment for the final measurement at 6.75 years is shown. This data set will be referred to as the 'POINT' data set and is typically used in the fitting of guide curve functions. To fit difference form functions, a data set with interval data is required. All combinations of forward intervals were generated and then constrained so that the interval age difference was greater than 2 years. This dataset is hereafter referred to as the 'INTERVAL' data set.

Initial analysis showed that the very high stand density above 6000 stems per hectare was very influential and influenced the behaviour of the planting densities in the commercial range negatively. It was therefore excluded from the dataset for the fitting of all three model components.

Table 4-3: Summary data for the Nelder 1a spacing trial for the final measurement at 6.75 years. Data are the mean of 48 trees per stand density.

Stand density **(trees ha^{-1})**	Survival **(%)**	Volume i.b. **(m^3 ha^{-1})**	Basal Area **(m^2 ha^{-1})**	MAI **(m^{3}ha^{-1}y^{-1})**	Dominant Height HD **(m)**	Quadratic mean Diameter D_q **(cm)**
6809	64.6	187.7	41.6	27.8	22.6	11.0
5211	79.2	122.7	33.9	18.2	22.7	10.2
3988	81.3	192.5	35.8	28.5	23.7	11.9
3052	87.5	249.1	38.1	36.9	24.6	13.5
2336	89.6	216.5	31.8	32.1	24.5	13.9
1787	93.8	164.7	24.7	24.4	24.8	13.7
1368	93.8	229.4	28.4	34.0	26.0	16.8
1047	97.9	243.5	28.2	36.1	26.5	18.7
801	93.8	204.6	23.0	30.3	27.2	19.8
613	95.8	232.6	24.4	34.5	27.8	23.0
469	93.8	180.7	18.9	26.7	28.0	23.4
359	95.8	185.8	18.6	27.5	28.9	26.3
275	100.0	154.1	15.4	22.8	28.7	26.7
210	95.8	139.7	13.6	20.7	29.4	29.3
161	100.0	108.73	10.6	16.1	29.2	28.9

4.3.1.1 Survival of trees

The downward trend in stand density over time is shown in Figure 4-2. Higher mortality occurred in the high stand density treatments and zero mortality occurred at low stand densities. For clarity, only a sub-set of 8 out of 15 available planting density (TPH_0) treatments are shown. These treatments are well spaced on the graphs, include the minimum and maximum and are used consistently to illustrate the development of stand density, dominant height and basal area over time. The NS2CLJ-function as shown in Table 4-2 will be fitted to the data.

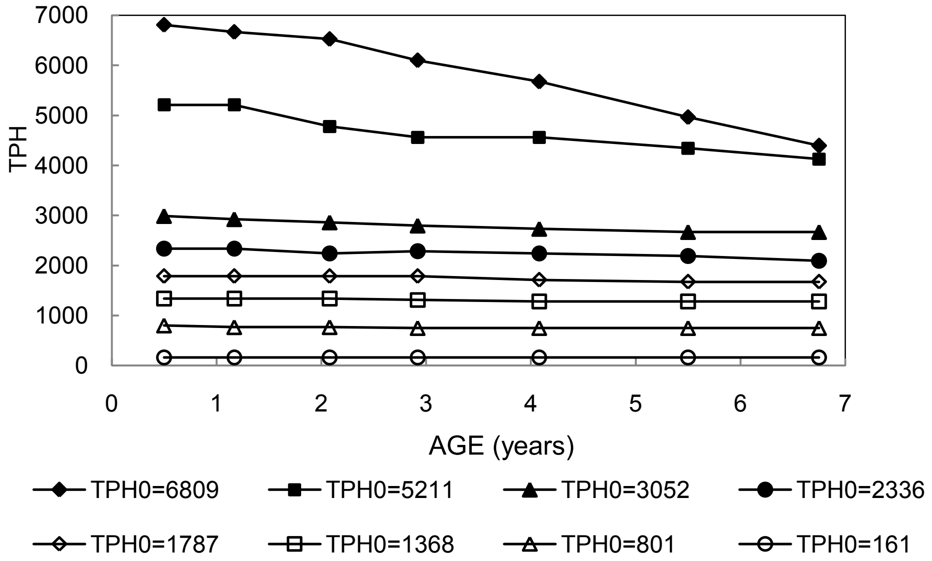

Figure 4-2: Trends in stand density over time.

4.3.1.2 Tree height

Dominant height was calculated from a regression, where in the South African context, HD is defined as the regression height associated with the quadratic mean diameter at breast height (dbh) of the 20 % thickest trees in the sample, provided the regression is developed from at least 30 dbh-height pairs (Bredenkamp 1993). The development of dominant height over time and the range over stand density can be seen in Figure 4-3. Moreover, it is noticeable that dominant height was affected by the spacing treatments. Dominant height might have been affected by the rainfall pattern. The height increment for the period between five and six years was lower than previous years. Examination of the detailed rainfall figures recorded for the site, showed a reduced rainfall in the 2003 and 2004 periods of 912 mm and 908 mm which are respectively 38.2 % and 38.5 % lower than the 30 year long term average of 1477 mm recorded for the site. The HT1CR3-function as shown in Table 4-2 will be fitted to the data.

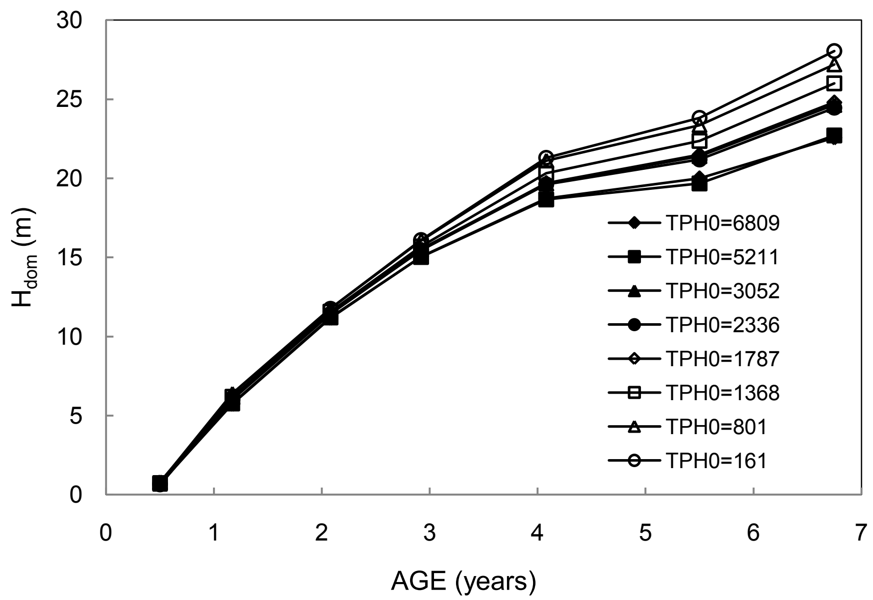

Figure 4-3: Development of dominant height over time.

4.3.1.3 Basal area

Basal area (BA) is a measure of the biological carrying capacity of a site and sometimes exhibits an S-shaped curve which tends to an apparent asymptote. BA is calculated as the total sum of cross-sectional area of the individual trees in a stand measured at dbh (over-bark). Figure 4-4 shows the development of BA over time for a selected sub-set of treatments. It is evident from Figure 4-4 that the high planting density levels of 6809 TPH_0 had a BA value of 41.6 m^2 ha^{-1}, four times higher than the lowest planting density of 161 TPH_0, where BA was a mere 10.6 m^2 ha^{-1}, both measured at 6.75 years at termination of the experiment. It seems that the planting density of 6809 TPH_0 reached an apparent asymptote of approximately 42 m^2 ha^{-1} at the age of 4 years; this coincides with the onset of the temporary drought in the period the trial was in the ground. Noticeable from Figure 4-4 is the cross-over of 5211 TPH_0 with 3052 TPH_0, which may be indicative of the high competition levels experienced in high stand densities relative to the low stand densities. The BA1MR1-function as shown in Table 4-2 will be fitted to the data.

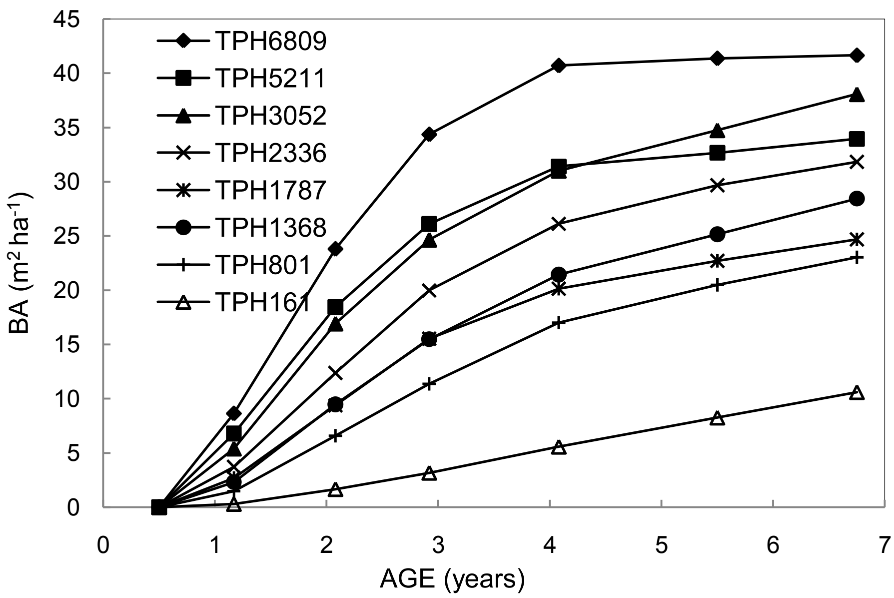

Figure 4-4: Development of basal area over time.

The highest actual volume and mean annual increment of 249.1 m^3 ha^{-1} and 37.6 m^3 ha^{-1} y^{-1} respectively were recorded for the 3052 TPH_0 treatment.

4.3.2 Statistical modelling

4.3.2.1 Logical behaviour of models

A suitable commercial model for comparative purposes was found in the Langepan CCT- model, hereafter referred to as the ‘Langepan model’, as described by Pienaar et al. (1988). The Langepan CCT experimental plots were established with *E. grandis* on the Zululand coastal plain in 1952 as a replicated RCB-trial. This model was deemed suitable because it was developed for the evaluation of management regimes of unthinned stands and the range of planting densities (TPH_0) coincided with the densities tested in the Nelder 1a experiment in Swaziland. The function forms are similar to the functions used for the Nelder 1a. Table 4-4 gives the models and coefficients used for the comparison with the newly developed Nelder 1a models.

Table 4-4: The Langepan model configuration (Pienaar et al. 1988).

Model component	Name	Coefficient sets
Survival	NS2CLJ	β_1 = –1.8480 β_2 = 0.00001407 β_3 = 1.8062
Height	HT2CR3	β_1 = –0.0596 β_2 = 0.8072
Basal area	BA2MR1	β_0 = 0.0 β_1 = –16.8860 β_2 = 0.1513 β_3 = 0.8218 β_4 = 1.4264 β_5 = 1.6347

4.3.2.2 Survival function

Table 4-5 gives the parameter estimates and fit statistics for the survival function (NS2CLJ). All parameters were significant at the $p \leq 0.05$ level. Figure 4-5, a plot of studentized residuals versus predicted values, shows that the variation increases with an increase in the predicted values, otherwise known as heteroscedasticity.

Table 4-5: Parameter estimates and fit statistics for the survival model.

Model	$ß_1$	$ß_2$	$ß_3$	n	MSE
NS2CLJ	–1.92465	0.00000613	1.78445	203	6232.8

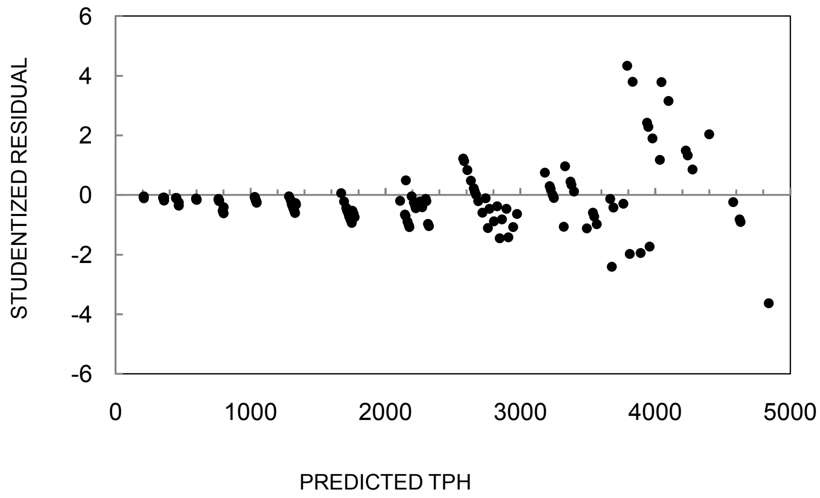

Figure 4-5: Studentized residuals versus predicted values for NS2CLJ.

Figure 4-6 shows the behaviour of the NC2CLJ function when projected to 10 years, over a range of selected planting densities against the observed values. The function was calibrated with observed data at age 4.08 years. Commercial planting density for pulp wood production is normally 1667 TPH_0 and therefore treatments were selected to bracket this range, at *c.* double (3052 TPH_0) and *c.* half (801 TPH_0) of that.

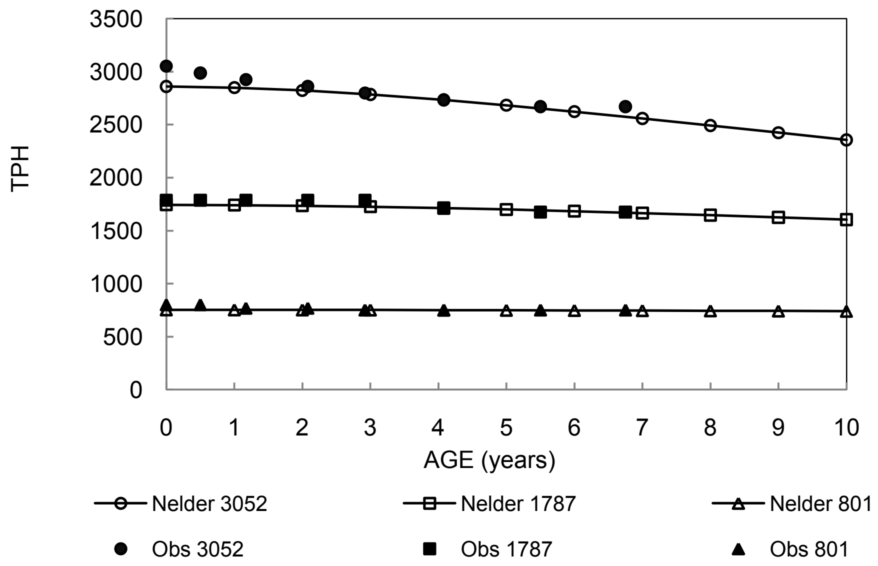

Figure 4-6: Performance of NS2CLJ against actual data when calibrated at 4.08 years.

4.3.2.3 Dominant height growth function

In this Nelder 1a experiment, dominant height growth was clearly affected by planting density. Figure 4-3 shows that the dominant height growth curves started to differentiate soon after an age of two years. In stage one, the height function (HT1CR3) was fitted as a guide curve for each of the stand density treatments. Figure 4-7, Figure 4-8 and Figure 4-9 show the trends in the $ß_0$, $ß_1$, and $ß_2$ parameters. They are clearly functions of planting density and in stage two, the parameters were modelled as functions of planting density (TPH0). Table 4-6 gives the functions, the parameter estimates and fit statistics. Figure 4-7, Figure 4-8 and Figure 4-9 show the behaviour of the regression model for each parameter. In all cases, the parameter estimates were significant at the $p \leq 0.05$ level and residuals were evenly distributed over the data range.

Table 4-6: Parameter estimates and fit statistics for HT1CR3.

Model	ß$_{i1}$	ß$_{i2}$	n	MSE	R^{2}adj
$\beta_0 = \beta_{01} \cdot TPH_0^{\beta_{02}}$	88.2420	– 0.1479	112	0.4796	—
$\beta_1 = -1 \cdot (\beta_{11} \cdot TPH_0^{\beta_{12}})$	0.05677	0.2243	112	0.0001541	—
$\beta_2 = \beta_{21} + \beta_{22} \cdot TPH_0$	0.9401	0.00002393	111	0.0003418	0.865

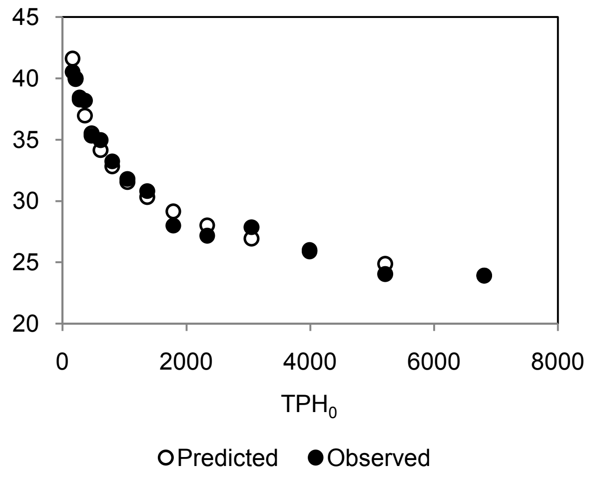

Figure 4-7: Behaviour of the ß$_0$ parameter as a function of stand density.

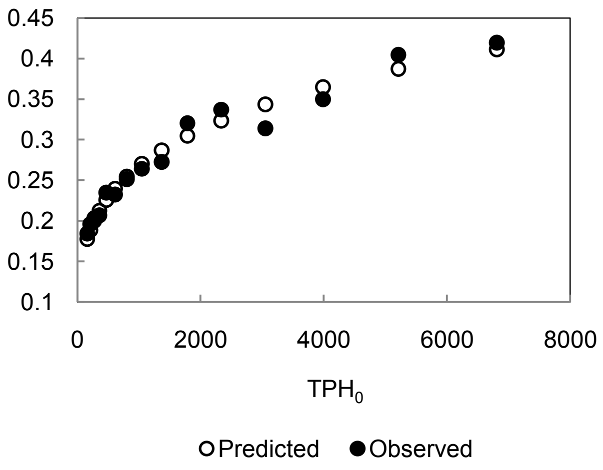

Figure 4-8: Behaviour of the ß$_1$ parameter as a function of stand density.

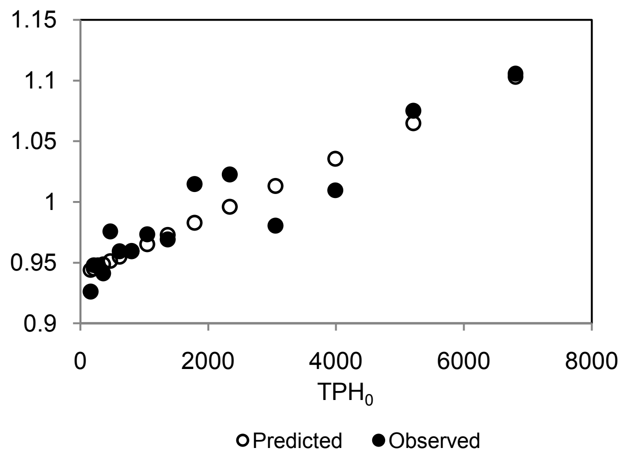

Figure 4-9: Behaviour of the ß$_2$ parameter as a function of stand density.

Figure 4-10 shows the logical behaviour of the final HD function, when calibrated at 4.08 years and projected to 10 years, for a range of selected planting densities, compared to the observed data.

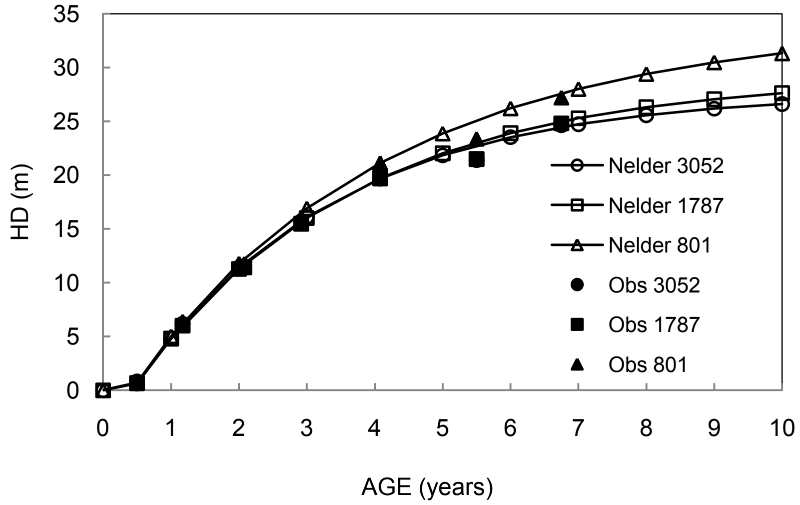

Figure 4-10: Performance of the HT2CR3 model against actual data when calibrated at 4.08 years.

4.3.2.4 Basal area function

The basal area functions (BA1MR1 and BA2MR1) were fitted simultaneously to the combined data set with Proc Model in SAS. Table 4-7 shows the parameter estimates and fit statistics for the simultaneously fitted basal area functions (BA1MR1 and BA2MR1). All parameter estimates were significant at the $p \leq 0.05$ level. Residuals were well distributed over the predicted values but variation increased with increasing predicted values.

Table 4-7: Parameter estimates and fit statistics for BA1MR1 and BA2MR1.

Model	$ß_0$	$ß_1$	$ß_2$	$ß_3$	$ß_4$	$ß_5$	n	R^2-adj	MSE
BA1MR1	–3.8242	–7.4535	0.3798	1.3362	0.7181	0.9181	290	0.994	0.098
BA2MR1							291	0.994	0.066

Figure 4-11 shows the behaviour of the BA2MR1 function for a range of selected planting densities against the observed data. The model was calibrated with observed data (HD_1, TPH_1, BA_1) at Age_1 equal 4.08 years. The future values for TPH_2, HD_2 at Age_2 were then predicted with the NS2CLJ and HT2CR3 functions respectively and BA_2 at Age_2 then calculated.

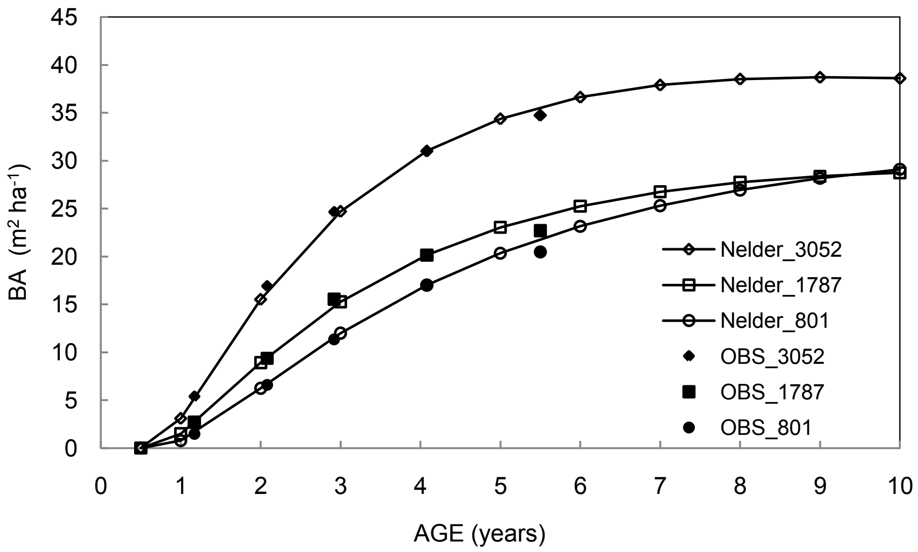

Figure 4-11: Performance of BA2MR1 against actual data when calibrated at 4.08 years.

4.4 DISCUSSION

The Nelder 1a spacing trial provided unreplicated data over a very wide range of planting densities. The development of basal area development over time, as shown in Figure 4-4, clearly illustrates how planting densities cross each other in an inconsistent manner and this shows the instability in this type of unreplicated data. Nevertheless, the modelling approach relies on the overall trend over the range of planting densities.

It is important that the stand-level model predicts sensible responses to management interventions, e.g. over a wide range of different stand density levels in this case. The logical behaviour of each of the derived functions was evaluated by plotting the dependent variable over time for different spacing treatments with the observed data in the background. Visually, the functions corresponded well to the range of the observed data trends over time and spacing treatments.

The behaviour of each function was compared to its expected behaviour over the stand density range. It should be noted, however, that when applied as a holistic growth model, the overall system performance is considered to be more important than the performance of the individual components (Schmidt et al. 2006).

4.4.1 Tree survival function

Tree mortality is caused by many factors, e.g. competition, drought stress and disease. A large part of mortality occurs at establishment in the first year after planting and in most cases commercial measurements only start at the age of two years or later. The newly derived NS2CLJ model was compared with the Langepan-model (Pienaar et al. 1988). Figure 4-12 shows the comparative behaviour of the models when calibrated at 4.08 years.

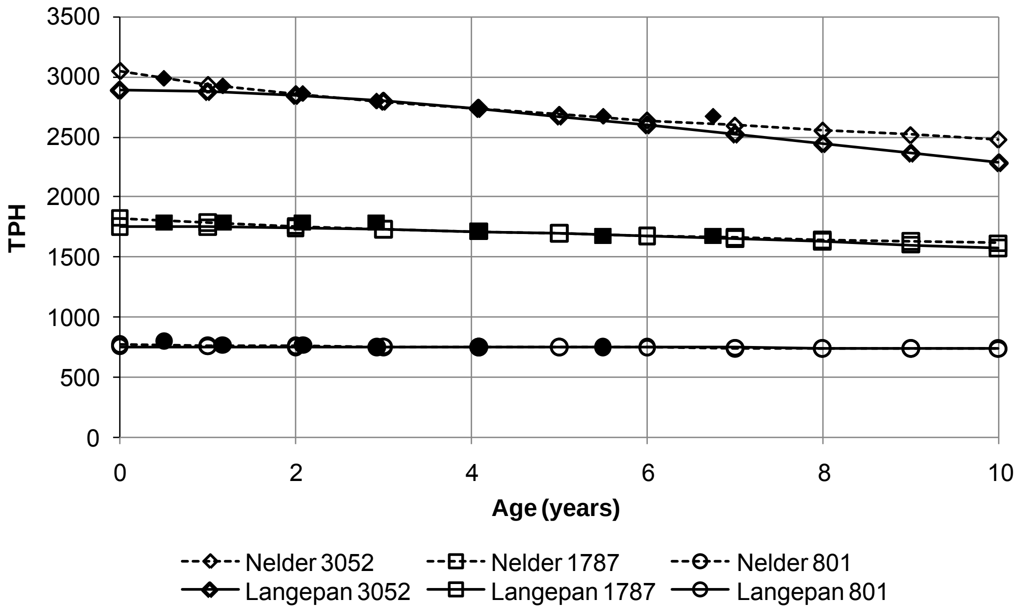

Figure 4-12: Comparative behaviour of the Nelder and Langepan survival models against observed data.

From Figure 4-2 it is evident that the stand density treatments applied in the Nelder spacing trial exhibit unique rates of mortality over time; steep gradients at very high stand density levels and low gradients for the very low stand density levels.

The NS2CLJ function fitted the data reasonably well as shown in Table 4-5. It behaved logically over the range of stand density treatments around the commercial stand density of 1667 trees per hectare, as shown in Figure 4-6. It also behaved logically when projected to 10 years, beyond the range of the observed data. When tested with the full data set, the very high stand densities above 6000 stems per hectare were very influential and the NS2CLJ function did not represent the wide range in stand densities very well.

As expected, the Nelder model represents the data more precisely than the Langepan model. Furthermore, from Figure 4-2 and Figure 4-12 it is evident that the planting density treatments applied in the Nelder spacing trial exhibited different rates of mortality over time; steep gradients at very high stand density levels and low for the very low stand density levels.

The predictive ability of the NS2CLJ model was tested for a selection of the planting density treatments using the mid-interval data set. The range of stand-densities used (359 - 5211 TPH) was chosen to coincide with the range which the Langepan model was developed for. Table 4-8 shows a comparison of predictive ability between the Nelder 1a and Langepan survival models. The overall Total Square Error (TSE) of the Nelder model (1752) was much lower than that of the Langepan model (14851). The Langepan model also showed an over-prediction at lower stand densities and an under-prediction at high stand densities.

This result shows that the Nelder model would be more appropriate at Swaziland Piggs Peak than the Langepan model.

Table 4-8: Comparative predictive ability of the Nelder and Langepan NS2CLJ models.

Model	**TPH_0**	**n**	**Mean Bias**		**SDD**	**TSE**
			(TPH)	**(%)**	**(TPH)**	
Nelder-NS2CLJ	359	4	–8.62	–2.51	3.58	87.23
	469	8	–5.34	–1.22	1.46	30.74
	613	4	–4.13	–0.70	1.75	20.13
	801	4	–1.91	–0.25	2.96	12.44
	1047	4	7.31	0.71	5.70	86.15
	1368	6	–4.59	–0.36	10.08	122.73
	1787	8	–23.59	–1.41	22.71	1072.71
	2336	8	–14.98	–0.73	45.24	2271.76
	3052	8	30.39	1.14	28.79	1753.20
	3988	8	–27.72	–0.86	46.05	2889.85
	5211	8	17.83	0.40	91.29	8652.68
	All	**70**	**–3.49**	**–0.49**	**41.71**	**1752.27**

Langepan-NS2CLJ	359	4	–10.67	–3.10	3.97	129.80
	469	8	–7.64	–1.74	0.45	58.69
	613	4	–9.37	–1.60	0.86	88.71
	801	4	–9.72	–1.29	1.72	97.53
	1047	4	–4.60	–0.45	4.09	37.90
	1368	6	–16.29	–1.27	13.23	440.65
	1787	8	–29.26	–1.75	25.72	1518.52
	2336	8	–6.63	–0.33	35.35	1293.94
	3052	8	69.99	2.62	54.39	7857.42
	3988	8	96.20	2.90	12.02	9400.06
	5211	8	315.45	7.48	100.66	109646.46
	All	**70**	**46.71**	**0.57**	**112.56**	**14850.99**

4.4.2 Dominant height function

Rainfall during the experimentation period and stand density had a substantial effect on height growth as presented in Figure 4-3, showing dominant height growth diverging soon after two years of age. This resulted in the lowest planting density, 161 TPH_0, to have the highest dominant height (29.8 m) and the 6809 TPH_0 treatment the lowest (22.6 m) at final measurement age of 6.75 years. The same effect of increased height with reduced stand density was found in a study by Bernardo et al. (1998) carried out on *E. camaldulensis*, *E. pellita* and *E. urophylla* in south-eastern Brazil, as well as in the South African *E. grandis* Langepan study (Pienaar et al. 1988). The phenomenon of height growth levelling off due to the ensuing dry conditions was also described by Smith et al. (2005c) and Morley (2009).

Initial analysis showed that the dominant height variable was very influential in the basal area functions. The effect of stand density on dominant height was very marked. Therefore it was deemed necessary to model the effect of stand density on dominant height. The two-stage modelling exercise worked well and it was clear from the modelling that parameters $ß_0$, $ß_1$, and $ß_2$ were functions of stand density, as shown in Figure 4-7, Figure 4-8 and Figure 4-9, and fitted the data reasonably well, as shown in Table 4-6. The Nelder HT2CR3 model was compared with the Langepan model. Figure 4-13 shows the comparative behaviour of the models when calibrated at age 4.08 years.

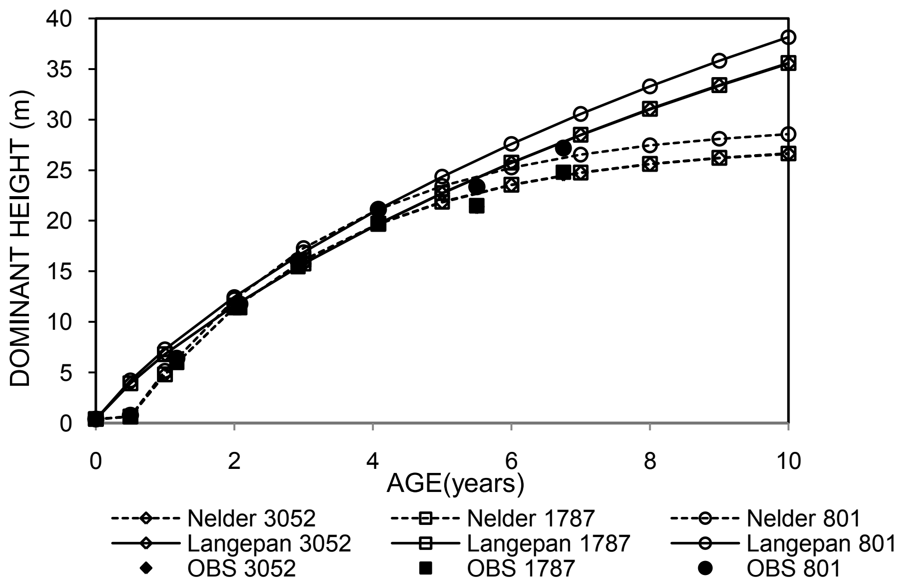

Figure 4-13: Comparative behaviour of the Nelder and Langepan dominant height model against observed data.

The HT2CR3 function performed logically over the range of stand density treatments around the commercial stand density of 1667 trees per hectare, as shown in Figure 4-10 and also behaved logically when projected to 10 years, beyond the range of the observed data. The predictive ability of the HT2CR3 model was tested for each of the planting density treatments using the mid-interval dataset. As for NS2CLJ, the range of stand densities was bracketed between 359 and 5211 TPH. The overall TSE of the Nelder model (0.86) was much lower than that of the Langepan model (7.53) (See Table 4-9). The Mean % bias is evenly distributed over the range of planting densities while that of the Langepan model shows an increasing over-prediction as planting density increases. This result clearly shows that the Nelder model adequately represents the effect of planting density whereas the Langepan model does not.

Table 4-9: Comparative predictive ability of the height growth model HT2CR3 between Nelder and Langepan models.

Model	TPH_0	n	Mean Bias (m)	Mean Bias (%)	SDD (m)	TSE
Nelder – HT2CR3	359	8	–0.49	–2.06	0.97	1.18
	469	8	–0.25	–1.22	0.96	0.99
	613	8	–0.16	–0.87	0.97	0.97
	801	8	–0.38	–1.71	0.92	0.99
	1047	8	–0.12	–0.75	0.99	0.99
	1368	8	–0.09	–0.62	0.94	0.90
	1787	8	–0.29	–1.46	0.85	0.81
	2336	8	–0.34	–1.72	0.88	0.89
	3052	8	–0.11	–0.72	0.90	0.83
	3988	8	–0.38	–1.96	0.85	0.87
	5211	8	–0.58	–3.05	0.91	1.16
	All	**88**	**–0.29**	**–1.47**	**0.88**	**0.86**
Langepan – HT2CR3	359	8	0.73	2.62	2.91	9.00
	469	8	0.53	1.94	3.08	9.79
	613	8	0.28	0.99	2.82	8.05
	801	8	–0.28	–1.18	2.59	6.81
	1047	8	–0.40	–1.69	2.68	7.33
	1368	8	–0.69	–2.89	2.50	6.74
	1787	8	–1.19	–5.14	2.53	7.78
	2336	8	–1.51	–6.64	2.45	8.30
	3052	8	–1.51	–6.62	2.29	7.58
	3988	8	–1.96	–8.83	2.17	8.54
	5211	8	–2.28	–10.80	2.48	11.36
	All	**88**	**–0.75**	**–3.48**	**2.64**	**7.53**

4.4.3 Basal area function

Stand density had a noticeable effect on diameter growth and hence, on basal area development. Individual trees responded to the wider spacing treatments and to lower competition levels with greater individual diameter growth. The BA1MR1 and BA2MR1 functions fitted the data reasonably well as shown in Table 4-7. The difference form basal area function (BA2MR1) relies on output from both the height (HT2CR3) and survival functions (NS2CLJ) and therefore provides the opportunity to evaluate the behaviour of the entire growth model. Figure 4-11 shows that it behaved logically over the range of stand density treatments around the commercial stand density of 1667 trees per hectare. When extended beyond the data range to 10 years, the lower stand density of 801 TPH caught up with the higher stand density of 1787 TPH.

Figure 4-14 graphically displays the projected basal area when calibrated with observed data at 4.08 years. There was a large difference in the behaviour of the system of equations, and as expected, the Nelder model represented the data much more accurately than the Langepan model.

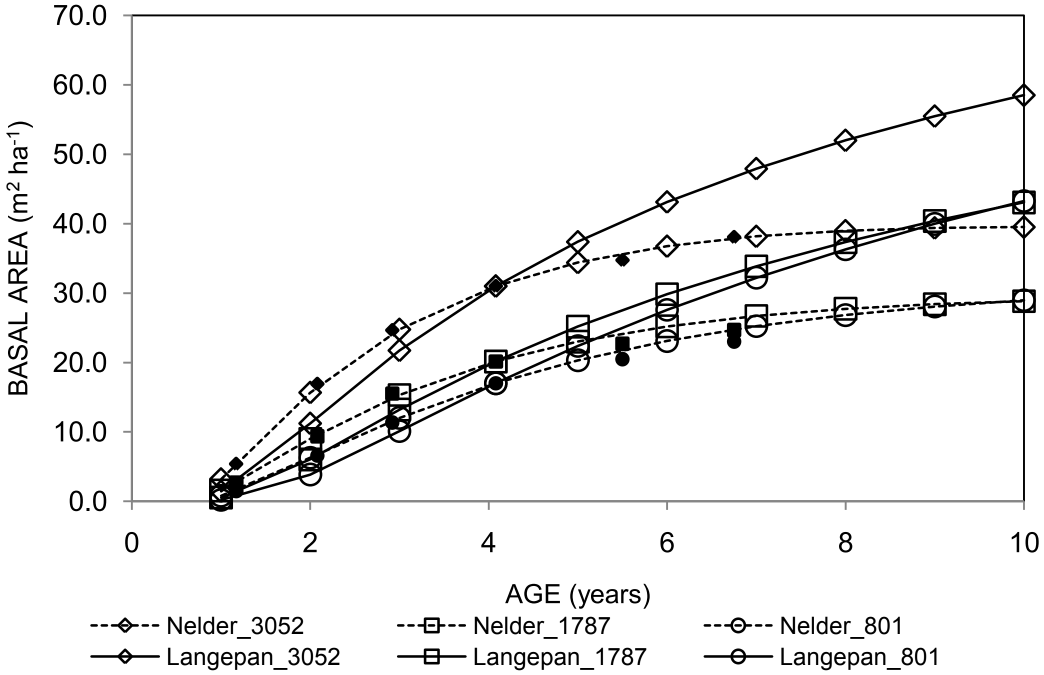

Figure 4-14: Comparative behaviour of the Nelder and Langepan Basal area models.

In Table 4-10 the predictive ability statistics of the Nelder and Langepan models are shown respectively with the same stand density range as for survival and dominant height.

Table 4-10: Comparative Predictive ability of the Nelder BA2MR1 and Langepan BA2MR1 models.

Model	TPH_0	n	Mean Bias		SDD	TSE
			(m^2 ha^{-1})	(%)	(m^2 ha^{-1})	
Nelder-BA2MR1	359	8	0.0189	0.71	0.0563	0.0035
	469	8	0.0622	2.22	0.0549	0.0069
	613	8	0.0861	2.79	0.0898	0.0155
	801	8	–0.0315	–0.99	0.0590	0.0045
	1047	8	0.0079	0.27	0.0556	0.0032
	1368	8	–0.0117	–0.33	0.0543	0.0031
	1787	8	–0.0513	–1.60	0.0643	0.0068
	2336	8	0.0159	0.48	0.0496	0.0027
	3052	8	–0.0287	–0.78	0.0544	0.0038
	3988	8	0.0047	0.14	0.0439	0.0019
	5211	8	–0.0190	–0.54	0.0594	0.0039
	All	**88**	**0.004859**	**0.21**	**0.0583**	**0.0050**

Langepan-BA2MR1	359	8	–0.8561	–29.99	0.8238	1.4116
	469	8	–0.7695	–26.91	0.7609	1.1711
	613	8	–0.6829	–21.83	0.6666	0.9108
	801	8	–0.7513	–24.38	0.6895	1.0399
	1047	8	–0.6504	–19.80	0.6395	0.8320
	1368	8	–0.6220	–18.91	0.5851	0.7291
	1787	8	–0.6133	–19.36	0.5881	0.7220
	2336	8	–0.4953	–14.45	0.5100	0.5054
	3052	8	–0.4858	–13.51	0.4852	0.4714
	3988	8	–0.4095	–11.53	0.4353	0.3572
	5211	8	–0.3882	–11.07	0.3940	0.3060
	All	**88**	**–0.6113**	**–19.24**	**0.5980**	**0.7687**

The overall TSE of the Nelder model (0.0050) was much smaller than that of Langepan model (0.7687). The mean bias of the Nelder model was evenly distributed over the range of planting densities, while that of the Langepan model showed a decreasing over-prediction as stand density increased. This result clearly shows that the Nelder model represented the effect of planting density much better than the Langepan model.

4.5 CONCLUSION

The regression methodology used to describe the effect of stand density on survival, dominant height and basal area development was applied successfully. This was particularly obvious when the set criteria for the goodness of fit, namely significant parameter estimates and the distribution of residuals around the mean, were evaluated. The functions fitted well for the bulk of the planting densities below 6000 stems per hectare. Furthermore, the functions showed good logical behaviour when plotted against test data and when extended to 10 years beyond the observed data. When the functions of the model, namely survival, dominant height and basal area were tested against a suitable growth and yield model such as Langepan, the outcome confirmed that local models, when fitted to local data are the most desirable for accurate growth and yield predictions.

The models can thus be used with confidence in simulation systems where the effect of stand density needs to be considered for the prediction of wood properties within a *E. grandis* plantation in the high summer rainfall regions of South Africa.

Furthermore, the functions have clearly indicated the robustness and accuracy of its predictions and hence the model developed comes highly recommended to predict the quantitative component of growth, in a fibre productivity index.

4.6 ACKNOWLEDGEMENTS

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<u>CHAPTER 5 : Variation in wood density and cellular morphology of a *Eucalyptus grandis* clone as influenced by planting density</u>

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CHAPTER 5 : Variation in wood density and cellular morphology of a *Eucalyptus grandis* clone as influenced by planting density.

Abstract

A study was conducted on wood from a *Eucalyptus grandis* clone grown in a Nelder 1a experiment in Swaziland. The purpose was to investigate physical and anatomical wood quality properties which would prove suitable to be taken up in a full value chain (tree/wood/pulp/paper), fibre productivity index (FPI). Trees were sampled from four stand density treatments, 6809, 2336, 801 and 275 trees per hectare (TPH). Discs from trees were sampled at three height levels, diameter at breast height (DBH at 1.3 m), 35 % and 65 % merchantable tree height. Gamma-ray densitometry was used to obtain **air-dry** wood density data. Fibre tracheid and vessel element properties were determined with fluorescent microscopy on which image analysis was applied. Statistical analyses of data including ANOVA, correlation, multivariate analysis and regression were successfully conducted. Planting density was significant in all instances when weighted mean tree values were analysed with wood, fibre tracheid and vessel element properties ($p<0.0001$). Correlation between stand density and wood/cellular properties were meaningful (wood density $r = –0.67$, fibre diameter $r = 0.61$, fibre lumen diameter $r = 0.73$, fibre cell wall thickness $r = –0.68$ and vessel diameter $r = –0.50$). Wood density also correlated well with fibre properties (fibre cross sectional area $r = 0.51$, fibre diameter $r = –0.51$, fibre lumen diameter $r = 0.61$ and fibre cell wall thickness $r = 0.57$). PCA was effectively used to develop principal components and when regressed with wood properties, high R^2 - values were obtained. When the most extreme stand density treatments; 275 and 6809 TPH, were evaluated, it was evident that larger trees, grown at 275 TPH, produced wood of better quality for pulp processing (wood density at 0.520 g cm^{-3} was 21 % higher, fibre cell wall thickness at 2.10 µm was 18.6 % thicker and fibre lumen diameter at 8.16 µm was 9.9 % lower than for 6809 TPH). The associated PCA biplots were constructed. Canonical variate analysis (CVA) which is a widely used method for analysing group structure in multivariate data was used to construct CVA biplots to visually display the overlap and separation among the different groups of data. The data analyses suggested wood density to be a suitable property for a Fibre Productivity Index (FPI) due to the high correlation with stand density, ease of measurement and modelling success. Furthermore, wood density correlated well with fibre tracheid and vessel element properties and can thus be used as a quality parameter for other important properties not included in a full value chain FPI.

Keywords: Air-dry wood density, gamma-ray densitometry, image analysis, *Eucalyptus grandis*, fibre, vessel properties, Nelder 1a spacing experiment, PCA, CVA, biplot

5.1 INTRODUCTION

The growth and tending of forest trees, described as silvicultural management, include management practices such as the selection of tree species and genotype, planting density, fertilization and thinning regime, all of which are known to affect the growth and formation of wood properties of tree stands. Much is contained in the ability to identify and improve wood properties by management and tree breeding with end-use in mind.

Wood properties of forest grown trees can be described as physical, e.g. a bulk property such as wood density where volume and mass are measured, or can refer to a lower structural level, i.e. the cellular or anatomical level, where various dimensional properties, shapes, orientation, distribution, amounts, etc. of wood cell types such as tracheid fibres and vessel elements are considered.

The value of tree genetics is in the implementation of advanced selections through a well structured silviculture program. Until recently, tree breeding focused only on tree phenotypic properties. However, it has become more prominent for genetic improvement programs to include wood and fibre properties such as wood density and fibre dimension as selection criteria (Raymond and Apiolaza 2004). Properties at the cellular level are important especially with end-use in mind, e.g. for pulp and paper these can include characteristics such as vessel element diameter and frequency, fibre diameter, fibre length, cell wall thickness and lumen diameter. The ability to improve on wood and end-user properties according to Pot et al. (2002) lies in the ability to measure and understand the properties as well as the within tree variability of a large set of wood and fibre properties as mentioned above. Variability is heritable and can be utilized within breeding programs to produce trees with improved wood properties and thus enhanced end-product quality (Bailleres et al. 2002). Wood quality characteristics are also optimized through silviculture when the effects of fertilizer on wood and fibre properties are concerned as reported in work done by du Toit and Drew (2003) and Malan (2005), or in the event of different spacing regimes (Kang et al. 2004, Malan 2005).

Although the base-line characteristics measured can be established beforehand by consultation of the available literature, the importance is their contribution to quality pulpwood produced in the forest and with fitness of purpose in mind to the end-user. To assist in the modelling of wood properties, selected properties must have high levels of predictive ability, must be easy and cheap to measure and contribute to the compilation of a fibre productivity indicator (index). Therefore, in this study the variability of wood properties that are influenced by planting density at establishment and which have an effect on the qualitative and quantitative aspects of the working of a Kraft pulp mill, are analysed.

5.1.1 Basic wood density

Basic wood density, is widely regarded as one of the most influential properties affecting the strength and several other characteristics of pulp and paper (Horn 1978, Zobel and van Buijtenen 1989, Malan and Arbuthnot 1995, Lundqvist 2002). It was further stated by Savidge (2003) that basic wood density is the prime wood quality consideration for industry as higher wood density values yield stronger wood and more pulp. It is thus essential from a selection of parameters for a fibre productivity indicator, to have a good understanding of basic wood density.

Wood density is affected both by the amount of earlywood and latewood, and the thickness and composition of the individual cells. Empirically, **basic wood density** is calculated as the mass of oven-dried wood expressed as a fraction of green wood volume (Grundelius 1990) and it is a popular indicator of the quality of eucalypt pulp wood, making use of the following calculation:

$$BWD = \frac{M}{V} \qquad \textit{Equation 1}$$

where

BWD = basic wood density, g cm^{-3}

M = oven-dry mass, g

V = green volume of a wood sample in equilibrium with surrounding water during immersion and measured in cm^3

In a review of genetic control of wood and fibre properties by Malan and Verryn (1996), Muneri and Raymond (2000) and Raymond and Apiolza (2004) it was noted that basic wood density generally has a relatively large value of heritability (h^2) and is thus under strict genetic control.

The trees in this study were only 6.75 years old at sampling and therefore it is assumed that the wood was predominantly of juvenile nature. A high level of variability in wood properties should be expected, especially in basic wood density as described by Ilic et al. (2003). Since the cylinder of juvenile wood extends from the base to the top of the tree, the proportion of juvenile wood increases in that direction resulting in overall lower basic wood density towards the tip of the tree (Malan 1991). The relationship between the juvenile and mature wood is schematically illustrated in Figure 5-1. Notable is the high proportion of juvenile core that stretches to the growing tip of the tree, where it has its origin (Larson et al. 2001) to mature wood which is just a shell that has formed around it. Although the juvenile/mature wood is indicated as a distinct line, it must be borne in mind that there is no clear transition between juvenile and mature wood.

Saranpaa (2003) noted that most wood properties of hardwoods are highly variable from ring to ring in the juvenile section but much more constant in the mature wood zone.

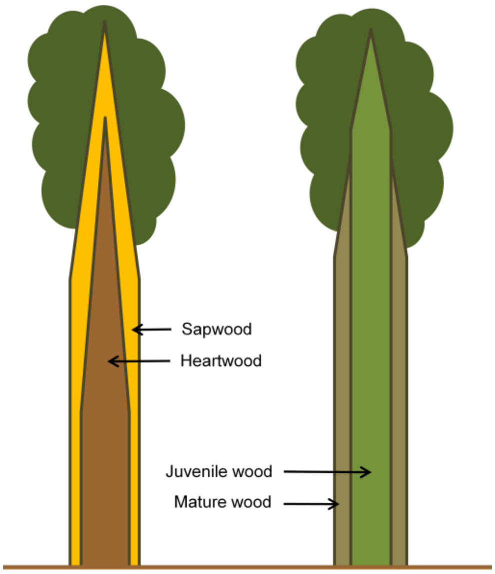


Figure 5-1: Location of sap- and heartwood, and juvenile core and mature wood (taken from Jozsa and Middleton 1994).

As noted above, basic wood density has considerable variation which is contributable to the inverse proportionality between basic wood density and vessel frequency and diameter, especially as seen in ring-porous woods having large earlywood vessels (Savidge 2003). A good indicator of high basic wood density in hardwoods according to Savidge (2003) is a high ratio between fibre tracheid and vessel element frequency. A photograph of fibre and vessel distribution is seen in Photo 5-1 taken from the *Eucalyptus grandis* clone material used for this study.

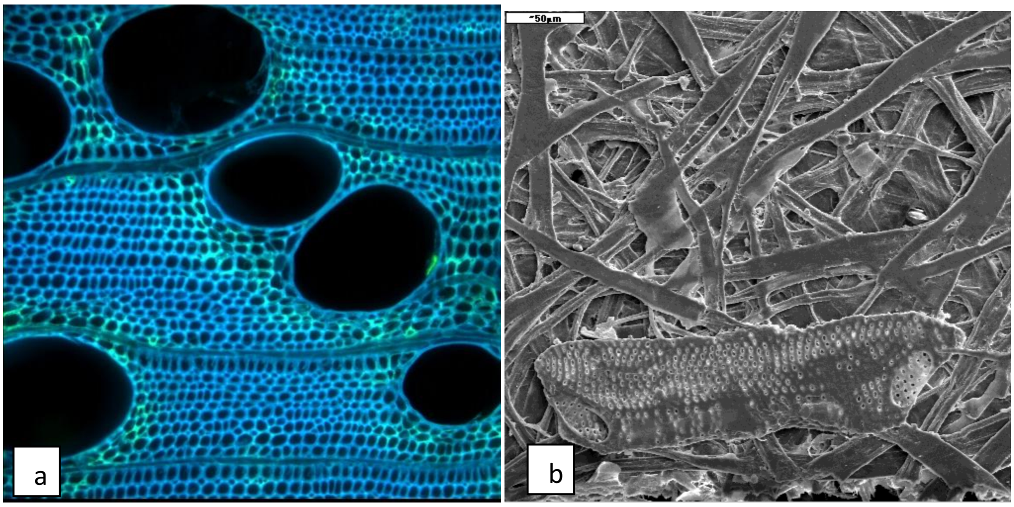


Photo 5-1: Photograph of fibres and vessels taken from the *Eucalyptus grandis* clone material used for this study. Photo a): the ratio between fibre and vessel frequency at cross sectional plane; and b) a photo showing the relative size of a vessel element compared with a network of fibres. (Photo taken by M. du Plessis, 2009)

A significant interaction was found by Malan (1991) between basic wood density and the radial position in the stem. In mature *Eucalyptus grandis*, basic wood density increases rapidly from the pith to the bark, especially in the zone of the juvenile wood (Taylor 1973, Malan and Hoon 1992, Malan and Arbuthnot 1995, Malan 2005).

Basic wood density has been found to correlate well with some pulp and paper properties; e.g. positive relationships with handsheet bulk properties (mass and thickness) and negatively correlated with strength properties (tensile, tear and bending stiffness), (du Toit and Drew 2003, Miranda et al. 2009). The correlations are often inconsistent because large inter-tree variation exists between species and intra-tree variation between trees within the same species and within the individual tree (Hudson et al. 1998, Ramirez et al. 2009).

Environment interaction also plays a role. As indicated by MacFarlane and Adams (1998) drought causes lower basic wood density in *E. globulus* when they used the $\delta^{13}C$ technique to assess cambial activity in relation to water availability. Conversely it was indicated by du Toit et al. (2001), du Toit and Drew (2003) and Savidge (2003) that an increase in basic wood density is commonly observed with an increase in resource availability of short-rotation, fast-growing eucalypt stands. Cown (1999) indicated for *Pinus radiata* that within a species, the latewood component is highly sensitive to environmental and site effects. The latter statement is consistent with the findings of the study of variability of tree growth rings studied with the aid of gamma ray densitometry (Chapter 2).

5.1.2 Growth rings

Trees growing in temperate regions produce growth rings that reflect the onset of spring growth and autumn cessation of cambial division and cell differentiation. Anatomically they can be visible as bands of earlywood and latewood. In hardwoods the size, number, position, arrangement, etc. of two cell types, fibre tracheids and vessel elements, in each growth ring and the arrangement of axial parenchyma in various patterns, are responsible for an infinite number of anatomical combinations. Seasonal growth rings in the tropics for example, do not imitate a demarcated annual calendar cycle but reflect significant short term climatic (weather) events and hence cannot be referred to as annual growth rings.

Eucalyptus grandis is an example of a hardwood species that does not have distinct or clearly defined ring boundaries (Naidoo et al. 2010), most often due to a lack of response of cambial activity to the specific seasonal variation of a site (Bhattacharyya et al. 1992, Sandercock et al. 1995, Downes et al. 2002, Downes et al. 2009). Visually, the earlywood and latewood bands are poorly contrasted in *E. grandis,* do not always correspond with the annual growing season and are known to be indistinct (Savidge 2003). This makes it difficult in a number of *Eucalyptus* spp. to distinguish seasonal or short term growth rings from annual increments for the purposes of studying wood properties (Malan 2005, Downes and Drew 2007, Downes et al. 2009).

The usefulness of identifying growth rings in a tree breeding program was illustrated by Greaves et al. (1997). In this age-age correlation study it was shown that individual growth ring wood density of *E. nitens* at an early age can be used to predict wood density at later ages and hence shorten the assessment age for wood density in a breeding program.

5.1.3 Cellular structures

Woods are often described as softwoods and hardwoods, depending from what type of tree they were cut. The terms are misleading because they have nothing to do with the actual physical property, i.e. hardness or softness of the wood. The distinction is based on a taxonomy grouping of the trees; softwoods belong to the Gymnospermae or cone bearing plants and hardwoods to the Angiospermae or flowering plants. Anatomically, softwoods and hardwoods are made up of different cell types and as a result have different structures (Butterfield 2003).

Unlike softwoods with elongated tracheids fulfilling most functions of water conduction and support, hardwoods separate the functions of structural support and conduction into two different cell types: axially orientated, elongated fibre tracheids modified for support, and vessel elements joined end to end to form long, vertical/axial conduits for long distance water transport. These two cell types, together with parenchyma arranged in patterns, form the crux of hardwood anatomy.

Anatomically, hardwood fibre tracheids differ from softwood tracheids on the following aspects:

- they are smaller but have much thicker cell walls
- they have smaller lumina
- their pits are reduced in size because they do not have a conductivity function
- hardwood fibres have much more elongated tips than softwood tracheids to maintain a dense interlacing pattern of cell tips, giving its strength property (Davin and Lewis 2000, Butterfield 2003).

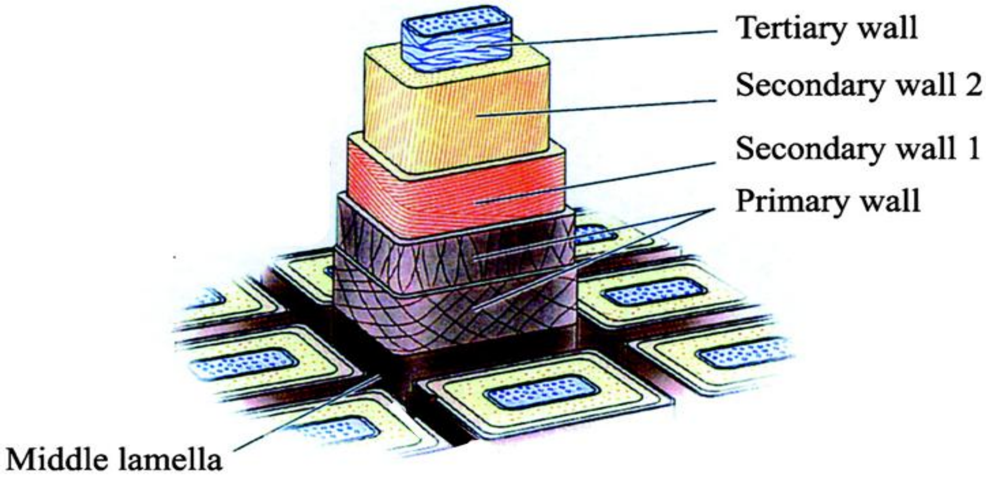


Figure 5-2: A schematic idealized model of the cell wall of softwood tracheids and libriform hardwood fibres. Taken over from Davin and Lewis (2000).

A general schematic model of the cell wall of softwood tracheids and libriform fibres in hardwoods is shown in Figure 5-2 (Davin and Lewis 2000). The primary or most outer cell wall layer is very thin (0.1 - 0.2 µm) and remains plastic prior to the deposition of the secondary cell wall (Butterfield 2003). The secondary cell wall is laid down after the primary cell wall, often in three distinct layers, S1, S2 and S3 (or teriary wall as in dicated in Figure 5-2). The cellulose microfibrils are highly ordered in the S1 layer (0.1 - 0.3 µm) and often the microfibril angle is noted on this wall. The S2 cell wall, for pulp purposes is of most interest; it is 1 - 5 µm thick and dominates the tracheid fibre secondary cell walls especially in latewood of the growth ring. The structure of these walls determine the mechanical and physical properties of wood. Wood density, as influenced by cell wall thickness, has long been known to affect stiffness in wood, and the micro-fibril angle in the S2-layer governs two wood properties namely axial stiffness and longitudinal shrinkage, especially important in softwoods and when sawn timber is considered as end product.

The higher growth rate in the hardwood tropical plantations promoted longer fibre length (Kojima et al. 2009). It was further described by Kojima et al. (2009) that amending silvicultural treatments to increase the lateral growth rate (e.g. optimizing planting espacement and thinning intensity) of *E. grandis*, would result in longer fibre length in tropical climates.

Vessel elements in contrast are larger than tracheid fibres, the microfibril angels are aligned close to 90° to the long axis of the vessel element and cell ends are often perforated to allow for rapid water movement (Butterfield 2003). The vessel elements in a living tree are under water tension. An attempt was made by February et al. (1995) to predict water use efficiency in

Eucalyptus species. It was found that vessel diameter and vessel length of *E. grandis* and *E. grandis* × *E. camaldulensis* increased significantly with available water in the soil profile while vessel count did not correlate with water use efficiency. Water availability had a significant influence on stem diameter and transversal sectional stem area. There are at least three ways in which a tree may improve on its sap transport efficiency; one is by producing more cross sectional xylem, and the other is by changing some anatomical features that affect conductivity such as changes in vessel diameter, length and number of vessels, and a third, is by reducing the transformation of sapwood to heartwood. It was shown by Zimmerman (1983) and Carlquist (1988) that hydraulic conductivity was proportional to the vessel radius raised to the 4^{th} power; this means that even a small increase in vessel diameter was equivalent to an enormous ability to transport sap.

Significant differences in vessel element diameter (µm) and vessel frequency (number of vessels mm^{-2}) were found between fast and slow growing *E. grandis*, with the larger but fewer vessels found in faster growing trees Malan (1991).

5.1.4 Silvicultural management

Valuable insights into how wood density and other wood quality properties can be manipulated through silvicultural treatment have been described by numerous researchers in the past. Clarke et al. (1999), DeBell et al. (2001), Concalves et al. (2004), Clarke et al. (2008) and many others have considered the theoretical basis for exploiting the phenotopic plasticity through silviculture (Drew et al. 2001, du Toit and Drew 2003, Muneri and Raymond 2000).

Irrigation for example, can greatly increase the latewood to earlywood ratio of conifers grown in temperate zones, evidently by preventing the cambium from going into dormancy in mid- to late- summer (Savidge 2003). Water availability also determines the nature of wood formation in hardwoods (Clarke et al. 1999, Jacobs and Drew 2001). Early nutrition, either by adding fertiliser directly after planting or indirectly through residue management, have also shown to increase total biomass of eucalypt plantations by between 20 and 90 m^3 ha^{-1} and basic wood density by 15-30 kg m^{-3} (du Toit et al. 2010).

A significant impact of initial planting density and hence early improvements in resource availability as reported by du Toit et al. (2010), and the effect it has on tree growth, basic wood density, fibre and pulp properties have been reported by a number of authors (Grzeskowiak and Turner 2000, Wimmer et al. 2002, Concalves et al. 2004, Kang et al. 2004, Malan 2005, Miranda et al. 2009). An increase in distance between trees has the effect of increasing the amount of soil water and minerals available to each tree and an increase in light penetration through the canopy. It was noted that through controlling stand density either through thinning or at initial planting or a combination of the two, strong influences were observed between growth and wood formation. In a South African example, significant increases in basic wood density were reported where increased growth rates were evident due to extra growing space in a CCT-spacing trial in KwaZulu-Natal (Malan and Hoon 1992). Free growing individuals showed a tendency to level-off the increase in basic wood density fairly early in their growth, resulting in timber with a larger proportion of mature wood that is more homogenous (Malan and Hoon 1992, DeBell et al. 2001, Malan 2005).

5.1.5 Objectives of this study

The main objective of this study was to investigate the effect of planting density on wood, fibre and vessel properties, with the purpose to define a suitable fibre productivity index to measure the contribution of wood from plantations to the pulping process and manufacturing of pulp and paper.

Fibre and vessel properties were studied to explain the variation between different spacing treatments (main effect), between tree variation (inter-tree) and within tree variation (intra-tree) variation.

The experimental approach in this study was to destructively sample selected trees from various planting density treatments at various height intervals up the stem, analysing the development of the **air-dry wood density** (further only referred to as "*wood density*"), and fibre and vessel properties in a radial direction, from the pith to the bark. Gamma-ray densitometry techniques and light fluorescence microscopy combined with image analysis were used to describe the variation of wood density and fibre and vessel characteristics of a *Eucalyptus grandis* clone grown in a Nelder 1a design spacing trial.

5.2 MATERIALS AND METHODS

5.2.1 Material origin

The wood material investigated in this study was obtained from a Nelder 1a spacing trial (Nelder, 1962) established by Mondi SA in Swaziland with a commercial *Eucalyptus grandis* clone in the planting season of 1998. This experimental site is located in the Piggs Peak region of Swaziland, at 760 m elevation and positioned on the coordinates 25º58'58.05"S; 31º17'46.60"E. The site is located in the WT9 climate zone (Smith et al. 2005) which places it in the 18 - 19 ºC MAT class; located within the warm temperate climatic zones. The rainfall, which is closely related to forest productivity, is regarded to be high; the long term MAP exceeding 1000 mm per annum. The mean annual measured rainfall on the site for the seven year period of experimentation (1998 -

2005), was 1432 mm. The trial site is situated on a mid slope and the lithology is a granite colluvium resulting in soils of the Oakleaf and Inanda families (Soil Classification Working Group 1991).

5.2.2 Trial design

The Nelder 1a spacing experiment is a single systematic experimental design based on a single tree plot design. It is highly sensitive to mortality, suitable for plantation spacing experiments and the statistical analysis can be conducted accordingly (Mark 1983). The design, which was first described by Nelder (1962) allows for the testing of a number of spacing treatments in a relative small area. It comprises of single tree plots in which the available growing space or rectangularity, or both, is varied in a continuous and systematic way in the experiment. The experimental lay-out for the study described here was a full circle design known as the 1a-variant in which the rectangularity is kept constant. The trial contains different stocking densities, comprising of 15 measured spacing treatments ranging from 6,809 trees per hectare (TPH) in the inner most circle to 161 TPH in the most outer ring. Figure 5-3 is a schematic presentation of the trial design. The trial was measured annually and the growth and yield results have been reported by du Plessis and Kotze (2011).

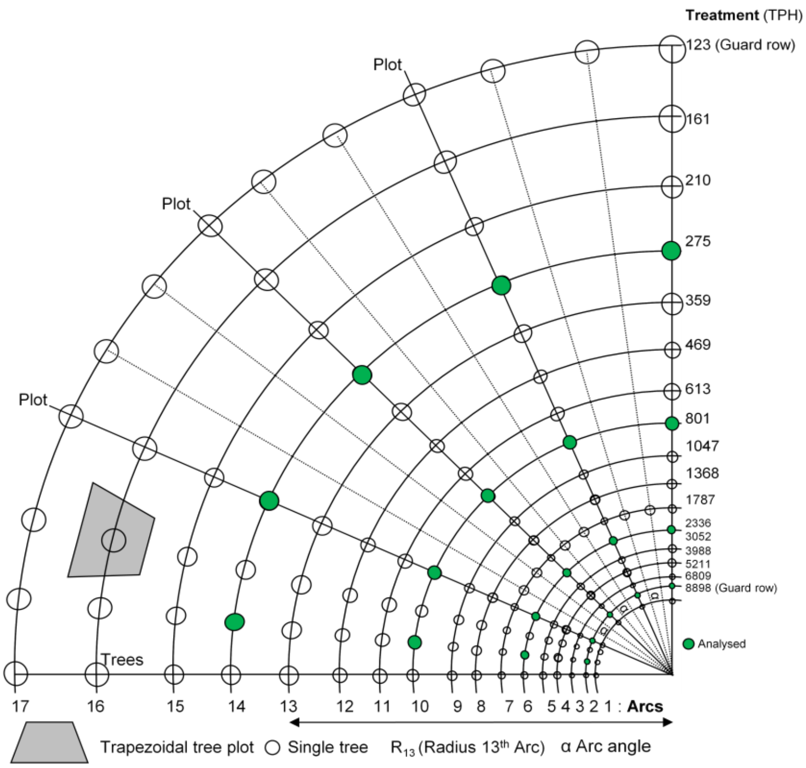


Figure 5-3: Illustration of a quarter of the Nelder 1a experimental design. Circles in green represent trees that have been intensely sampled for this study.

A quarter of the trial was selectively harvested at 6.75 years of age, doing destructive sampling of selected treatments of which the stand characteristics are shown in Table 5-1.

Table 5-1: List of spacing treatments applied in the Nelder 1a experiment.

Arc no.	Treatment (TPH_0)	Radius (m)	Arc distance (m)	Area/tree (m^2)
1 (Guard row)	8898	8.00	1.05	1.12
2	6809	9.14	1.20	1.47
3	5211	10.45	1.37	1.92
4	3988	11.95	1.56	2.51
5	3052	13.66	1.79	3.28
6	2336	15.61	2.04	4.28
7	1787	17.85	2.34	5.59
8	1368	20.40	2.67	7.31
9	1047	23.32	3.05	9.55
10	801	26.66	3.49	12.48
11	613	30.48	3.99	16.31
12	469	34.84	4.56	21.31
13	359	39.82	5.21	27.85
14	275	45.52	5.96	36.39
15	210	52.04	6.81	47.56
16	161	59.49	7.79	62.14
17 (Guard row)	123	68.00	8.90	81.20
Rays	48 trees per spacing treatment			
Shape	1a; Circular (full wagon wheel)			

5.2.3 Wood sampling

Trees, free of defects were selected for destructive sampling from four treatments in the first quadrant of the trial where growing conditions were regarded as being uniform. A total of 20 trees (T1 - T20) from five replications (located along each arc) from four treatments (6809 TPH, 2336 TPH, 801 TPH and 275 TPH) (see Table 5-1) were sampled for this wood products study. Due to the constitution of the Nelder 1a trial design (Nelder 1962), each tree is a single tree plot and also regarded as a replication. Destructive sampling was done according to Figure 5-4, taking three round discs from each tree at DBH (1.3 m), 35 % and 65 % of total tree height respectively. The billets below each sample discs were also kept for a pulping investigation reported in Chapter 6.

Later, 15 trees from three additional treatments (3988 TPH, 1368 TPH and 469 TPH; T21 - T35) were sampled. Due to cost constraints, only a single disc at DBH from T21 - T35 was taken and a 1 m long billet used for pulping and paper making was sampled. It must be noted that a devastating fire raged through the trial in 2007 (FSA 2008) before the final 15 trees were sampled and although the wood was intact, caution was exercised with the interpretation of the results.

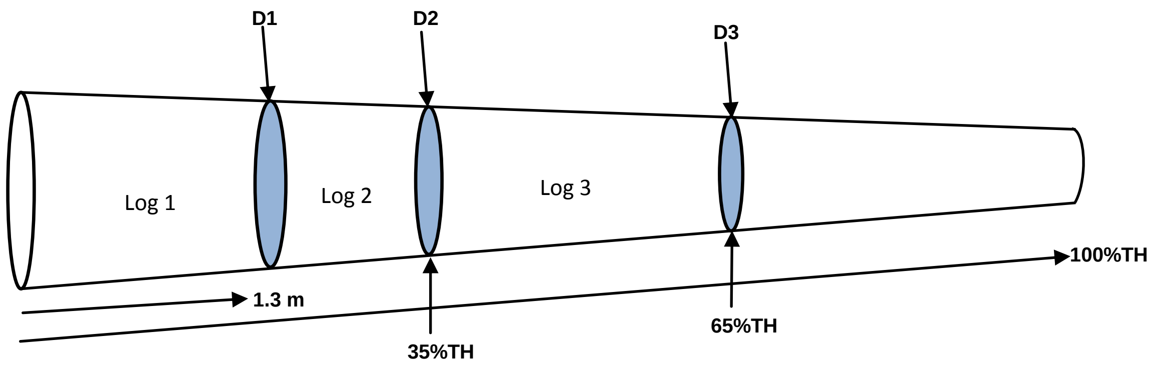


Figure 5-4: Disc sampling protocol indicating the relative position of the three discs (D1-3) taken for density and cell morphology measurements.

5.2.3.1 Measurement of air-dry wood density

A rectangular wooden block was sawn through the centre of each disc, all in the same direction relative to the orientation of each tree in the trial (see Figure 5-5). The cores from each disc were stored at 23 ºC and 50 % RH to achieve an equilibrium moisture content of *c.* 10 %. Strips of uniform thickness were cut along the radius using a twin-blade saw. As illustrated in Fig 5-5, the sample dimensions were 12 mm in the longitudinal and 2.5 mm in the tangential direction along the entire length of the core determined by the radius of each individual disc. Figure 5-5 also illustrates the scanning direction of the sample. To measure wood density profiles in the radial-plane from bark to pith, strips were scanned at 0.5 mm intervals using a gamma-ray densitometer with a Fe^{55} radiation source. **Air dry** wood density (this study) can be as much as 10 % higher than **basic** wood density (Equation 1). The data acquisition was computer controlled with a stepper motor drive that ensured exact 0.5 mm incremental moves at a time. The use of gamma-ray densitometry was considered to be an accurate and reliable technique to determine wood density (Malan and Marais 1991, Kang et al. 2004) as demonstrated by Naidoo et al. (2006). The weighted mean wood density of the entire disc was calculated from the density profile (explained in *section 5.2.4.1*). Extractives were not removed prior to scanning consistent with standard procedures at the CSIR-FFP laboratory (Zboňák, 2002).

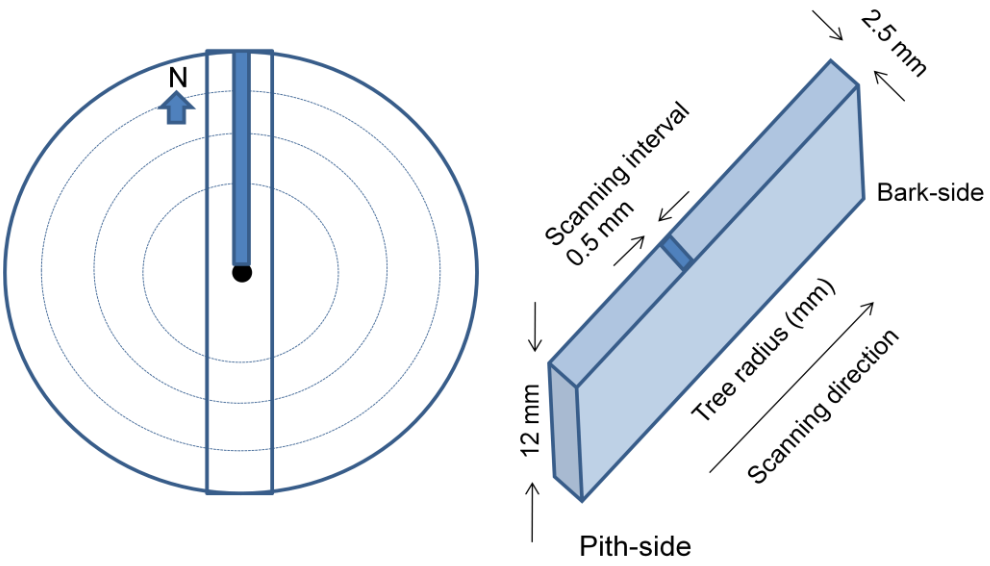


Figure 5-5: Wood sampling protocol from discs indicating block taken through the centre and strip sawn.

5.2.4 Measurement of cellular properties

Anatomical properties of fibre tracheids and vessel elements were measured from discs taken from trees (T1 - 20; green circles from Figure 5-3) at DBH (1.3 m), 35 % and 65 % of total tree height. Radial strips, 2.5 mm thick, additional to those used for wood densitometry, were sampled from pith to bark and left to soak in water overnight. Once saturated, the strips were cut with a sledge microtome to obtain a 20 - 25 μm thick section. Sections were mounted with ethanol on a glass slide, covered with a cover-slip, and examined using a Leica fluorescent microscope. Vessel and fibre tracheid properties were measurements from the pith to the bark every 0.5 mm making use of an image analysis system (Leica QWin). An algorithm developed by the CSIR (Zboňák and Bush 2006, Zboňák et al. 2007), making use of image analysis software, enabled the automatic separation of vessels from the fibres and parenchyma in each image acquired. Vessel characteristics measured included cross sectional area, diameter, frequency and percentage (% of total area measured in the frame occupied by vessel elements). For wood fibres their outside diameter, lumen diameter and cell wall thickness were measured.

5.2.4.1 Weighting of data

Weighted values for all wood properties were calculated to make provision for the proportional representation of wood to be lowest at the pith and highest close to the bark-end. To obtain a weighted mean value, the relevant wood property, e.g. wood density measured at each position in the radial plane from the pith to the bark was multiplied by the area measured; these values were added and divided by the sum of squares of all distances from the pith. The results were used for general assessment of main effects of the spacing treatments on wood and cellular properties. First, the area weighted mean for each disc at the interval heights (DBH, 35 % and 65 % of tree height) was calculated.

$$WMD = \frac{\sum_{i=1}^{n}(x_i a_i)}{\sum_{i=1}^{n} a_i}$$ *Equation 2*

where

WMD refers to weighted mean of the disc

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

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

n is the number of observations.

Subsequently, whole tree properties were determined by weighting for example for mean wood density and other anatomical measurements, e.g. fibre and vessel dimensions, of the three height intervals (DBH, 35 % and 65 % of tree height) by the volume (m^3) of the logs, indicated in Figure 5-4, between these measurements. The following equation was used:

$$WMT = \frac{\sum_{i=1}^{n} WMD_i v_i}{\sum_{i=1}^{n} v_i}$$ *Equation 3*

where:

WMT - Weighted mean tree refers to weighted mean of selected properties of the tree

WMD_i is the weighted wood property value of the disc of the i^{th} height interval;

v_i is the volume of the i^{th} height interval

n is the number of observations.

5.2.5 Statistical analysis

Various statistical analyses procedures were selected to achieve the following objectives:

- Descriptive statistics including graphical analysis were used to evaluate for normality, underlying distribution of variables and fitness for parametric statistics.

- Due to the lay-out of the Nelder experiment, it was important to analyse and correct fixed (introduced) effects such as possible effects of replication of treatments, where necessary.
- Data were tested for significance between means by comparing variance, e.g. weighted mean wood density between spacing treatments by means of ANOVA.
- Correlations between variables were established to determine the "relatedness" between them.
- A linear dimensionality reduction technique was applied to project the data into a lower-dimensionality space, formed of a sub-set of the highest-variance components with Principal Component Analysis techniques and also displaying the data in biplots.
- Finally, prediction models were developed with regression techniques to establish the predictive ability of the statistical relationships.

The data was analysed using SAS/STAT Enterprise software, Version 4.2 and SAS/IML 3.2. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, NC, USA. (SAS Institute Inc. 2006). Programs written in R (R Development Core Team, 2010) as given in Gower et al. (2011) were used to represent data in monoplots and biplots.

5.2.5.1 ANOVA

Testing the main effects, data were subjected to Analysis of Variance to test the hypothesis that there were no differences between the means of wood density, fibre and vessel variables across treatments.

The model was defined as follows:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij} \quad \text{for } j = 1, \ldots, n \; i = 1, \ldots, k \qquad \textit{Equation 4}$$

where:

Y_{ij} = the j - th observation of the i - th treatment

μ = overall mean

α_i = the effect due to treatment

β_j = the effect due to replications

ε_{ij} = the random error associated with the j-th observation of treatment i

Data were represented in a correlation matrix in order to explore the relationships between wood density and fibre and vessel anatomy, and to determine whether there was linear association between the data sets. Treatment levels were compared with the Duncan's multiple range test (DMRT) which belongs to the general class of multiple comparison procedures that use the studentized range statistic to compare sets of means. DMRT involves the computation of numerical boundaries that allow for the classification of the difference between any two treatment means as significant or non-significant and are denoted in the Tables by the letters *a*, *b*, *c* and *d*, indicating significance between groups of planting density treatments.

5.2.5.2 Principal Component Analysis (PCA)

The measured dataset was normalised to zero means and unit variances and was further subjected to principal component analysis (PCA). PCA involves a mathematical procedure that transforms a number of (possibly) correlated variables into a (smaller) number of uncorrelated variables called *principal components* (Cooley et al. 1971). The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. Each principal component is a linear combination of the original variables. Eigenvectors and eigenvalues, associated with the original correlation matrix are calculated. The first principal component has the largest eigenvalue, the second principal component has a smaller eigenvalue, and so on. It is generally accepted that only those principal components that account for an appreciable portion of the variation (e.g. 70 % and above) should be chosen for further analysis. Once the principal components were identified, multiple regression analyses were conducted to identify the significant physical and anatomical parameters that may be used to predict variation in wood anatomical properties. Only significant ($p < 0.05$) wood parameters that explained the variation in data sets properties were tabulated.

5.2.5.3 Graphical display of data in biplots

Biplots were first described by (Gabriel 1971) as a simultaneous display of the rows (sampling units) and columns (the variables) of a data matrix. The eigenvectors resulting from a PCA can be used to construct a (PCA) biplot in one, two or three dimensions. Only two-dimensional biplots are considered in this investigation. Any two principal components (eigenvectors) can be used for constructing a two-dimensional PCA biplot. However, unless specified otherwise in this study, the first two eigenvectors (i.e. those eigenvectors associated with the two largest eigenvalues) are used. These axes are not shown in the biplot. However, they form the framework or biplot scaffolding for placement of the points and constructing calibrated axes to represent the variables in the graph (Gardner et al. 2005). Two types of bilpots, the PCA and CVA biplots are discussed when applied to the wood density, vessel and fibre data sets. In the PCA biplots presented in this study the interpoint distances are approximated. All variables are represented in the biplot as non-perpendicular calibrated axes. By dropping a line from any point in the graph perpendicular onto any of the biplot axes allows the user to read off the point's value for that particular variable. Although the standardised variables are used as input, the convention followed here is to transform the calibrations on the biplot axes back to the original scales of measurement. An overall quality measure of the approximations in two dimensions is provided as well as the accuracy of the approximation of each axis. The latter values are given as proportions or percentages following the name of the respective biplot axes. Although the angles between the biplot axes give an indication of the correlations between them, corelations between variables are not optimally approximated in the PCA biplots. In order to judge the correlations between the variables, the correlation monoplots (Gower et al. 2011) that are given should be consulted. The distances between the points in a PCA biplot might reveal a grouping structure. Therefore, predeterminded groups are colour-coded in order to investigate possible differences between the groups. Canonical variate analysis (CVA) biplots on the other hand are designed for optimally representing differences between group means. CVA, which is closely related to linear discriminant analysis, is a popular technique to separate predetermined groups in data by finding linear combinations of variables that optimise the ratio of the inter-group variation to the intra-group variation. CVA, unlike PCA, is unaffected by standardising the data. Therefore, the unstandardised data were used for constructing the CVA biplots presented in this study. These CVA biplots optimally separate the group means and in addition, shows the within group variation by interpolating all the sample points into the biplot (Gower et al. 2011). The CVA biplot therefore, is a visual display of the separation and overlap among the groups together with information on the role played by the different variables in distinguishing the groups from one another.

5.3 RESULTS

5.3.1 Wood density

A series of wood density data (*air-dry*) for each of the trees sampled at the various heights was generated from the gamma-ray densitometer generating a value for wood density (g cm^{-3}) from the pith to the bark every 0.5 mm of the distance from pith to bark. Mean wood density curves for all four spacing treatments (6809 TPH, 2336 TPH, 801 TPH and 275 TPH) are shown in Figure 5-6. Figure 5-7 represents the same data but is normalized to be of equal length (removing the effect of different sample diameters) representing the relative position from pith to bark on a scale from 0 (pith) to 1 (bark). Mean wood density in Figure 5-7 now uses increments of 0.05 on a scale from 0 to 1.

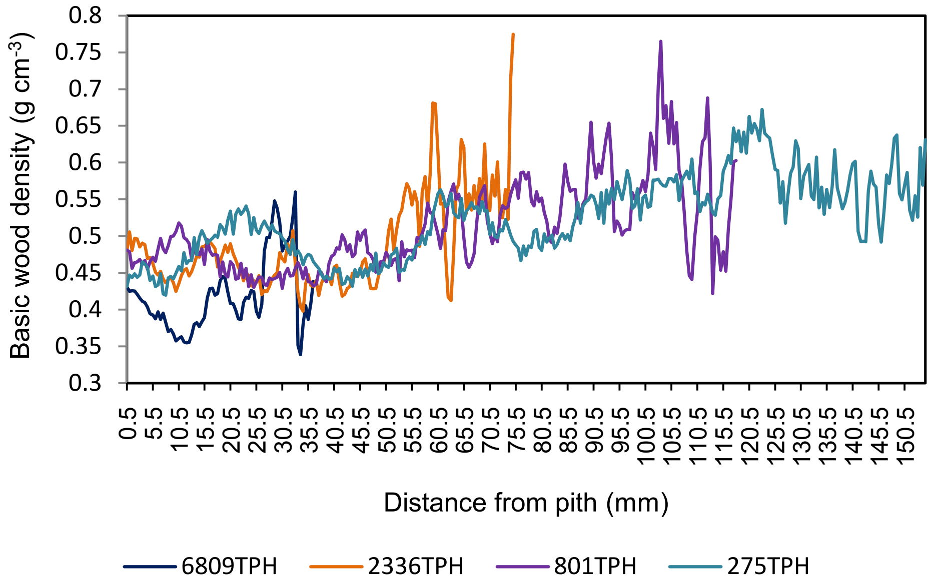


Figure 5-6: Variation in mean wood density measured at DBH (1.3 m) and for four spacing treatments.

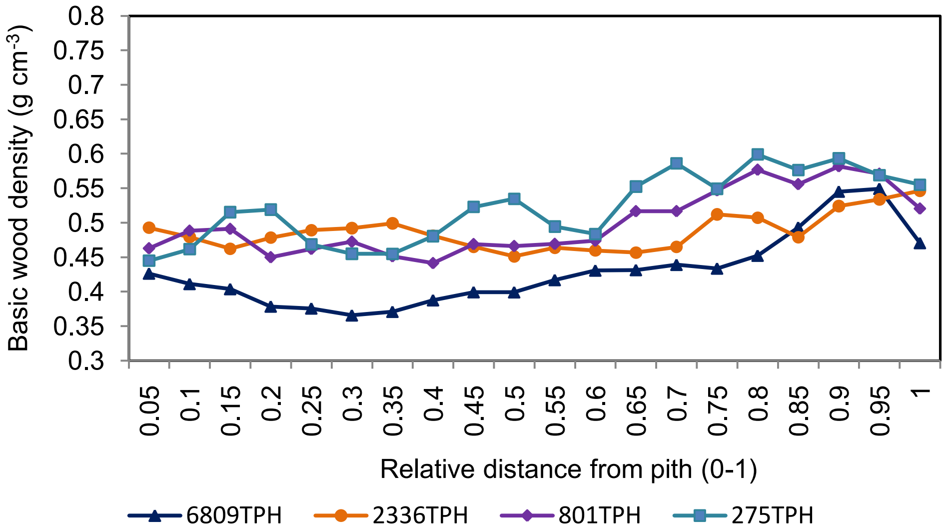


Figure 5-7: Mean wood density for four spacing treatments at DBH and normalized from 0 - 1 from the pith to the bark.

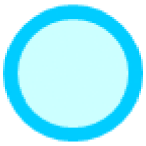
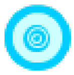
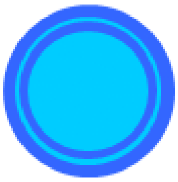
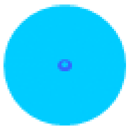
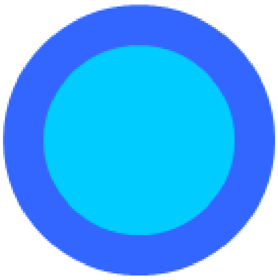
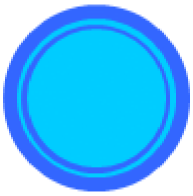
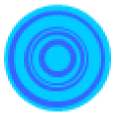
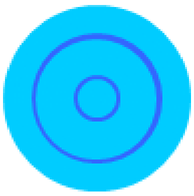
	At 1.3m height (DBH)	35 % of tree height	65 % of tree height
6809 TPH	WD =0.429 g cm^{-3}; sd=0.08	WD =0.394 g cm^{-3}; sd=0.05	WD =0.409 g cm^{-3}; sd=0.08
			
2336 TPH	WD =0.486 g cm^{-3}; sd=0.06	WD =0.449 g cm^{-3}; sd=0.07	WD =0.435 g cm^{-3}; sd=0.08
			
801 TPH	WD =0.499 g cm^{-3}; sd=0.06	WD =0.466 g cm^{-3}; sd=0.06	WD =0.487 g cm^{-3}; sd=0.07
			
275 TPH	WD =0.520 g cm^{-3}; sd=0.06	WD =0.482 g cm^{-3}; sd=0.05	WD =0.510 g cm^{-3}; sd=0.06
			

Figure 5-8: Wheeled graphs showing mean wood density (WD) gradient and standard deviation (sd) at three tree diameters located at DBH, 35 % and 65 % tree height (HD) intervals for four tree spacing treatments.

Colour legend:

Low **WD < 0.4 g cm^{-3}** Medium **0.4 < WD < 0.5 g cm^{-3}** High **WD > 0.5 g cm^{-3}**

The wheeled graphs in Figure 5-8 are on scale with the mean tree diameter measured for each planting density and disc position in the tree. Three groupings of density, regarded as low, medium and high were selected. The pattern of the blue colouration is an indication of the variability of each treatment. When scrutinizing the wheeled graphs from the left to right it is observed that wood density in the bottom discs were higher than in the higher positions in the tree and observed from the top to the bottom that density increases with reduced TPH.

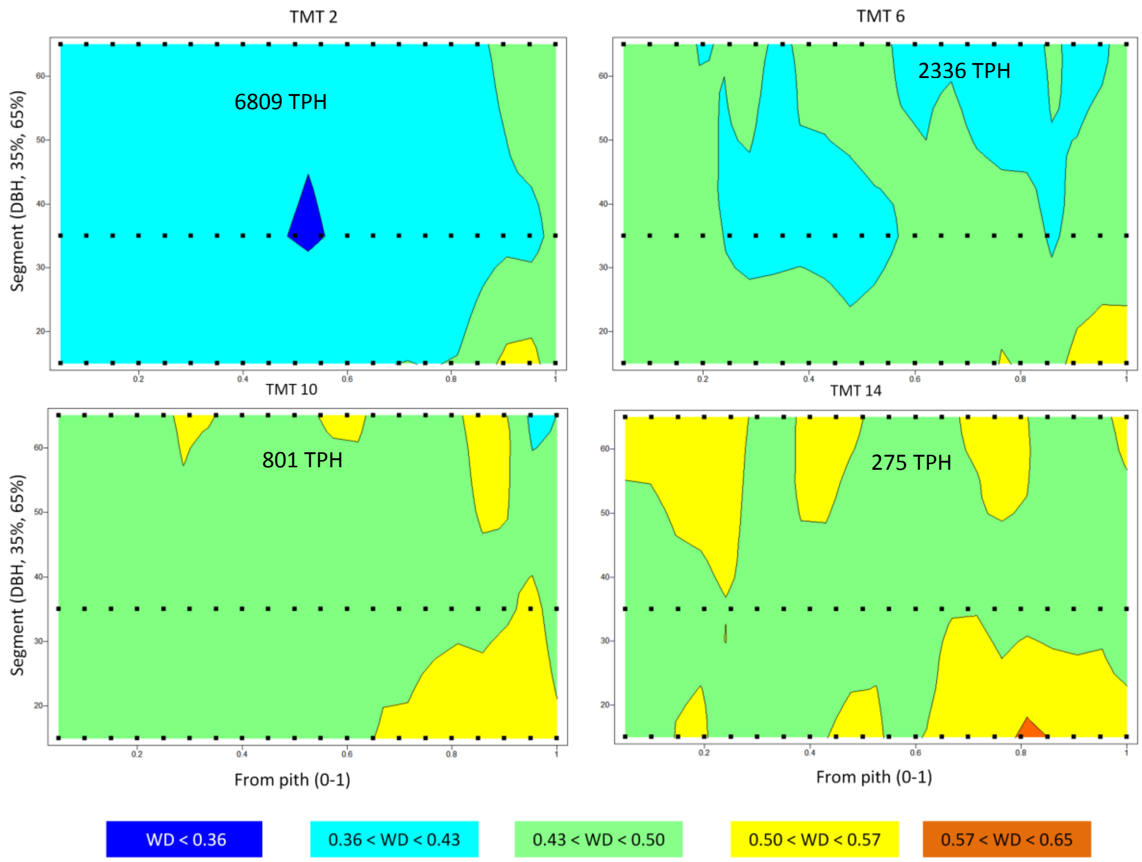


Figure 5-9: Contour graphic display of the wood density means by spacing treatment and disc height position. **Legend:** WD = Mean wood density, TMT = spacing treatments.

It is observed from the contour plot in Figure 5-9 that the higher mean wood density was found in the spacing treatments with larger and fewer trees (801TPH and 275 TPH), whereas lower mean wood density was found in treatments with high (2336 TPH) to extremely high (6809 TPH). There is no change in the order of spacing treatments relative to one another and from the wheeled graphs displayed in Figure 5-8. In Figure 5-9 it is seen that the 35 % tree height position generally exhibited lower mean wood density than at the DBH (1.3m) and 65 % tree height respectively.

The single tree plot replications were tested for uniformity within the replications and it was shown that there were no block (replication) effects on the data. Data was found to be normally distributed by using the Kolmogorov-Smirnov (D) statistic.

In the analysis of variance, weighted mean tree (WMT) wood density data combined for heights (calculated according to Equation 3) was used as the dependent variable "whole tree" and the independent variable treatment on four levels of spacing treatments. Similarly, the weighted mean disc (WMD) value computed from Equation 2 was used in the ANOVA as disc values at "DBH", "35 %" and "65 %" of tree height in Table 5-2.

In Table 5-2 the fit statistics of an analysis of variance and DMRT are given. It can be observed that the means on wood density is significantly different ($p < 0.0001$) from zero.

Table 5-2: Analysis of variance statistics for wood density across spacing tretaments and three height positions.

Weighted mean wood density (air-dry)	**R^2**	**MSE**	**Pr>F**	**Means**	**Duncan group**			
					275TPH	**801**	**2336**	**6809**
Whole tree	0.56	0.038	<0.0001	0.464	0.504[a]	0.484[b]	0.457[c]	0.410[d]
DBH	0.37	0.044	<0.0001	0.483	0.520[a]	0.499[ab]	0.486[b]	0.429[c]
35 %	0.65	0.029	<0.0001	0.448	0.482[a]	0.466[b]	0.449[c]	0.394[d]
65 %	0.63	0.043	<0.0001	0.460	0.510[a]	0.487[b]	0.435[c]	0.409[d]

From Table 5-2 it is seen that the mean wood density differs at whole tree level and within the four spacing treatments; each treatments has a different alpha-letter (a, b, c, d) assigned to it and hence the Duncan's multiple range test indicates significant differences between all planting density treatments. At the whole tree level, mean wood density is lowest in 6809 TPH (0.410 g cm^{-3}) and highest in 275 TPH (0.504 g cm^{-3}). When the within tree levels are considered, at DBH-level; 275 TPH ([a]) at 0.520 g cm^{-3} is significantly different from the other groupings except 801 TPH ([ab]), moreover 2336 TPH ([b]) is significantly different from 275 TPH ([a]) and 6809 TPH ([c]) but not from 801 TPH. The 35 % of tree height position has the highest coefficient of determination ($R^2 = 0.65$), the highest mean wood density (0.520 g cm^{-3}) was found on the DBH (1.3 m) level of 275 TPH and the lowest (0.394 g cm^{-3}) in 6809 TPH, 35 % tree height position.

5.3.2 Cellular morphology

The data for vessel and fibre characteristics were evaluated similar to the average wood density data set; i.e. the WMT and WMD data were normalized to have relative representation from the pith to the bark on a scale from 0 to 1.

5.3.2.1 Vessel elements

The variables considered for the analyses were: Vessel element diameter (μm), Vessel element frequency (number of vessels per mm^2) and Vessel percentage (% of unit area covered by vessel elements).

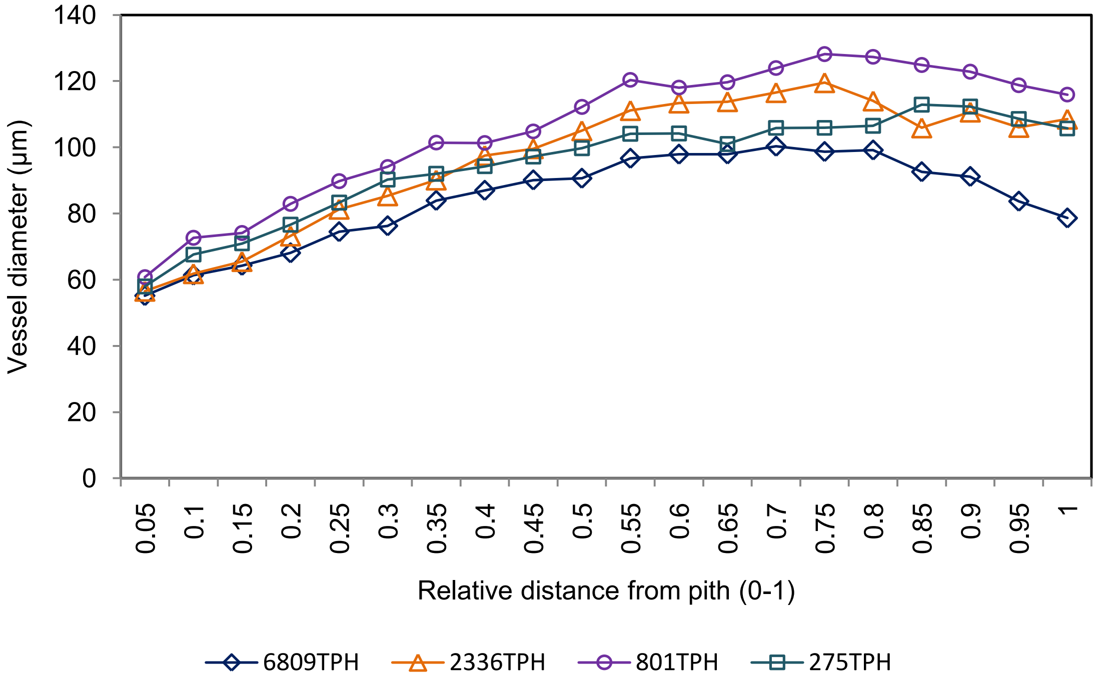


Figure 5-10: Pith to bark vessel element mean diameter for spacing treatments averaged for the whole tree data (WMT).

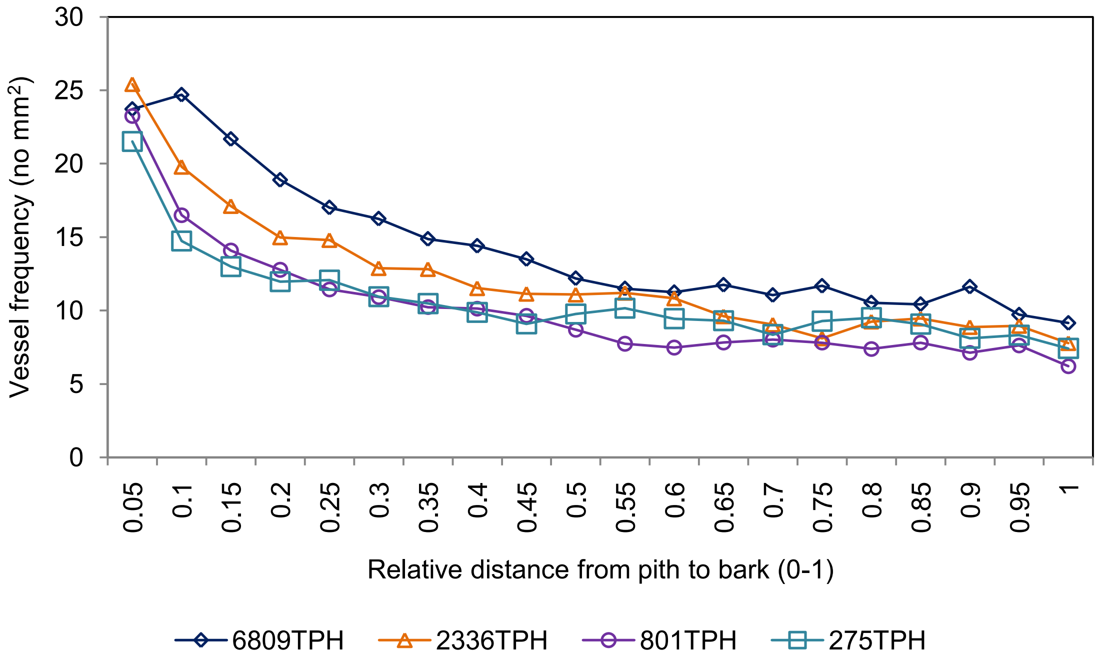


Figure 5-11: Pith to bark vessel element mean frequency for spacing treatments averaged for the whole tree data (WMT).

The variation in vessel element characteristics is presented in Figure 5-10 and Figure 5-11. It is noted from Table 5-3a, that the average vessel element diameter for WMT (whole tree level), which is the average of both the tangential and radial dimensions, was larger for the two low stand density treatments, 275 TPH and 801 TPH. In all treatments the shape of the curves remained similar, reflecting the shape of a parabola curve, with a small vessel element diameter close the pith and the bark and highest in the middle.

The vessel frequency data curves in Figure 5-11 are shaped typically in a power function on which a curve can be fitted. In all the spacing treatments, the higher stand densities, treatments 6809 TPH and 2336 TPH, had a higher frequency of vessels than the lower stand densities (treatments 801 TPH and 275 TPH), with all the spacing treatments approaching almost the same levels closest to the bark. Analysis of variance was carried out as per Equation 4.

Table 5-3a and 5-3b show fit statistics of the analysis of variance. In both tables, the Duncan groupings are given. They are read from left to right and not up and down. It should also be noted that the sequence in which the Duncan-statistic per TMT is reported in these tables changes according to its means, from left to right. The “Whole tree”-category takes all data on a per tree basis into account whereas tree position data are indicated in percentage height intervals of the tree stem.

Table 5-3: Fit statistics and Duncan groupings of Vessel element characteristics: a) vessel diameter; b) vessel frequency.

a. Mean vessel element diameter

Weighted Mean Vessel Element Diameter	**R^2**	**MSE**	**Pr>F**	**Means (µm)**	**Duncan group**			
					801	**275**	**2336**	**6809**
Whole tree	0.31	11.79	0.0001	103.94	113.7[a]	106.4[ab]	103.1[b]	92.5[c]
DBH	0.12	13.21	0.5475	96.61	103.6[a]	97.1[a]	93.0[a]	92.8[a]
35 %	0.60	10.01	0.0016	109.46	122.2[a]	114.0[a]	109.7[a]	91.9[b]
65 %	0.58	7.78	0.0025	105.73	115.4[a]	108.0[a]	106.7[a]	92.8[b]

b. Mean vessel element frequency

Weighted Mean Vessel Element Frequency	**R^2**	**MSE**	**Pr>F**	**Means (no. mm^{-2})**	**Duncan group**			
					6809	**2336**	**275**	**801**
Whole tree	0.27	1.75	0.0004	9.88	11.4[a]	10.3[ab]	9.0[bc]	8.8[c]
DBH	0.09	1.81	0.6598	9.67	10.1[a]	10.2[a]	8.8[a]	9.5[a]
35 %	0.61	1.25	0.0015	9.18	11.5[a]	8.6[b]	8.8[b]	7.8[b]
65 %	0.56	1.54	0.0033	10.77	12.4[a]	12.2[a]	9.5[b]	8.9[b]

From Table 5-3a and Figure 5-10 it is noted that for Vessel Diameter (VD), 6809 TPH differs from 2336 TPH, 801 TPH and 275 TPH for the 35 % and 65 % position in the tree, but not at DBH (15 %) height. The coefficient of determination (R^2) for heights 35 % and 65 % are relatively high, 0.61 and 0.58 respectively, indicating that a high level of variation in the data was due to the groupings, in this case spacing treatments. Similar R^2 - values are reported in Table 5-3b for Vessel element Frequency (VF) which described the number of vessel elements per unit area. At both the 35 % and 65 % heights, two groupings (A and B) exist for VD and VF, described by a significantly lower VD in the high stand density (6809 TPH) corresponding with a higher number of vessel elements at the same time. Fewer and larger vessel elements are found in the fast growing - low stand densities.

5.3.2.2 Hardwood fibre tracheids

The variation of whole tree fibre tracheid characteristics are shown in Figure 5-12, Figure 5-13 and Figure 5-14. The following fibre characteristics are noteworthy: Fibre Diameter (FD), Fibre Length (FL), fibre Cell Wall Thickness (CWT), fibre Lumen Diameter (LD).

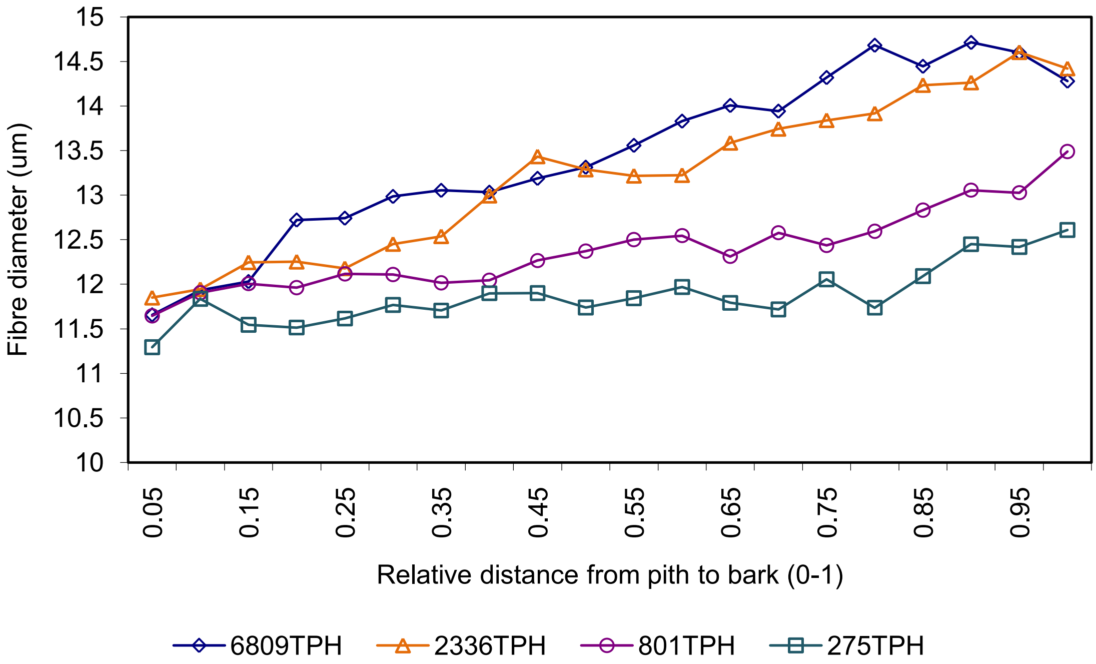


Figure 5-12: Pith to bark whole tree mean fibre tracheid diameter (FD) development shown by spacing treatment.

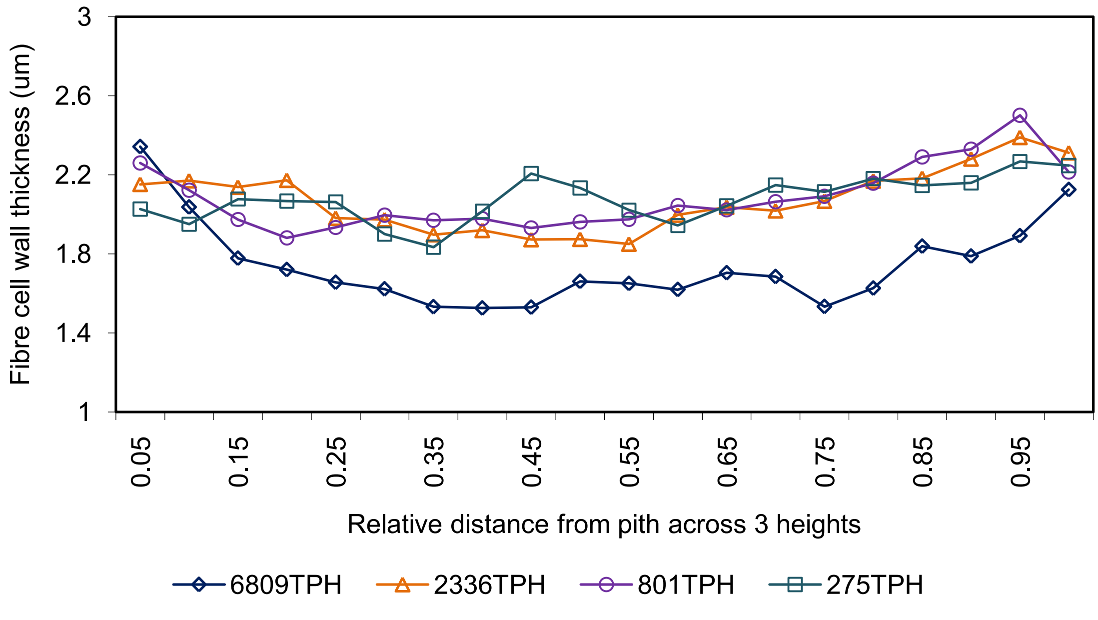


Figure 5-13: Pith to bark whole tree mean fibre cell wall thickness (CWT) development shown for spacing treatments.

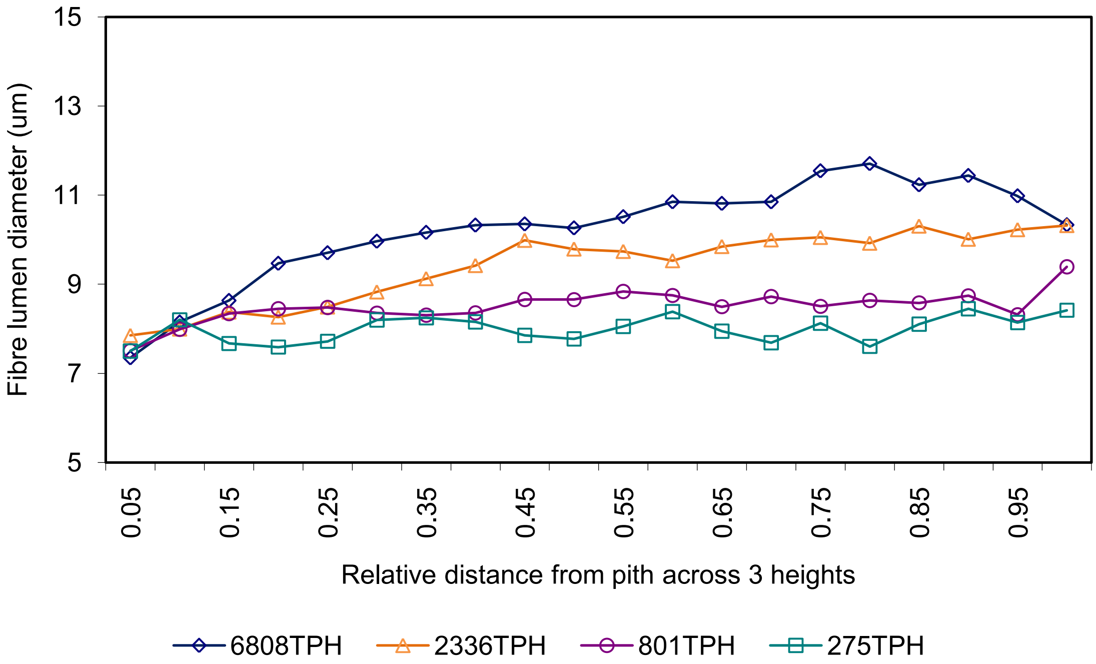


Figure 5-14: Pith to bark whole tree mean fibre lumen diameter (LD) development by spacing treatment.

Table 5-4 contains the analysis of variance fit statistics for three weighted mean fibre characteristics; fibre diameter, cell wall thickness and lumen diameter.

Table 5-4: Fit statistics developed by analysis of variance for fibre characteristics.

a) Mean fibre diameter

Weighted Mean Fibre Diameter (FD)	**R^2**	**MSE**	**Pr>F**	**Means**	**Duncan group**			
					6809	**2336**	**801**	**275**
Whole tree	0.52	0.755	<0.0001	13.09	13.79[a]	13.70[a]	12.62[b]	12.09[b]
DBH	0.57	0.500	0.0027	13.26	13.73[a]	13.78[a]	13.02[b]	12.52[b]
35 %	0.74	0.642	<0.0001	13.43	14.59[a]	14.16[a]	12.80[b]	12.19[b]
65 %	0.55	0.824	0.0040	12.59	13.59[a]	13.16[a]	12.04[b]	11.55[b]

b) Mean cell wall thickness

Weighted Mean Cell Wall Thickness (CWT)	**R^2**	**MSE**	**Pr>F**	**Means**	**Duncan group**			
					801	**2336**	**275**	**6809**
Whole tree	0.50	0.15	<0.0001	2.02	2.12[a]	2.11[a]	2.10[a]	1.77[b]
DBH	0.69	0.10	0.0002	2.04	2.14[a]	2.05[a]	2.17[a]	1.82[b]
35 %	0.60	0.17	0.0016	2.02	2.11[a]	2.21[a]	2.05[a]	1.72[b]
65 %	0.44	0.18	0.0220	2.01	2.13[a]	2.06[a]	2.09[a]	1.76[b]

c) Mean lumen diameter

Weighted Mean Lumen Diameter (LD)	R^2	MSE	Pr>F	Means	Duncan group			
					6809	2336	801	275
Whole tree	0.60	0.84	<0.0001	9.34	10.72[a]	9.83[b]	8.65[c]	8.16[c]
DBH	0.74	0.53	<0.0001	9.51	10.46[a]	10.09[a]	9.06[b]	8.45[b]
35 %	0.77	0.70	<0.0001	9.67	11.35[a]	10.07[b]	8.85[c]	8.37[c]
65 %	0.57	1.03	0.003	8.84	10.32[a]	9.34[ab]	8.05[bc]	7.64[c]

The densely populated spacing treatments, 6809 TPH and 2336 TPH, have a higher mean Fibre Diameter (FD) than 801TPH and 275 TPH as observed in Figure 5-12 and Table 5-4a. This pattern is followed in all three stem positions (DBH, 35 % and 65 % heights) in all trees. The analysis of variance procedure identified these groupings as two distinct groups with the Duncan groupings.

For cell wall thickness (CWT) in all height intervals, 6809 TPH formed a separate grouping and produced much thinner cell walls than spacing treatments 2336, 801 and 275 TPH (see Figure 5-13 and Table 5-4b). No differences were observed between WMT (cell wall thickness) and positions up the stem.

The fibre lumen diameter as seen in Figure 5-14 and Table 5-4c followed the same pattern as fibre diameter. Stand densities at 6809 and 2336 TPH have a wider lumen compared with 801 and 275 TPH, which have smaller fibre lumens.

When the coefficient of determination (R^2) is considered for the fibre characteristics, high figures are produced by analysis of variance. The groupings or planting density treatments thus explain high proportions of the variance in fibre characteristics. The R^2 - values are respectively; FD 0.52, LD 0.60, CWT 0.50 and FL 0.23.

5.3.3 Properties correlation analyses

Given below in Table 5-5 is the abbreviated correlation matrix of selected variables. Important variables included in the correlation matrix are stand density, position in the stem and mean wood density which were correlated with the fibre and vessel data, namely: fibre cross sectional area, fibre diameter, fibre lumen diameter, fibre cell wall thickness, vessel element diameter, vessel element frequency and vessel element percentage. The complete correlation matrix is attached as Annexure 1. It should be noted the p - values are an indication of the significance of the difference from zero, but do not give any knowledge about the practical importance of the correlation. The size of Pearson's correlation r - statistic is an indication of the usefulness of the relationship.

Table 5-5: Abbreviated correlation matrix with Pearson (r) and p values shown.

Pearson Correlation Coefficients (n = 60)			
Variable (whole tree mean values)	**Stand density (TPH)**	**Position in stem**	**Wood density**
Stand density	– –	r = 0 p = 1.000	r = –0.6706 $p < 0.0001$
Wood density	r = –0.6706 $p < 0.0001$	r = –0.2406 $p = 0.0640^{ns}$	– –
Fibre cross sectional area	r = –0.3517 p = 0.0020	r = –0.6346 $p < 0.0001$	r = 0.5099 $p < 0.0001$
Fibre diameter	r = 0.6163 $p < 0.0001$	r = –0.2845 p = 0.0276	r = –0.5106 $p < 0.0001$
Fibre lumen diameter	r = 0.7290 $p < 0.0001$	r = –0.2329 $p = 0.0733^{ns}$	r = –0.6172 $p < 0.0001$
Fibre cell wall thickness	r = –0.6809 $p < 0.0001$	r = –0.0537 $p = 0.6835^{ns}$	r = 0.5753 $p < 0.0001$
Vessel element diameter	r = –0.5056 $p < 0.0001$	r = 0.2370 $p = 0.0683^{ns}$	r = 0.0976 $p = 0.4583^{ns}$
Vessel element frequency	r = 0.4916 $p < 0.0001$	r = 0.2509 $p = 0.0531^{ns}$	r = –0.2696 p = 0.0372
Vessel element percentage	r = –0.2433 $p = 0.0610^{ns}$	r = 0.5292 $p < 0.0001$	r = –0.0673 $p = 0.6095^{ns}$

When the correlation matrix in Table 5-5 is evaluated, it is evident that stand density is negatively correlated with wood density (–0.67) and fibre cell wall thickness (–0.68), and positively correlated with fibre diameter (0.62) and fibre lumen diameter (0.73). Wood density and fibre cell wall thickness increased with lower TPH (wider apart), however the fibre and lumen diameters decreased as a function of thicker cell walls in the low stand density. Sampling tree height position was negatively correlated with the following fibre variables: fibre cross sectional area (–0.63), fibre diameter (–0.28) and lumen diameter (–0.23); i.e. the fibres becoming thinner with tree height, whereas the other vessel characteristics were getting more prominent upwards in the stem: vessel diameter (0.23^{ns}); vessel frequency (0.25^{ns}) and vessel percentage (0.52).

All the correlations given in the correlation matrixes in Annexure 1 can be optimally approximated and simultaneously displayed using the correlation monoplot described by Gower et al. (2011). The correlations between the original variables (fibre cross sectional area, wood density, fibre cell wall thickness, vessel diameter, vessel percentage, fibre diameter, fibre lumen diameter and vessel frequency) are shown in Figure 5-15.

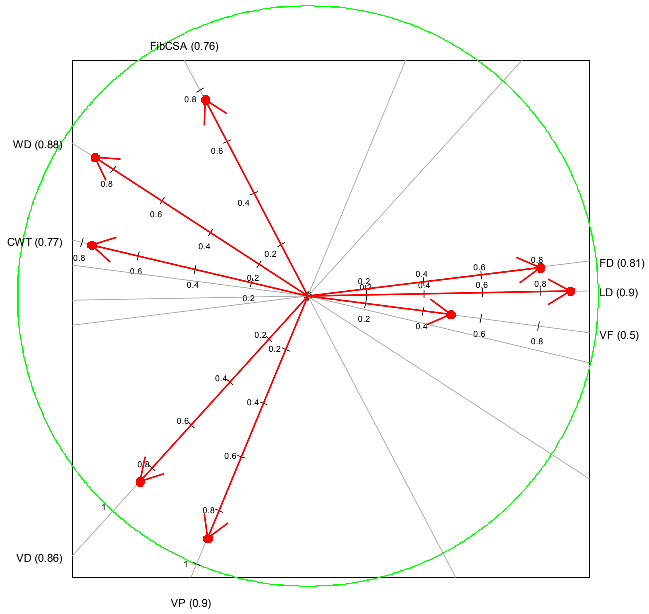


Figure 5-15: Monoplot of wood density, fibre and vessel properties. The green circle indicating how well every variable is represented in the two dimensional plot; the closer to the green circle (1.0) the better is the visual representation.

Monoplots are two-dimensional graphical representations of symmetrical matrices (Gower et al. 2011); in this case (Figure 5-15) it gives an approximation in two dimensions of all the 8 x 8 inter-correlations in the wood density and fibre abbreviated data set (Table 5). The length of the red arrow is an indication of how well each variable approximates the unit correlation (indicated by the green circle) of exact representations in the full 8 - dimensional space. The relative length of each arrow is also given in parentheses following the name of the variable.

Strongly positively correlated variables point in the same direction, e.g. fibre diameter and lumen diameter (angle close to 0°). They are moderately negatively correlated with wood density (WD) and stronger with fibre CWT. Vessel frequency and fibre CWT are strongly negatively correlated (angle close to 180°). Uncorrelated variables are at right angles (close to 90°) to one another, e.g. fibre CSA is not significantly correlated to vessel diameter (VD) or vessel percentage (VP).

5.3.4 Principal Component Analysis (PCA)

Suitable variables (r > ± 0.5; p < 0.05) were selected from the correlation matrix to be used in the PCA. They were: fibre cross sectional area (CSA), wood density, fibre cell wall thickness (CWT), vessel diameter (VD), vessel percentage (VP), fibre diameter (FD), fibre lumen diameter (FLD), vessel frequency (VF). Wood density, fibre and vessel variables have vastly different scales and therefore the correlation matrix was used to compile the PCA as opposed to covariance matrix used when variables are of similar unit and scale. Standardised data originating from the correlation analysis was entered in the PCA analysis.

Table 5-6 contains all the eigenvalues of the correlation matrix, differences between successive eigenvalues, the proportion of variance explained by each eigenvalue and the cumulative proportion of the variance explained. The eigenvalues correspond to the principal components and the associated eigenvalues describe the partitioning of the variance.

Table 5-6: Eigenvalue matrix for cell morphology data.

Eigenvalues of the Correlation Matrix				
No.	**Eigenvalue**	**Difference**	**Proportion**	**Cumulative**
1	3.3522	1.5091	0.4190	0.4190
2	1.8431	0.5112	0.2304	0.6494
3	1.3318	0.6863	0.1665	0.8159
4	0.6455	0.1349	0.0807	0.8966

The four principal components collectively account for 89.6 % of the variation in the data set. The eigenvectors for the four eigenvectors are shown in Table 5-7.

Table 5-7: Eigenvectors by principal components developed from variables used in analysis.

Eigenvectors				
	Principal 1	**Principal 2**	**Principal 3**	**Principal 4**
Fibre cross sectional area	0.196366	–0.494770	0.093838	0.735238
Wood density	0.403175	–0.346821	–0.081275	0.022218
Fibre cell wall thickness	0.400175	–0.149317	0.142846	–0.547928
Vessel element diameter	0.310831	0.474213	0.415832	0.199952
Vessel percentage	0.188723	0.615576	–0.142288	0.308362
Fibre diameter	–0.438310	–0.081089	0.411222	–0.057905
Fibre lumen diameter	–0.495503	–0.018298	0.306765	0.128486
Vessel frequency	–0.262449	0.043607	–0.712610	0.061452

The eigenvectors in the first column of Table 5-7 correspond with the first principal component in Table 5-6, a linear combination of the variables. The first principal component is a function of the following linear equations:

PC_1= 0.196366·(fibre CSA) + 0.403175·(wood density) + 0.400175·(fibre CWT) + ……..… – 0.495503·(fibre lumen diameter) – 0.262449·(vessel frequency),

PC_2= – 0.494770·(fibre CSA) – 0.346821·(wood density) – 0.149317·(fibre CWT) + ……..… – 0.018298·(fibre lumen diameter) + 0.043607·(vessel frequency).

The first principal component (PC_1) appears to be a weighted measure of mainly wood density, fibre CWT, fibre diameter and fibre lumen diameter as seen by the relative magnitudes of the coefficients. More weight is given to wood density, fibre CWT, fibre lumen diameter and fibre diameter where ($0.40 < |r| < 0.49$) than to vessel element properties for example. PC_2 is primarily related to vessel percentage, vessel element diameter and fibre cross sectional area ($0.47 < |r| < 0.61$), and PC_3 is primarily related to vessel properties, vessel diameter and vessel frequency ($0.41 < |r| < 0.71$).

5.3.5 Representing data in biplots

5.3.5.1 PCA biplots

Different units of measurement necessitated the data to be scaled to unit variances (i.e. the PCA biplot is based on the correlation matrix and hence, standardised data). However, for clarity of reading the biplots, the calibrations on the axes were rescaled to original units. The whole tree mean wood density and fibre properties were plotted in PCA biplots and coloured coded for sample height position (Figure 5-16) in the tree and planting density (main effect) in Figure 5-17, showing some interesting properties of the data. A short interpretation of the PCA biplots follows below:

- PCA for the purpose of being used in biplots acts as a dimension reduction technique.
- The PCA biplot approximates the distances between sample points.
- The approximate variable values associated with each sample point can be read from the calibrated linear biplot axes.
- Although the angles between biplot axes give some indication of the correlations between the respective variables, these correlations are not optimally approximated in the PCA biplots. Therefore, the correlation monoplots should be used in conjunction with the PCA biplots for judging the correlations between the variables.

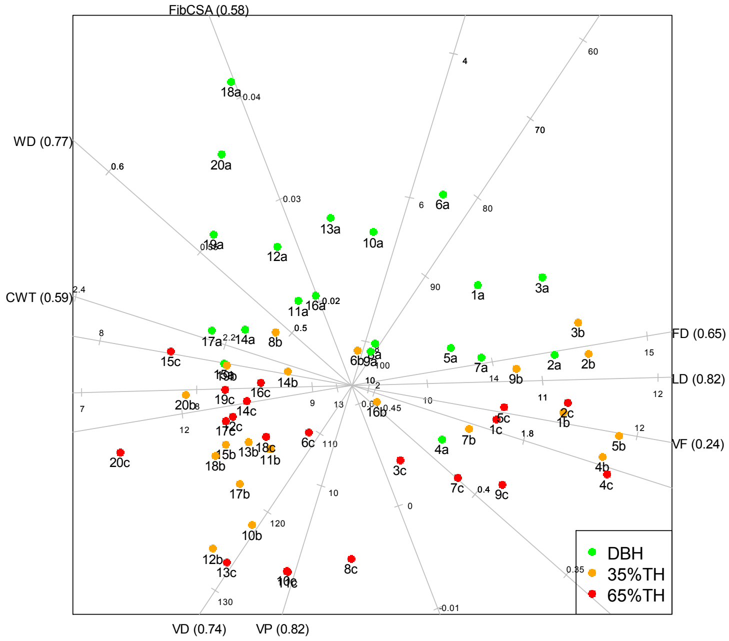


Figure 5-16: PCA biplot of whole tree mean wood density and mean fibre properties with individual samples categorised in colour by the sample position in the tree.

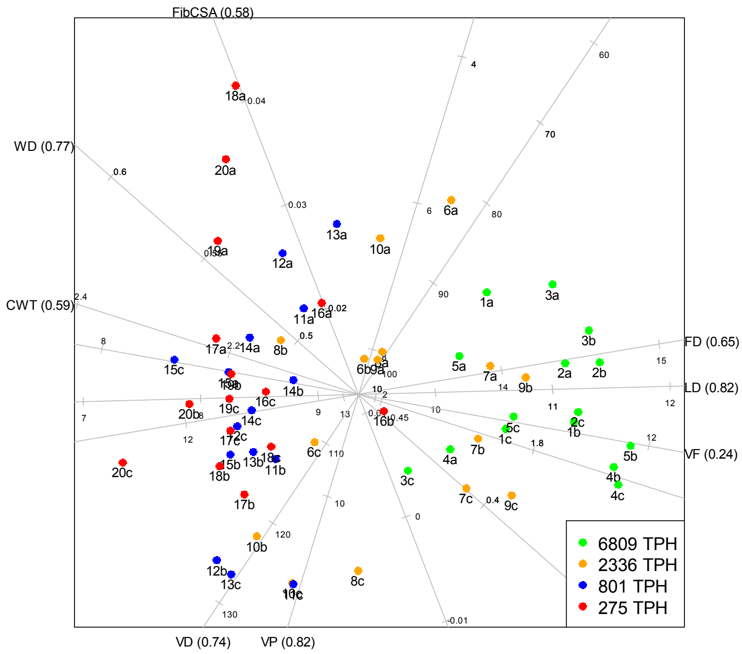


Figure 5-17: PCA biplot of whole tree mean wood density and mean fibre properties with individual samples categorised in colour by planting density treatment.

From Figure 5-16 the following key conclusions are made:

- The various disc sample height positions are visually clustered in distinct groupings.
- When considering fibre cross sectional area (FibCSA on the graph), the higher values (c. 0.04 µm^2) are found in the DBH position, followed by the 35 % and then 65 % position.
- Mean wood density (WD on the graph) follows a similar pattern with highest values (*c.* 0.6 g cm^{-3}) located in the DBH section tapering off to much lower values (*c.* 0.3 - 0.4 g cm^{-3}) at the higher positions in the tree.
- In vessel percentage (VP) and vessel diameter (VD), the lower values are in the DBH position and higher values in the higher positions.

From Figure 5-17 the following key conclusions are made:

- Observations for planting density by disc sample extracted are well clustered in their respective groupings.
- Fibre diameter (FD) which is well correlated with the treatments visually tracks the planting density treatments with high values (*c.* 15 µm) in the high stand densities, and low values (*c.* 12 µm) in the low stand densities around 275 TPH.
- Fibre cell wall thickness (CWT) is highest in the low stand densities (801 and 275 TPH) and lowest in high stand densities (2336 and 6809 TPH).

These and other inferences are supported by the ANOVA and correlation analysis conducted on the data earlier in this chapter.

5.3.5.2 Canonical Variate Analysis (CVA) biplot

The group structure evident in Figure 5-16 and Figure 5-17 suggested the constructing of displays that optimise the between to within group variation. CVA biplots were constructed from canonical variates to optimally separate the means of the three tree height positions (Figure 5-18) and four planting density treatments (Figure 5-19) with respect to the properties wood density, fibre and vessel data. Individual samples are colour coded in their respective groups and embedded into the CVA biplot to give a graphical display of the overlap or separation among the groups. The calibrated biplot axes representing the variables are interpreted similar to the axes of an ordinary scatterplot, through projecting any point in the graph perpendicular onto an axis to read off the value for that particular variable; the inside axis with the units on them are known as prediction axis. Each axis in Figure 5-18 and Figure 5-19 is calibrated in the original units of measurement; therefore it allows, similar to the PCA biplot, the reading-off of the value of the respective variable for a given point. Moreover, all the class means for all three variables can be determined graphically almost without error in this way.

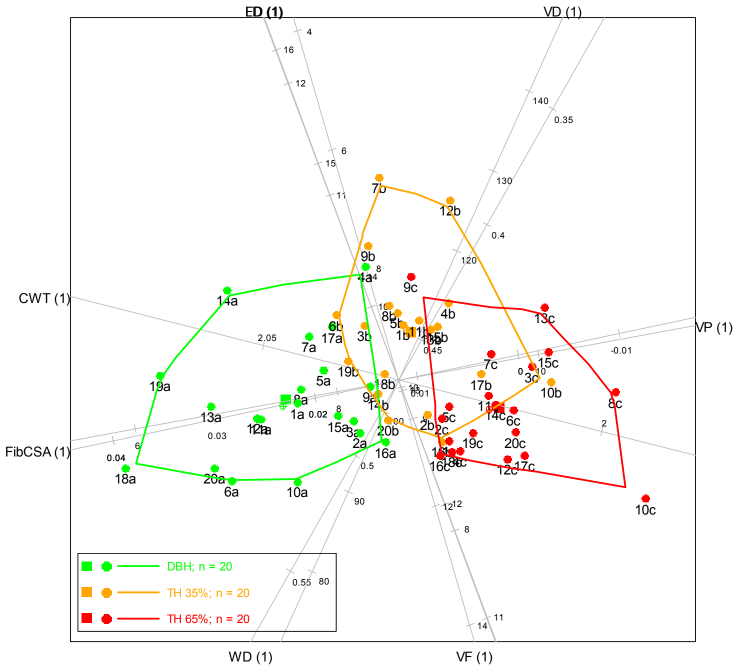


Figure 5-18: CVA Biplot showing data for along the stem (DBH, 35 % and 65 %) of tree height embedded in the wood density, vessel and fibre data set. Group means are shown as sold squares and within group dispersion is shown as series of solid circles.

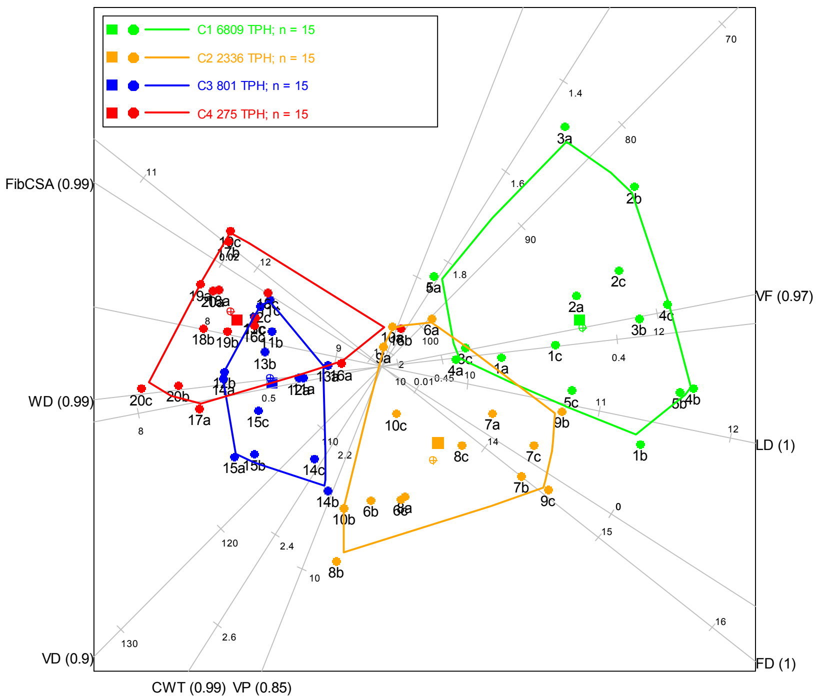


Figure 5-19: CVA Biplot showing the planting density treatments (main effects) embedded in the wood density, fibre and vessel data set. Group means are shown as sold squares and within group dispersion is shown as series of solid circles.

From Figure 5-18 and Figure 5-19 the following key conclusions are made:

- The within group dispersion (solid line polygons) are indicated on the graph.
- With 95 % bags shown on the graph (dark coloured contour lines including 95 % of the data), it is noticed that there is no overlap in any property from the DBH and 65 % height grouping for the variables.
- In addition, this is confirmed in Figure 5-19 that planting densities, 6809, 2336 and 275 TPH have perfect separation (no overlap) also in confirming the ANOVA results (Table 5-2, Figure 5-3 and Figure 5-4, e.g. wood density Duncan groupings: *a*, *c* and *d*, showing no overlap when the ANOVA statistics were obtained. The same is valid for most of the fibre and vessel variables; distinct groupings for height position and planting density.

5.3.6 Curve fitting

For purposes of using regression models further in the study to assist development of a prediction system for a fibre productivity index, variables that can be easily and cheaply acquired at high levels of accuracy were chosen as the explanatory variable. Fit statistics are shown in Table 5-8.

Table 5-8: Fit statistics of linear model predicting for selected variables.

Model	β_1	β_2	**n**	**MSE**	R^2 **- adj.**
Wood Density= β1+ β2 (TPH)	0.4984	-0.0000134	60	0.00055	0.6841
Fibre Diameter= β1+ β2 (TPH)	14.6043	–0.1802	60	0.4276	0.5959
Lumen Diameter = β1+ β2 (TPH)	11.2211	–0.2285	60	0.5239	0.6641
Cell Wall Thickness= β1+ β2 (TPH)	1.8474	0.0250	60	0.0315	0.4237

The fitting of the linear curve resulted in moderately good R^2 - values for WD, FD, LD and CWT (Table 5-8). Cook's *D*-statistic was used to indicate influential observations that when removed from the analysis, improved the regression fitting and was applied.

The observed versus predicted plot (Figure 5-20) for wood density, fibre diameter, fibre lumen diameter and fibre cell wall thickness shows the variation over spacing and is an indication of the predictive ability of the models. A high R^2 - value for lumen and fibre diameter was noted and can, together with wood density, be used in prediction modelling to develop a fibre productivity index.

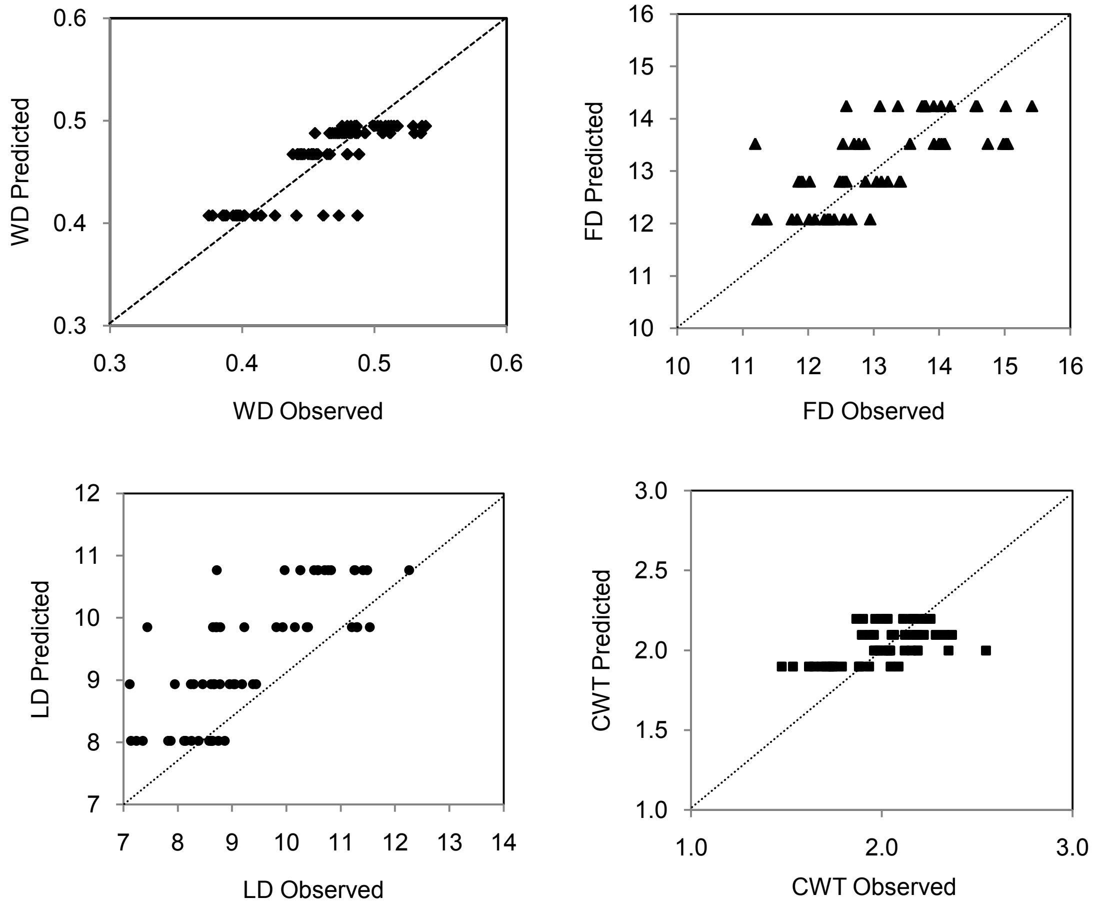


Figure 5-20: Observed versus predicted values for wood density, fibre diameter, lumen diameter and cell wall thickness.

5.4 DISCUSSION

The growth and yield models (Chapter 3) showed that planting density, i.e. spacing treatment, as the main effect, had a significant influence on the growth and yield of trees (du Plessis and Kotze 2011). The present study investigated *air-dry* wood density, parameters of wood tracheid fibres and vessel elements and the effects that spacing treatment have on their morphology and distribution and their interdependency on one another; a synopsis of findings with respect to these is discussed below.

5.4.1 Mean wood density

Weighted mean tree (WMT) wood density (Equation 3) was negatively correlated ($r = -0.67$, $p < 0.0001$) with stand density and all four spacing treatments were significantly different with 275 TPH (0.504 g cm^{-3}) the highest and 6809 TPH (0.410 g cm^{-3}) the lowest mean wood densities. The wheeled graphs of wood density in Figure 5-8 form an excellent visual representation of the magnitude and variability of wood density. When the colour contour map in Figure 5-9 is considered, it is noted that lower stand density (275 TPH) produced denser wood at a faster rate than the higher stand density treatments. Furthermore, mean wood density differs in all height positions of the tree, the lowest position (DBH) producing the highest density wood then tapering off to 35 % of tree height and increasing again towards the top of the tree. Wood density is a prominent variable in the principal component analysis especially when considering the PCA monoplot (Figure 5-15), the strong negative association (–) with lumen and fibre diameter and vessel frequency, and strong positive association (+) with cell wall thickness, and medium positive association with fibre cross sectional area, are seen. It appears from the analysis that wood density can be manipulated silviculturally, it can also be accurately predicted ($R^2 = 0.76$ when principal components and 0.56 when spacing treatment are used as independent variables).

With the expected influence of wood density (Savidge 2003) on pulp and paper properties (Malan and Arbuthnot 1995, Lundqvist 2002), it may proof invaluable to develop a fibre productivity index. It is especially the strict genetic control and high heritability of wood density from one generation to the next (Raymond and Apiolza 2004) that makes it attractive for both tree breeders (Muneri and Raymond 2000) and also foresters to optimise the production (du Toit et al. 2010). Wood density is a candidate property that will be considered in a fibre productivity index (Chapter 7).

5.4.2 Vessel elements

Three vessel properties, vessel diameter, frequency and percentage, were studied. Both vessel diameter and frequency were significant ($p < 0.05$) when the variance was analysed but vessel percentage was not significant. The high stand density levels (6809 TPH) had the highest vessel frequency (no. vessels mm^{-2}) and lowest vessel diameter while low stand density (801 TPH) levels had fewer but larger vessels, a factor indicating more abundant resources. This is consistent with the findings of February et al. (1995) as described earlier, indicating a positive association between water availability and vessel diameter. The correlation between stand density and vessel diameter ($r = -0.51$) and frequency ($r = 0.49$) was moderately high indicating an increase in vessel element diameter with lower stand density treatments and a decrease in frequency as trees were spaced wider apart. Linear regression did not work for the prediction of vessel element properties, only when principal components were used but the development of these components is suggested to be impractical. The most important conclusion is that the vessel diameter increased with wider spacing, coinciding with a reduction in vessel frequency, leading to higher tree diameter growth (February et al. 1995). It is hypothesized that the availability of water in the wider spacing triggers larger but fewer vessels to transport water more efficiently. Vessel properties are related to paper quality, especially the problem of vessel picking in printing presses may be an important parameter to consider for a paper quality indicator.

5.4.3 Fibre tracheids

Fibres were studied on the cross sectional level (diameter, lumen diameter, cell wall thickness) and not lengthwise. The highest stand density (6809 TPH) had the highest fibre diameter and the thinnest cell walls; observed as large lumen diameters and low-density wood. The wood, when handled, had a papery-feel to it. The opposite was true for low stand density (275 TPH) which had thinner fibres, thicker cell walls, consequently small fibre lumens and high-density wood. These inferences are all significant at the WMT-level with a significance of $p<0.0001$.

From the correlation matrix (Table 5-5) it is observed that fibre diameter and fibre lumen diameter were positively correlated with stand density; $r = 0.61$ and $r = 0.72$ respectively. The monoplot (Figure 5-15) illustrates the strong positive correlation between fibre diameter and lumen diameter and strong negative correlation with cell wall thickness.

In some of the graphics presented here, the order of the property, e.g. fibre diameter in Figure 5-12 between stand density treatments remained the same. Other characteristics cross lines over time, giving rise to polymorphic curves, e.g. cell wall thickness (Figure 5-13). CWT development was influenced by the season, specifically rainfall and hence the formation of earlywood and latewood (Downes and Drew 2007).

5.4.4 Correlation monoplots, PCA biplots and CVA biplots

The power of canonical variate analysis (CVA) biplots to describe the variation and group structure in multivariate observations was demonstrated in the wood density, fibre and vessel data. Although the ANOVAs returned favourable analysis statistics, it was mentioned by Gardner et al. (2005) that the implementation of CVA biplots and permutation tests could replace analysis of variance when sample sizes are small and large heterogeneity of covariance matrices is encountered. An important feature of the CVA biplot is its visual confirmation and summary of the associated analysis of variance. The monoplots and PCA biplots were very useful to interpret relationships in a multivariate data matrix.

5.5 CONCLUSION

The quality of the timber resource as opposed to quantity only, is becoming an important factor to the pulp and paper industry. Quality, as a measure of "fitness for purpose" is multi-dimensional and complex when applied to a raw material such as wood. This study investigated physical wood properties that will, as part of the processing and product value chain, add value to the optimisation of the fibre resource. Stand density as a management intervention was selected to provide a tool to manipulate the variability of the resource.

The objective of this research was to identify those wood properties that can be manipulated by silviculture, that have effect on quality and quantity of final product and that will contribute to a fibre optimisation index. Based on literature and past work, a series of bulk (wood density) and anatomical properties (fibre tracheids and vessel elements) were selected to be included in this study. Data acquisition techniques that were proven suitable for data collection of woody materials were incorporated with statistical methods. Wood properties were studied at three height intervals up the tree stem (DBH, 35 % and 65 %) by means of weighted mean disc and weighted mean tree variables.

Gamma-ray densitometry and fluorescent microscopy combined with image analysis have proven valuable tools to study the variability in wood density and cellular characteristics.

The data were scrutinized for normality and fixed effects and corrected if necessary. Analysis of variance indicated that significant differences exist between means. Significant differences between weighted mean tree-level data for wood properties and stand density were described (wood density R^2 = 0.56, vessel diameter R^2 = 0.31, vessel frequency R^2 = 0.27, fibre diameter R^2 = 0.52, cell wall thickness R^2 = 0.50 and Lumen diameter R^2 = 0.74; all significant at $p<0.0001$). Correlations between stand density and selected properties were high; wood density r = –0.67, fibre diameter r = 0.61, fibre lumen diameter r = 0.73, fibre cell wall thickness r = –0.68 and vessel diameter r = –0.50; all significant at $p<0.0001$). When the most extreme stand density treatments, 275 TPH and 6809 TPH were evaluated it was evident that larger trees found at 275 TPH produced wood of better quality for pulp processing (wood density at 0.520 g cm^{-3}, 21 % higher, fibre cell wall thickness at 2.10 µm, 18.6 % thicker, fibre lumen diameter at 8.16 µm, 9.9 % lower than for 6809 TPH). This information, if read together with the growth and yield analysis by du Plessis and Kotze (2011), does indicate that although forest management in pulpwood production is aimed towards volume (quantity) as a benchmark of value, it is soon becoming essential that forest management optimizes the wood properties in relation to the desired end-product (e.g. pulp and paper).

It is construed from the above that stand density at planting had an effect on fibre geometrical properties and hence wood density and planting density was highly correlated with fibre properties more so than with vessel properties. Principal component analysis (PCA) worked well and valuable information is read from the PCA biplot. The PCA process was suitable to develop latent variables that were effective as a linear dimension reduction technique to make the interpretation of the dataset less complex. Linear regression with the main effect (stand density) returned suitable coefficients of determination (wood density $R^2 = 0.56$, fibre diameter $R^2 = 0.59$, cell wall thickness $R^2 = 0.66$ and lumen diameter $R^2 = 0.66$). The CVA biplots were effective in the visual confirmation and summary of the associated analysis of variance when partitioned for height position in the tree and planting density treatments.

The data analyses suggested wood density to be a suitable property for a Fibre Productivity Index (FPI) due to the high correlation with stand density, ease of measurement and modelling success. It was also shown in Chapter 3 that NIR prediction of wood density from wood meal is a reliable (precise and unbiased) prediction method. Furthermore, wood density was positive correlated with fibre properties such as cross sectional area and fibre cell wall thickness, and negatively correlated with fibre lumen and fibre diameter. Wood density can thus act as a surrogate property in a FPI for those other important anatomical characteristics which are difficult and expensive to measure.

In the next chapter (Chapter 6), pulp and paper characteristics based on process, physical and chemical properties are studied in relation with stand density treatments. The correlation analyses, principal components and regression curves fitted for wood density, vessel and fibre characteristics and the interaction with stand density (this chapter), will be used in the last chapter (Chapter 7) to demonstrate a plantation fibre productivity indicator. The FPI will demonstrate sensitivity for i) plantation volume growth (Chapter 4), ii) wood density (this chapter), and iii) pulp and paper characteristics (Chapter 6) to determine optimum fibre productivity levels when used in a Kraft pulp mill.

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Annexure 5-1: Complete correlation matrix developed from SAS ver. 9.2 for wood density and fibre data.

Pearson Correlation Coefficients, N = 60
Prob > |r| under H0: Rho=0

	TPH	Height_Pos	WoodDens	FibreDiam	FibreCSA	LumenDiam	CellWThick	VesselDiam	VesselFreq	VesselPerc
TPH	1.00000	0.00000	–0.67065	0.61635	–0.35173	0.72900	–0.68090	–0.50561	0.49166	–0.24333
		1.0000	<.0001	<.0001	0.0059	<.0001	<.0001	<.0001	<.0001	0.0610
Height_Pos	0.00000	1.00000	–0.24064	–0.28453	–0.63465	–0.23294	–0.05372	0.23698	0.25098	0.52922
	1.0000		0.0640	0.0276	<.0001	0.0733	0.6835	0.0683	0.0531	<.0001
WoodDens	–0.67065	–0.24064	1.00000	–0.51058	0.50992	–0.61717	0.57535	0.09758	–0.26962	–0.06728
	<.0001	0.0640		<.0001	<.0001	<.0001	<.0001	0.4583	0.0372	0.6095
FibreDiam	0.61635	–0.28453	–0.51058	1.00000	–0.15827	0.95368	–0.34786	–0.30001	0.08288	–0.35672
	<.0001	0.0276	<.0001		0.2271	<.0001	0.0065	0.0199	0.5290	0.0051
FibreCSA	–0.35173	–0.63465	0.50992	–0.15827	1.00000	–0.21008	0.25281	–0.08843	–0.23030	–0.27169
	0.0059	<.0001	<.0001	0.2271		0.1072	0.0513	0.5017	0.0767	0.0357
LumenDiam	0.72900	–0.23294	–0.61717	0.95368	–0.21008	1.00000	–0.60382	–0.33881	0.19441	–0.31523
	<.0001	0.0733	<.0001	<.0001	0.1072		<.0001	0.0081	0.1366	0.0142
CellWThick	–0.68090	–0.05372	0.57535	–0.34786	0.25281	–0.60382	1.00000	0.29056	–0.40269	0.06377
	<.0001	0.6835	<.0001	0.0065	0.0513	<.0001		0.0243	0.0014	0.6284

Pearson Correlation Coefficients, N = 60 Prob > |r| under H0: Rho=0										
	TPH	Height_Pos	WoodDens	FibreDiam	FibreCSA	LumenDiam	CellWThick	VesselDiam	VesselFreq	VesselPerc
VesselDiam	–0.50561	0.23698	0.09758	–0.30001	–0.08843	–0.33881	0.29056	1.00000	–0.61650	0.69795
	<.0001	0.0683	0.4583	0.0199	0.5017	0.0081	0.0243		<.0001	<.0001
VesselFreq	0.49166	0.25098	–0.26962	0.08288	–0.23030	0.19441	–0.40269	–0.61650	1.00000	0.11666
	<.0001	0.0531	0.0372	0.5290	0.0767	0.1366	0.0014	<.0001		0.3747
VesselPerc	–0.24333	0.52922	–0.06728	–0.35672	–0.27169	–0.31523	0.06377	0.69795	0.11666	1.00000
	0.0610	<.0001	0.6095	0.0051	0.0357	0.0142	0.6284	<.0001	0.3747	

CHAPTER 6: Variation in pulp & paper properties of a *Eucalyptus grandis* clone as influenced by planting density

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CHAPTER 6 : Variation in pulp & paper properties of a *Eucalyptus grandis* clone as influenced by planting density

Abstract

Logs from a *Eucalyptus grandis* clone grown in a Nelder 1a experiment in Swaziland were sampled and pulped to evaluate wood, pulp fiber and paper properties suitable to be taken up in a fibre productivity index. Wood chips were prepared from 1.5 m logs sourced from four planting density treatments: 6809, 2336, 801 and 275 trees per hectare (TPH). The chips were pulped in a mini-digester and the physical and chemical attributes of the ensuing unbleached pulp were evaluated. Small representative quantities of pulp fibres were analysed with HPLC and the data set was used to calibrate near infrared analysis (NIRA) models developed earlier (Chapter 3). Pulp was refined in a laboratory beater (PFI-mill) at 500, 1000, 2000 and 3000 rpm. The nonwoven paper handsheets were submitted to a full series of paper tests. Successful statistical analyses of the data included ANOVA, correlation, multivariate analysis and model fitting.

Kappa number, as an indication of residual lignin in pulp, was highly significant to explain the variation in paper product quality, e.g. brightness (r = –0.78) and tear (r = –0.57). Pulp yield correlated well with basal area of the tree (r = 0.56). Since the highest stand basal area was found in the high stand densities, it was apparent that the interaction between stand density and pulp yield was non-linear with highest values between the extremes tested, with an optimum between 801 and 2336 TPH, as confirmed by the regression analysis. Stand density at planting had a significant effect throughout the value chain of the timber product, not only influencing growth and yield (basal area r = 0.94, log volumes r = –0.52) but also intermediate product quality parameters such as wood density (r = –0.66), fibre length and tear strength of the paper handsheets. Multiple regression analyses returned acceptable models, e.g. for pulp yield (R^2_{adj} = 0.61) when regressed with stand density and similarly for wood density when the gravimetrical method as opposed to a gamma-ray densitometry method (Chapter 5) was used. Regression equations for paper properties (brightness, R^2_{adj} = 0.67; tear, R^2_{adj} = 0.78; tensile stiffness, R^2_{adj} = 0.76) worked well when independent but attainable properties such as stand density, wood density, fibre diameter and length, kappa number and pulp yield, were regressed. These variables can be considered as indicators in a fibre productivity index.

Keywords: *Eucalyptus grandis*, pulp and paper, pulp chemistry, correlation, principal component analysis, canonical variate analysis, biplots

6.1 INTRODUCTION

Timber products are seldom used "as is" and in most instances undergo some fragmentation into individual constituents before synthesized into an end user product such as printing paper. The variance in wood quality of a given species, growing on a specific site and management regime, impacts on the quality of pulp and paper.

6.1.1 Eucalyptus forestry in South Africa

Plantation forestry in SA, which covers no less than 1.275 million hectares, is managed on a monoculture, even-aged silvicultural system to sustain a renewable fibre resource for the processing industry in South Africa. The *Eucalyptus* genus is planted most extensively in the KwaZulu-Natal (58.0 %) and Mpumalanga (34.1 %) provinces, supplying 85 % of the total hardwood intake or 10.3 million m^3 into pulp mills in South Africa (FSA 2011). Most of the *Eucalyptus* grown on the subtropical Zululand Coastal Plains is for pulp and paper production (Swain and Gardner 2003). The dominant hybrids are *E. grandis* × *E. urophylla* or *E. grandis* × *E. camaldulensis* in the sub-tropical zones while *E. grandis* × *E. nitens* are pre-dominant in the cooler temperate zones.

6.1.2 Wood quality

Quality has been defined as the totality of characteristics of a product or service that bear on its ability to meet stated or implied needs (Jozsa and Middleton 1994). Pulp and paper products requires specific standards of wood quality that impact on its integrity to meet service requirements. Wood quality standards therefore can only be defined with a particular end use in mind. Wood can for the definition of its quality attributes be classed in physical and chemical characteristics:

- The physical attributes of fibres such as fibre length, cell wall thickness and fibre diameter are major determinants of pulp and paper qualities including brightness, opacity, absorption, light scattering, tear, tensile and burst strength (Karlsson 2006).
- In the pulp and paper manufacturing process, many aspects such as pulp yield, consumption of cooking liquor, and potential for bleaching, are dependent on the chemical composition of wood, which are determined by the relative proportions of cellulose, lignin, hemicelluloses and extractives (Jozsa and Middleton 1994).

6.1.3 Wood physical properties

The most important constituent of wood for pulp and paper as end-use in *Eucalyptus spp.* are the fibre tracheids. Large variability exists in wood, even of the same species, tree or position within a tree (Hudson et al. 1998 and Zobel and van Buijtenen 1989). The difference between juvenile and mature wood fibres may have an effect on pulp properties; juvenile wood properties, e.g. basic wood density is linked to fibre anatomy of the shorter fibres with associated lower strength properties (Butterfield 2003). Similarly, earlywood cells are shorter and thin walled as opposed to latewood cells that are longer with thicker cell walls. Main fibre properties that are important for pulp and paper manufacture are fibre length, fibre diameter and fibre cell wall thickness. *Eucalyptus spp.* are ideal for this purpose since their fibres are short, slender, thin-walled and in-tact. As in other hardwoods, the fibre tracheids are arranged longitudinally bound together by a thin lignin layer, the middle lamella. Large hardwood vessel elements have shown to be problematic in paper manufacturing, especially related to printing and vessel picking problems (Hudson et al. 1998). Chemical pulping is set to liberate these fibres by dissolving the lignin. In paper, fibres are randomly organised dependent in the forming characteristics of the paper making machine, and bonded together by chemical bonds and mechanical forces. *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 2008 and Nunes et al. 2010).

6.1.4 Resource variability

The variability in wood species is a significant factor influencing the relationship between pulping process and pulp quality. A tree contains different types of fibres (cells) and hence, variations in chemical composition or fibre characteristics are observed not only between species or clones, also within a species or clone and within a tree (Malan 1988, Hudson et al. 1998 and da Silva Perez et al. 2003). There are several patterns of variability within trees that are important, e.g. the variation from the centre to the tree to the outside and differences associated with different heights in the same tree (da Silva Perez et al. 2003). The main consideration on the radial trend (pith to bark) is the presence of juvenile or mature wood. Young trees with mostly juvenile wood in the radial plane, produce lower pulp yields than that of mature wood but the paper quality, measured as tensile strength, sheet smoothness and burst index, is higher (Larson et al. 2001 and Ilic et al. 2003). It was also noted that paper brightness improved when the juvenile fraction was high (da Silva Perez et al. 2003). It is suggested by da Silva Perez et al. (2003) that differences in wood properties with tree height are only attributable to the juvenile / mature wood ratio, manifested as fibre length, with long fibres in the bottom log and short fibres towards the top.

6.1.5 Wood chemical properties

Anatomical and chemical properties are the ultimate factors that determine the overall properties of wood as a material and distinguishes wood from other non biological materials such as synthetic polymers, ceramics, metals, etc. Chemically, wood is composed of structural and extractive components. The underlying factors controlling wood properties are essentially the result of the chemical composition of the cellular structure as indicated below:

- chemical features of the structural constituents (cellulose, hemicelluloses and lignin molecules) of the cell wall and constituents contained within the cellular structure (extractives)
- distribution of the chemical components in the cell structure
- relative proportions of the different chemical components in the wood cells and tissue.

It is the variation in the relative amounts of these substances that gives rise to the wide variation in wood. The cell wall structural components of wood includes cellulose, hemicelluloses and lignin which are briefly discussed.

6.1.5.1 Cellulose

Cellulose (40-45 % of wood dry weight) is the main component of the fibre wall and the skeletal polysaccharide of cell walls. The linear, monomeric macromolecule chains consisting of β-D glucose molecules linked by β(1-4) glycosidic bonds with degree of polymerisation of *c.* 10,000 in native wood to 1,000 in bleached kraft pulp, is arranged in a crystalline structure (Pereira et al. 2003 and Savidge 2003). The principal source of fibre-to-fibre bonding in paper is the result of intermolecular attraction between the hydroxyl groups of cellulose molecules on the surfaces of fibres (Pereira et al. 2003). A schematic illustration of the cellulose molecule is given in Figure 6-1.

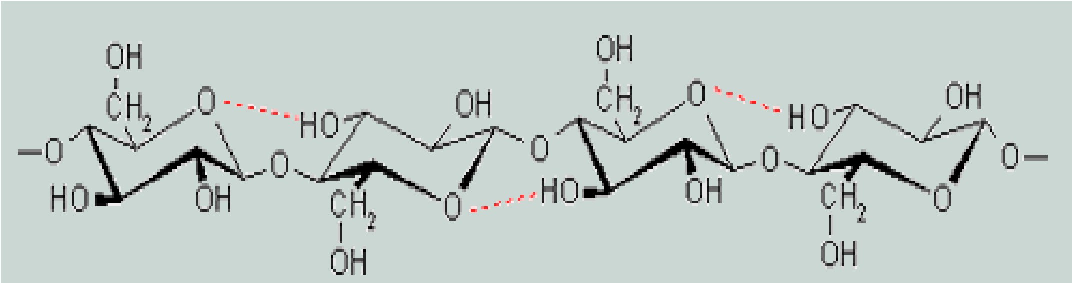

Figure 6-1: Representation of the cellulose molecule showing a chain of 3 glucose molecules bound together by elimination of one molecule of water (Fengel and Wegener 1984).

6.1.5.2 Hemicelluloses

Hemicelluloses, (15 - 30 % of dry wood) in contrast with cellulose are shorter chains polysaccharides (DP of only 50 - 300), constituting of non crystalline heteropolymers and often named after the main type of sugar residues attached to the main molecule. The molecular structure consists of a linear backbone chain with short side branching of usually one monomeric unit with possible side branching of the main backbone unit (Pereira et al. 2003). The most important hemicelluloses in wood cell walls are xylans and glucomannans. In hardwoods, the predominant hemicelluloses are xylans (*O*-acetyl-4-*O*-methylglucuronoxylans; DP 100 - 200) representing 5 - 25 % of wood, and glucomannans representing 2 - 5 % (Pereira et al. 2003). Glucomannan is very sensitive to Kraft cooking and is already dissolved to a large extent at the beginning of the cooking process (Suurnakki and Westermak 1996), whereas xylan is more resistant. Relocation of xylan can occur in Kraft cooking due to sorption of xylan from cooking liquor (Mitikka et al 1995). Consequently high levels of hemicelluloses have been reported on pulp fibre surfaces on both softwood and hardwood pulps (Suurnakki and Westermak 1996).

6.1.5.3 Lignin

Lignin is an aromatic polymer and often described as the 'glue' that holds the cellulose and hemicelluloses together and provides rigidity to the cells. Although essential to trees, it is undesirable in most chemical processes and removed during pulping and bleaching. Lignin comprises 15 - 25 % of dry weight hardwood chemistry (Wenger 1984). The lignin macromolecule, formed by the polymerization of three phenylpropane monomers (cinnamyl alcohols) contains a variety of functional groups that have an effect on its reactivity. Lignin is highly heterogeneous and consequently hardwoods have complex lignin; the aromatic rings of these alcohols are named respectively syringyl (S), guaiacyl (G) and *p*-hydroxyphenyl (H) units (Pereira et al. 2003). It was shown by Chang and Sarkanen (1973) and Nunes et al. (2010) that woods having high S/G ratios tend to deliver larger pulping yields and are easier to delignify during its conversion into chemical pulp. This important wood quality trait depends on factors like the species of tree, growth conditions, climate and management intervention (Kibblewhite and Brookes 1976).

6.1.5.4 Extractives

Wood includes in its composition a number of medium and low molecular mass compounds named extractives, not making up more than 10 % of the dry weight of wood.

> Extractives are preferentially deposited in the inner part of the stem, mainly the heartwood through the ray-parenchyma cells which often provide heartwood with distinct darker colouration. They are from the terpenoid or phenolic groups, are mostly secondary metabolites that have various purposes namely the protection of trees to pathogens or other biotic attacks, e.g. resin, a mixture of terpenoid compounds in softwoods, to resist some biotic agents from entering the stem. Extractives are dissolved by neutral solvents such as water, alcohol, acetone, benzene and ether (Fengel and Wegener 1984). 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).

The chemical composition of wood has a major impact on its pulpability, both from the structural and the extractives perspective. Large quantities of heartwood containing the highest amount of extractives can result in poor liquor penetration and hence high levels of uncooked reject fibre bundles. A complete cook in the presence of high levels of extractives can increase the use of chemicals and reduce pulp yield; the solubility of lignin may require more chemicals required for a standard bleaching level.

It has been reported by numerous authors that cellulose is positively correlated with pulp yield whereas lignin is negatively correlated (Mitikka et al. 1995 and Poke and Raymond 2006). It is known that hardwoods pulp easier than softwoods, attributable to the higher S-lignin in comparison with G-lignin (Nunes et al. 2010), causing hardwoods, including *Eucalyptus* spp, to pulp faster when the S/G ratio of lignin is high (Chang and Sarkanen 1973). These relationships are tested within the scope of this study.

6.1.6 Chemical pulping

Wood is converted to individual fibres through a pulping process which can be chemical, semi-chemical or mechanical. In chemical pulping, the separation of the fibres is brought about slowly by the action of chemicals in pressurized systems that partially depolymerise the lignin from the wood matrix (da Silva et al. 2003). There are two main types of chemical pulping processes, the (alkaline) Kraft process and the (acidic) sulphite process. Worldwide, and in South Africa, the Kraft process dominates and accounts for almost 70 % of pulp production (Washusen and Clark 2005). The Kraft process minimizes fibre damage, preserves inherent fibre strength (Washusen and Clark 2005), and is also less demanding in terms of wood species and tolerates bark in the pulping process (da Silva et al. 2003). The negative side of Kraft pulping is that due to the strong alkaline conditions involved, it causes the partial removal of some polysaccharides, especially hemicelluloses.

The pulping chemicals used in Kraft pulping are sodium hydroxide (NaOH) and sodium sulphide (Na_2S), also known as white liquor, applied at elevated temperatures. The white liquor is charged to a large pressures vessel, the digester and temperature ramped up to 140 - 170°C for two hours. Fibre separation is achieved through delignification of the middle lamella. The hydroxide and hydrosulphide anions react with the lignin causing the polymer to fragment into smaller alkali and water soluble fragments. The solubility of lignin is increased in the present of hydroxyl groups, meanwhile the carbon-carbon linkage of the cellulose molecule, being more stable then lignin tend to survive the Kraft pulping process (Smook 1992). The pulping chemicals are recovered after cooking. The yield of bleached Kraft pulp is approximately 48 - 53 % (Karlsson 2006). The residual lignin content of a typical Kraft cook is in the range of 4 - 5 % or 17 - 33 kappa number. Pulping to lower lignin content causes severe degradation of the carbohydrate fraction, resulting in pulp with poor papermaking properties (Sjöström 1993).

6.1.7 Influence of wood fibre on paper properties

A great deal of research has been carried out to identify exploitable relationships between wood and paper properties (Horn 1978, Grzeskowiak and Turner 2000, Wimmer et al. 2002, Wimmer et al. 2008). Wood density, fibre length and cell wall thickness are the driving factors in the relationship between raw wood properties and the strength properties of paper.

The wood density of eucalypt pulpwood is widely regarded as possibly one of the most influential factors contributing to the strength and several other characteristics of the paper sheet (du Plooy 1980, Malan 1988, Zobel and Van Buijtenen 1989, Malan and Marais 1991, and Malan and Arbuthnot 1995). The two most influential fibre properties on paper strength are fibre length and cell wall thickness (Horn 1978); fibre length determines inter-fibre bonding points and is directly proportional to tear strength. In softwoods, thin tracheid cell walls contribute to burst and tensile strength and thicker tracheid cell walls contribute favourably to bulk and light absorbance properties. The role of cell wall thickness in hardwoods, according to da Silva et al. (2003), is not as clear as in softwoods due to the high load of fines derived from fibre fragments, vessel elements and parenchyma cells. It will be valuable to industry, if these relationships can be exploited, to use the variability in wood to reduce costs and optimize product quality to meet user demand (Wimmer et al. 2002, Downes and Drew 2007).

6.1.8 Paper quality

While wood fibres are arranged in a predetermined way and bonded together by the lignin, fibres in the paper sheet are randomly arranged and bonded together by strong physico-chemical forces present at all points of contact (Turner 2001 and da Silva et al. 2003). 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 reliant on fibre characteristics (Horn 1978 and Karlsson 2006). It is shown that the ability of cells to collapse or flatten increases the inter-fibre bonding, which depends strongly on cell wall thickness which in turn is strongly related to density (Malan and Abuthnot 1995).

6.1.9 Objectives

The objectives of this chapter was to:

- Investigate the effect of planting density treatments in a *Eucalyptus grandis* clonal trial, on the pulping process, the characteristics of the pulped fibres and quality of the paper produced from the pulped wood.
- To develop models for the prediction of pulp and paper properties from wood properties including bulk properties such as wood density, fibre morphological properties such as fibre tracheid length and cell wall thickness, and characteristics of pulp processing, e.g. kappa number.

The growth and yield of trees described in Chapter 4, wood density identified as a potential fibre productivity indicator in Chapter 5, and relationships identified in this study (chapter) will be used to compile a fibre productivity index for an integrated forestry-pulp-paper value chain. These will constitute the technical aspects of the envisaged fibre productivity index.

6.2 MATERIALS AND METHODS

6.2.1 Sample origin

The wood material described in this study was obtained from a Nelder 1a spacing trial established by Mondi SA in Swaziland with a *Eucalyptus grandis* clone which was commercially available in the planting season of 1998. The experimental site is located in the Piggs Peak region of Swaziland, at 760 m elevation and positioned on the coordinates 25º58’58.05”S; 31º17’46.60”E. The site is located in the WT9 climate zone (Smith et al. 2005) which places it in the 18 - 19ºC MAT class; a class located within the warm temperate climatic zones. The rainfall which is closely related to forest productivity is regarded to be high, the long term MAP exceeding 1000 mm per annum. The average annual measured rainfall on the site for the seven year period of experimentation was 1432 mm. The trial site is situated on a mid slope and the lithology is a granite colluvium resulting in soils of the Oakleaf and Inanda families (Soil Classification Working Group 1991).

6.2.2 Trial design

The Nelder 1a spacing experiment is a single systematic experimental design based on a single tree plot design. The design is highly sensitive to mortality, is suitable for plantation spacing experiments and the statistical analysis of data generated is conducted accordingly (Mark 1983). The design, which was first described by Nelder (1962), allows for the testing of a number of tree spacing treatments in a relative small area. It comprises of single tree plots in which the available growing space or rectangularity, or both, is varied in a continuous and systematic way in the experiment. The experimental lay-out for the study described here was a full circle design known as the 1a-variant in which the rectangularity was kept constant. The trial contained different stocking densities, comprising of 17 spacing treatments ranging from 6,809 trees per hectare (TPH) in the inner most circle to 161 TPH in the most outer ring.

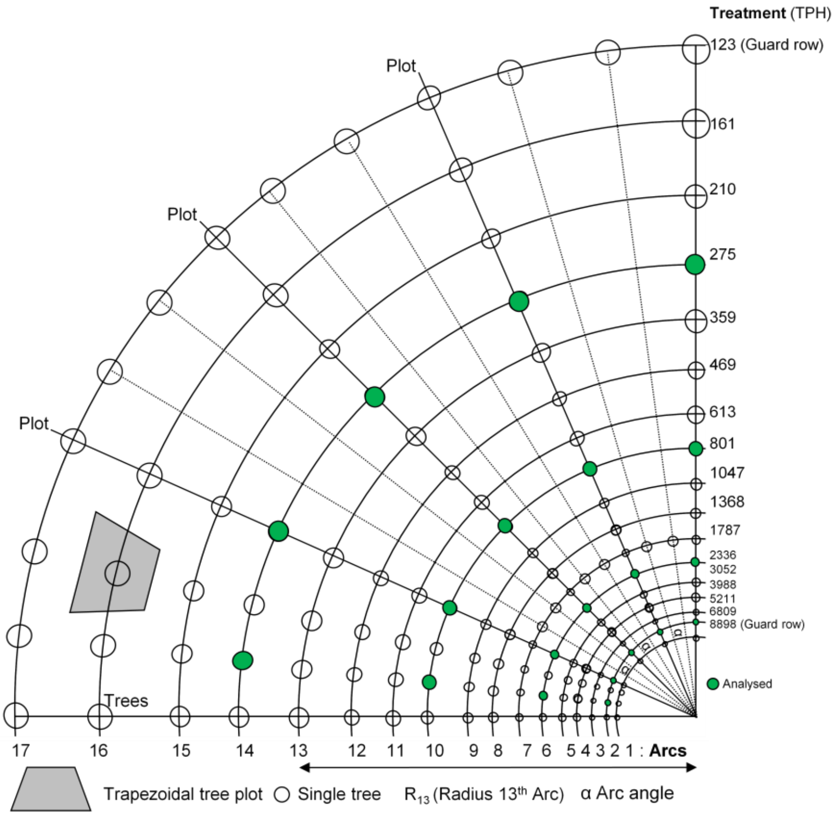

Figure 6-2: Illustration of a quarter of the Nelder 1a experimental design. Circles in green represent trees that were exhaustively sampled.

Figure 6-2 illustrates a quarter of the Nelder 1a experimental design with the green circles representing the trees that were exhaustively sampled for the study described in this chapter. The trial was measured annually and the growth and yield results were reported by du Plessis and Kotze (2011). The trial was partially harvested at 6.75 years of age when replicates of treatments

6809, 2336, 801 and 275 TPH (green circles in Figure 6-2) were removed. Stand characteristics are shown in Table 6-1.

Table 6-1: Spacing treatments applied in the Nelder 1a experiment.

Arc no.	**Treatment (TPH_0)**	**Radius (m)**	**Arc distance (m)**	**Area/tree (m^2)**
1 (Guard row)	8898	8.00	1.05	1.12
2	6809	9.14	1.20	1.47
3	5211	10.45	1.37	1.92
4	3988	11.95	1.56	2.51
5	3052	13.66	1.79	3.28
6	2336	15.61	2.04	4.28
7	1787	17.85	2.34	5.59
8	1368	20.40	2.67	7.31
9	1047	23.32	3.05	9.55
10	801	26.66	3.49	12.48
11	613	30.48	3.99	16.31
12	469	34.84	4.56	21.31
13	359	39.82	5.21	27.85
14	275	45.52	5.96	36.39
15	210	52.04	6.81	47.56
16	161	59.49	7.79	62.14
17 (Guard row)	123	68.00	8.90	81.20
Rays	48 trees per spacing treatment			
Shape	1a; Circular (full wagon wheel)			

6.2.3 Wood sampling

Twenty trees were selected for detailed wood material analyses, i.e. five individuals with good tree form and no visible defects from four spacing treatments, i.e. Treatments 2 (6809 TPH), 6 (3052 TPH), 10 (801 TPH) and 14 (275 TPH). From the intensively samples trees, three 1.5 m logs (B1, 2 and 3), adjacent to the corresponding discs, were taken for pulp and paper studies. They were sampled as shown in Figure 6-3.

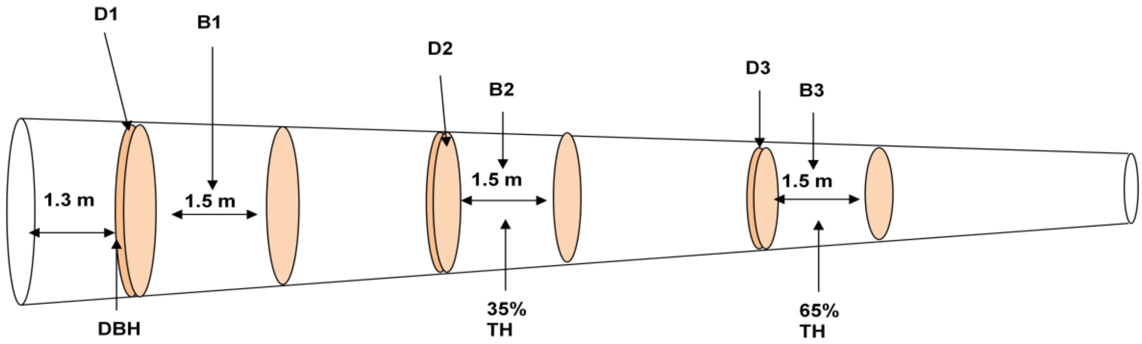

Figure 6-3: Schematic illustration of samples used for wood, pulp and paper studies (collecting discs 1 - 3 (D1-3) and 1,5m long logs 1-3 (B1-3) from three tree heights (TH); 1.3m (DBH), 35 % and 65 % TH).

6.2.4 Basic wood density measurement

Disc numbers D1, 2 and 3 were used to determine basic wood density of green wood with a gravimetric method proposed by Grundelius (1990). This basic wood density was used in the pulp and paper analyses for correlation purposes. It is calculated as

$$D = \frac{M}{V} \qquad \textit{Equation 1}$$

where:

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

M = oven-dry mass (g) and

V = green volume of a wood sample (cm^3) in equilibrium with surrounding water when immersed under water.

6.2.5 Kraft pulping

Logs (B1-3) were labelled and chipped individually with a 38" diameter horizontal feed disc chipper (Precision Husky Corporation, Alabama, USA) at the CSIR - FFP laboratory in Durban, South Africa. Chips were bagged and kept for pulping at the Mondi Richards' Bay Pulp Research laboratory. Three batches of chips per tree (B1, 2 and 3) were pulped in an Aurora re-circulating mini digester under standard cooking conditions normally used by the Mondi research laboratory, controlling the kappa number around *c.* 20. The following pulping protocol was used:

- 1000 g oven dry wood chips loaded per cook
- 15 % active alkali as Na_2O
- 25 % sulphidity
- 4.6:1 liquor to wood ratio

- ambient to 170 °C in 90 minutes
- h-factor of 900
- degassing at 90 °C and 110 °C.

The pulp was disintegrated before being sieved through a Packer screen to remove all reject material including shives and uncooked knots. The screened pulp yield, rejects and total pulp yield (TPY) were determined according to Tappi method T-236. Fibre length dimensions and distribution thereof were measured using a Kajaani Fibrelab. To determine fibre length, Tappi method, T233, designed to measure the weighted average fibre length of a pulp, was used. The following equation was used to determine weighted fibre length (WFL):

$$WFL = \frac{\sum wl}{\sum w} \qquad \textit{Equation 2}$$

where

w = fibre weight (mg)

l = measured fibre length (100 m)

Kappa number was determined as the volume (ml) of 0.1N potassium permanganate solution consumed by one gram of moisture-free pulp under the condition that the screened pulp yield was below 70 % as per T 236 Tappi standard. Details of the data are shown in Table 6-2.

6.2.6 Handsheet manufacture and evaluation

Unbleached pulp was subjected to a series of refining levels (0, 500, 1000, 2000, 3000) applied with a laboratory beater (PFI–mill; test method T-248). Twelve handsheets of c. 60 g m^{-2} were produced from every cook-sample according to Tappi Standard T 205, "Forming Handsheets for Physical Test of Pulp". The 10 best handsheets, visually inspected for formation and defects, were kept and a series of tests as seen from Table 6-2 were carried out on the handsheets.

6.2.7 HPLC analysis of pulp

Pulp samples, manufactured from logs 1-3, were subjected to a chemical analyses using high performance liquid chromatography (HPLC). A full description of the methodology is found in Gellerstedt and Li (1996). The solution of individual fibres was filtered through a regenerated cellulose membrane, pore size 0.45 μm, analysed with a Shimadzu CBM-10A HPLC, equipped with a reverse phase analytical column. The column temperature was kept at 40 °C, and a mobile phase flow of 1.5 mL min^{-1} was used.

Table 6-2: Wood, wood fibre, pulp fibre and paper handsheet properties measured.

Product/process	**Variable**	**Unit**	**Measuring standard**
Wood	Basic Wood Density (Gravimetric)	kg m^{-3}	(Grundelius 1990)
Pulping	Screen Pulp Yield	%	Aurora digester
	Total Pulp Yield (TPY)	%	Aurora digester
	Kappa number	integer	T-236
	Residual Black Liquor	g ml^{-1}	
Pulp fibre	Weighted Fibre length	mm	T 233
	Pulped fibre diameter	µm	Kajaani
	Pulped cell wall thickness	µm	Kajaani
	Pulped fibre coarseness	mg $100m^{-1}$	Kajaani
	Pulped fibre population	fibres gm^{-1}	Kajaani
Handsheet* PFI mill operated standard Tappi T248	Drainage	seconds	
	Canadian Standard Freeness (CSF)	ml	ISO 5267
	Mass	g	ISO 536
	Thickness	microns	ISO 534
	Basis mass	g m^{-2}	ISO 536
	Apparent sheet density	kg m^{-3}	ISO 534
	Porosity	sec $100ml^{-1}$	ISO 3687
	Smoothness	ml sec^{-1}	ISO 8791-2
	Brightness	%	ISO 2470
	Burst	kPa m^2 g^{-1}	ISO 2758
	Tear	mNm^2 g^{-1}	ISO 1974
	Tensile	Nm g^{-1}	ISO 1924
	Stretch	%	ISO 1924
	Tensile Energy Absorption (TEA)	J g^{-1}	ISO 1924
	Tensile Stiffness	kNm kg^{-1}	ISO 1924
	Bending Stiffness	mNm	SCAN-P-29:95
	Short Span Compressive Strength Test		ISO 5270
Pulp fibre chemistry (HPLC)	Arabinose	%	
	Galactose	%	
	Glucose	%	
	Xylose	%	
	Mannose	%	
	Klason Lignin (insoluble portion)	%	
	Acid Soluble Lignin	%	
	Extractives	%	
*All handsheets were manufactured at 0, 500, 1000, 2000 and 3000 rpm PFI-mill refining -Tappi T248 Tappi Standard T 205 "Forming Handsheets for Physical Test of Pulp" was used			

6.2.8 Statistical analysis

Various statistical analyses procedures were selected to achieve the following objectives:

- Descriptive statistics including graphical analysis were used to evaluate for normality, underlying distribution of variables and fitness for parametric statistics.

- Due to the lay-out of the Nelder experiment, it was important to analyse and correct fixed (introduced) effects such as possible effects of replication of treatments, where necessary.
- Data were tested for significance between means by comparing variance, e.g. weighted mean wood density between spacing treatments by means of ANOVA.
- Correlations between variables were established to determine the "relatedness" between them.
- A linear dimensionality reduction technique was applied to project the data into a lower-dimensionality space, formed of a sub-set of the highest-variance components with Principal Component Analysis techniques and also displaying the data in biplots.
- Prediction models were developed with regression techniques to establish the predictive ability of the statistical relationships.

The data was analysed using SAS (9.2), SAS IML Studio (3.2) and SAS Enterprise Guide (4.2). SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, NC, USA (SAS Institute Inc. 2006). Programs written in "R" (R Development Core Team 2010) as given in Gower et al. (2011) were used to represent data in monoplots and biplots.

6.2.8.1 ANOVA

To test the main effects, data were subjected to Analysis of Variance evaluating the hypothesis that there are no differences between the means of pulp and paper variables across treatments.

The model was defined as follows:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij} \quad \text{for } j = 1, \ldots, n \; i = 1, \ldots, k \qquad \textit{Equation 3}$$

where:

Y_{ij} = the j^{th} observation of the i^{th} treatment

μ = overall mean

α_i = the effect due to treatment

β_j = the effect due to replications

ε_{ij} = the random error associated with the j^{th} observation of treatment i.

A correlation matrix was computed in order to explore the relationships between planting density, basic wood density and pulp and paper variables, and to determine whether there was linear association between the data sets.

6.2.8.2 Principal Component Analysis (PCA)

The normalised data to zero means and unit variances were further subjected to Principal Component Analysis (PCA). PCA involves a mathematical procedure that transforms a number of (possibly) correlated variables into a (smaller) number of uncorrelated variables called *principal components* (Cooley et al. 1971). The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. Each principal component is a linear combination of the original variables. Eigenvectors and eigenvalues, associated with the original correlation matrix, are calculated. The first principal component has the largest eigenvalue, the second principal component has a smaller eigenvalue, and so on. It is generally accepted that only those principal components that account for an appreciable portion of the variation (e.g. 70 % and above) should be chosen for further analysis. Once the principal components were identified, Multiple regression analyses were conducted to identify the significant physical and anatomical variables that may be used to predict variation in pulp and paper properties. Only variables found to differ significantly from zero ($p < 0.05$) were tabulated.

6.2.8.3 Graphical display of data in biplots

The description of PCA and CVA biplots and the interpretation thereof were described in detail in ***Chapter 5.2.5.3*** and can be applied to the sections that follow in Results and Discussion.

6.3 RESULTS AND DISCUSSION

6.3.1 Wood and pulp fibre data

Data collected on the pulp and wood fibre variables listed in Figure 6-3 were first tested for normality. Shown in Figure 6-3 is the W-statistics from the Shapiro-Wilk test used for small sample sizes to determine normality. It is noted from Figure 6-3 that the only variable that does not show a normal distribution is kappa number. This was expected as kappa number was a control variable, set at level of *c.* 20 for the cooking process and hence should not be distributed normal around the mean. The remainder of the variables measured as wood and wood pulp fibre descriptors show normal distribution around the means and as a result, parametric statistics was applied to the data.

Table 6-3: W-statistic from the Shapiro-Wilk test for test of normality and descriptive statistics for wood, wood fibre and pulp variables.

Product	Variable	Shapiro-Wilk (W)	Pr< W*	Mean	Min	Max	SD	CV
Wood/ Pulp fibre (Kajaani)	Basic wood density (gravimetric)	0.9667	0.0534	472.4	343.7	578.5	56.1	11.8
	Weighted fibre length	0.9878	0.4955	0.71	0.55	0.91	0.0818	11.4
	Fibre diameter	0.9788	0.2668	16.89	14.60	19.90	1.23	7.3
	Cell wall thickness	0.9811	0.3560	5.14	4.10	6.18	0.43	8.3
	Coarseness	0.9854	0.5713	7.04	6.00	8.30	0.51	7.3
	Fibre population	0.9913	0.9077	25.36	17.03	34.26	3.60	14.2
Pulp (Digester)	Screened Pulp Yield	0.9780	0.2395	52.64	48.41	56.32	1.81	3.4
	Total Pulp Yield	0.9889	0.7833	53.38	49.37	56.69	1.58	3.0
	Kappa no	0.9143^{ns}	0.0001	21.64	16.46	32.40	3.35	15.5
	Residual BL	0.9810	0.4860	9.39	6.68	11.62	0.96	10.2
Sample size (N) = 60; all tests Pr > |*t*| < 0.0001; * Normal if p > 0.05								

6.3.2 Paper (handsheet) data

In Table 6-4 the normality tests for PFI refining at 0 and 2000 rpm are shown. Most Shapiro-Wilk figures (W-statistics) had a value of $p > 0.05$ and hence the distribution of data is regarded as normal. For most paper variables tested, the refining of the fibre was reflected by either an improvement or degradation of specific properties.

Table 6-4: Result of Shapiro-Wilk Test showing W-statistic for normality and standard summary statistics for handsheet paper data**.**

Product	Variable	Refining rpm	Shapiro-Wilk (W)	Pr <W	Mean	Min	Max	SD	CV
Handsheet	Drainage	0	0.9697	0.0884	5.08	4.52	5.94	0.31	6.16
		2000	0.9471	0.0051	9.36	7.14	13.48	1.41	15.13
	Canadian Standard Freeness (CSF)	0	0.9941	0.9863	445.50	353.00	535.00	37.12	8.33
		2000	0.9791	0.2911	288.88	231.00	362.00	28.81	9.97
	Mass	0	0.9843	0.5309	1.31	1.28	1.33	0.01	0.78
		2000	0.9850	0.5711	1.32	1.28	1.35	0.01	1.02
	Thickness	0	0.9813	0.3823	91.71	83.52	100.40	3.78	4.12
		2000	0.9678	0.0726	77.38	72.05	83.72	2.40	3.11
	Basis mass	0	0.9832	0.4709	65.65	64.08	66.81	0.51	0.78
		2000	0.9847	0.5571	66.10	64.29	67.88	0.67	1.02
	Apparent sheet density	0	0.9823	0.4305	716.86	658.70	775.60	28.93	4.03
		2000	0.9803	0.3395	854.75	800.70	902.90	25.37	2.96
	Porosity	0^{ns}	0.9276	0.0007	22.92	6.78	65.33	11.26	49.13
		2000^{ns}	0.8481	<0.0001	301.47	1.52	929.16	170.75	56.64
	Smoothness	0^{ns}	0.9327	0.0010	108.29	1.33	182.25	26.00	24.01
		2000	0.9659	0.0541	28.54	8.50	57.25	11.31	39.63
	Brightness	0^{ns}	0.9532	0.0108	30.57	24.69	33.78	2.08	6.81
		2000	0.9745	0.1642	25.26	20.58	28.60	1.85	7.34
	Burst	0	0.9696	0.0875	5.06	3.87	7.02	0.74	14.63
		2000	0.9772	0.2304	8.65	7.26	10.27	0.66	7.67
	Tear	0^{ns}	0.9546	0.0127	8.71	6.62	11.08	1.03	11.82
		2000	0.9861	0.6353	8.31	5.82	10.34	0.95	11.53
	Tensile	0	0.9758	0.1955	90.02	73.96	109.20	8.43	9.36
		2000	0.9723	0.1328	122.25	108.60	135.60	6.75	5.52
	Stretch	0	0.9750	0.1752	2.27	1.80	3.03	0.28	12.33
		2000	0.9721	0.1208	3.69	3.19	4.28	0.19	5.36
	Tensile Energy Absorption (TEA)	0	0.9711	0.1063	1.36	0.89	2.02	0.27	19.70
		2000	0.9578	0.0691	2.96	2.46	3.64	0.25	8.56
	Tensile Stiffness	0^{ns}	0.9599	0.0248	8.38	7.40	9.58	0.56	6.71
		2000	0.9804	0.3423	8.13	6.93	9.64	0.65	8.00
	Bending Stiffness	0	0.9706	0.0984	91.15	72.40	112.55	10.65	11.68
		2000	0.979	0.2092	64.88	53.70	80.00	6.47	9.97
	Short Span Compressive Strength Test (STFI)	0	0.9760	0.2002	1.83	1.61	2.12	0.12	6.53
		2000	0.9867	0.6805	1.87	1.60	2.21	0.12	6.52

Porosity at zero and 2000 rpm beating intervals, and smoothness, brightness, tear and tensile stiffness at zero revolutions min^{-1} only, were not distributed normally around their means (Shapiro-Wilk statistic) and were therefore excluded from further analyses. The remainder of the data were distributed normally around the mean with acceptable coefficients of variation (CV < 20 %) for further analyses.

6.3.3 Chemical data acquired with HPLC

Results of the analysis of individual fibres from pulp samples, submitted to HPLC for the determination of polysaccharides and wood elemental components, are listed in Table 6-5. Notable is the absence of data for arabinose and mannose. The non-detection of these sugars was attributable to the very degrading nature of the Kraft cooking chemicals. It was described by (Fardim and Duran 2003) that xylans and glucans are more resistant to the peeling action by the pulping chemicals while arabinose and mannose are dissolved during the commercial Kraft cooking process and thus were undetected.

Table 6-5: Shapiro-Wilk statistic test results for normality on wood and pulp data obtained with HPLC analyses.

Material and analysis method used	**Variable**	**Shapiro-Wilk (W)**	**Pr <W***	**Mean**	**Min**	**Max**	**SD**	**CV**
Pulp (HPLC)	Galactose	0.9826	0.4247	0.19	0.00	0.41	0.07	37.89
	Glucose	0.9854	0.5744	79.96	74.44	85.63	2.36	2.94
	Xylose	0.9771	0.2124	11.75	7.98	15.22	1.67	14.19
	Total Polysaccharides	0.8670	<0.0001	92.06	87.72	94.72	1.28	1.39
	Insoluble lignin	0.8980	<0.0001	4.42	2.86	8.46	1.19	26.95
	Acid Soluble Lignin	0.9815	0.3726	3.17	2.38	3.93	0.30	9.41
	Total Lignin	0.8671	<0.0001	7.60	5.26	11.92	1.32	17.38
	Extractives	0.9604	0.0233	0.34	0.00	0.83	0.22	66.51
	Hexuronic Acid	0.9669	0.1086	46.39	30.76	59.97	6.43	13.86
Sample size (N) = 72; Arabinose and Mannose; no values detected; * Normal if p > 0.05								

6.3.4 Beating levels

When CSF was considered with the PFI-beating levels (rpm) (Table 6-4), it is seen that the CSF value was reduced from a mean of 445.50 ml (0 rpm) to 288.88 ml (2000 rpm). This was a negative trend as the drainage is of paramount importance on a paper machine, especially on the running speed which is reduced when the drainage is slow. Tensile strength increased with beating revolutions from 90.02 to 122.25 Nm g^{-1} when beaten for 2000 rpm. This was a positive development of paper strength. Furthermore, it was noted that with increasing beating revolutions, that CSF, sheet thickness and brightness deteriorated rapidly. There was no change in extra revolutions with sheet or basis mass, while the mass remained constant; both variables increased with lower initial planting density. Apparent sheet density developed with increased beating revolutions and was generally higher in the lower planting density.

For paper strength variables; burst, tensile strength and stretch developed with increased beating revolutions. Tear decreased with higher beating revolution levels. Tensile stiffness and STFI remained constant over the beating levels, in certain cases deteriorated slightly. However, bending stiffness deteriorated rapidly over a series of beating levels.

6.3.5 Pulp properties

Analysis of variance was used to investigate the variance in the measured pulp physical and chemical properties data sets as influenced by the main effect. Stand density at establishment was used throughout as the main effect while the logs taken from trees at various positions (Figure 6-3) were regarded as group effects. No pattern was observed over the single tree replications and hence the model was regarded as sufficiently uniform. Shown in Table 6-6 are i) analyses of variance for total pulp yield and ii) kappa number iii) basic wood density iv) residual black liquor and v) pulp fibre length. All variables entered in the model were highly significant. High coefficients of determination were achieved for the main variables when analyses of variance, especially for kappa number. Pulp yield was the highest at 2336 TPH with 54.61 %, followed by 6809 TPH, 801 TPH and 275 TPH. The trees at wider spacing treatments had lower total pulp yield; 52.16 % in the case of 275 TPH. The reciprocal was found for kappa number, indicating the highest value of 25.95, to be found in 275 TPH, and lowest for 2336 TPH with a value of 18.46. Basic wood density followed a different pattern; the lowest basic wood density in the highest planting density 6809 TPH (410 kg m^{-3}) opposed to 275 TPH which had a density of 510 kg m^{-3}. Residual black liquor showed low significance.

Table 6-6: Analysis of variance statistics for physical pulp properties and planting density and position in the tree effects. Note that " Whole tree" sample is the average value of Logs 1, 2 and 3.

Total Pulp yield	**R^2**	**MSE**	**Pr > F**	**Means n = 60**	**Duncan group**			
					2336 TPH	**6809 TPH**	**801 TPH**	**275 TPH**
Whole tree	0.44	1.20	<0.0001	53.61	54.61^{a}	54.20^{ab}	53.49^{b}	52.16^{c}
Log 1	0.57	0.65	0.0043	53.36	54.05^{a}	54.00^{a}	53.08^{b}	52.44^{b}
Log 2	0.39	1.25	0.0417	53.99	55.03^{a}	54.30^{ab}	54.04^{ab}	52.56^{b}
Log 3	0.54	1.27	0.0046	53.47	54.75^{a}	54.26^{a}	53.37^{a}	51.48^{a}
Kappa number	**R^2**	**MSE**	**Pr > F**	**Means n = 60**	**Duncan group**			
					275	**801**	**6809**	**2336**
Whole tree	0.57	2.38	<0.0001	21.82	25.95^{a}	21.60^{b}	21.25^{b}	18.46^{c}
Log 1	0.71	2.57	0.0002	22.93	28.58^{a}	22.69^{b}	21.16^{bc}	19.94^{c}
Log 2	0.71	1.74	<0.0001	20.84	24.60^{a}	20.98^{b}	20.13^{b}	17.68^{c}
Log 3	0.51	30.63	0.0078	21.75	24.67^{a}	21.21^{bc}	22.46^{ab}	18.75^{c}

Basic wood density (gravimetric)	R^2	**MSE**	**Pr > F**	**Means n = 60**	**Duncan group**			
					275	**801**	**2336**	**6809**
Whole tree	0.46	42.85	<0.0001	468.59	510.7^{a}	492.9^{a}	456.8^{b}	410.0^{c}
Log 1	0.64	34.11	0.0012	500.24	543.8^{a}	518.9^{ab}	493.9^{b}	430.2^{c}
Log 2	0.53	36.47	0.0056	449.47	482.8^{a}	472.9^{a}	449.5^{a}	392.6^{b}
Log 3	0.48	45.01	0.0115	457.65	505.4^{a}	486.7^{ab}	427.2^{bc}	411.3^{c}
Residual black liquor	R^2	**MSE**	**Pr > F**	**Means n = 60**	**Duncan group**			
					801	**275**	**2336**	**6809**
Whole tree	0.22	0.98	0.0032	9.35	9.87^{a}	9.65^{a}	9.33^{a}	8.52^{b}
Log 1	0.12	0.84	0.5467	9.75	10.07^{ns}	9.82^{ns}	9.75^{ns}	9.25^{ns}
Log 2	0.56	0.59	0.0034	9.65	10.17^{a}	10.16^{a}	9.56^{a}	8.69^{b}
Log 3	0.23	1.19	0.2282	8.69	9.37^{ns}	8.96^{ns}	8.68^{ns}	7.77^{ns}
Weighted Mean Pulp Fibre Length (FL)	R^2	**MSE**	**Pr > F**	**Means n = 60**	**Duncan group**			
					2336	**801**	**6809**	**275**
Whole tree	0.23	0.07	0.0023	0.73	0.77^{a}	0.75^{a}	0.69^{b}	0.68^{b}
Log 1	0.45	0.05	0.0190	0.78	0.83^{a}	0.82^{a}	0.73^{b}	0.74^{b}
Log 2	0.41	0.06	0.0318	0.73	0.77^{a}	0.78^{a}	0.66^{b}	0.69^{b}
Log 3	0.56	0.04	0.0038	0.67	0.72^{a}	0.67^{a}	0.70^{a}	0.61^{b}

The area relationship between basic wood density, kappa number and pulp yield is shown in Figure 6-4. The contour plot has planting density (275, 801, 2336 and 6809 TPH) on the X-axis and the three logs on height positions (DBH, 35 % and 65 % of tree height) on the Y-axis. From Figure 6-4 the following inferences are made:

- Basic wood density (gravimetric), similar to Chapter 5, showed a general trend of higher density in the low planting density, 275 TPH; lowest density in the 2nd log of 6809 TPH (392.6 kg m^{-3}) and highest density in the bottom log of 275 TPH (543.8 kg m^{-3}).
- The kappa number and total pulp yield forms an inverse pattern, the lowest kappa and highest total pulp yield in the planting density zone where 1800 < TPH < 4000.

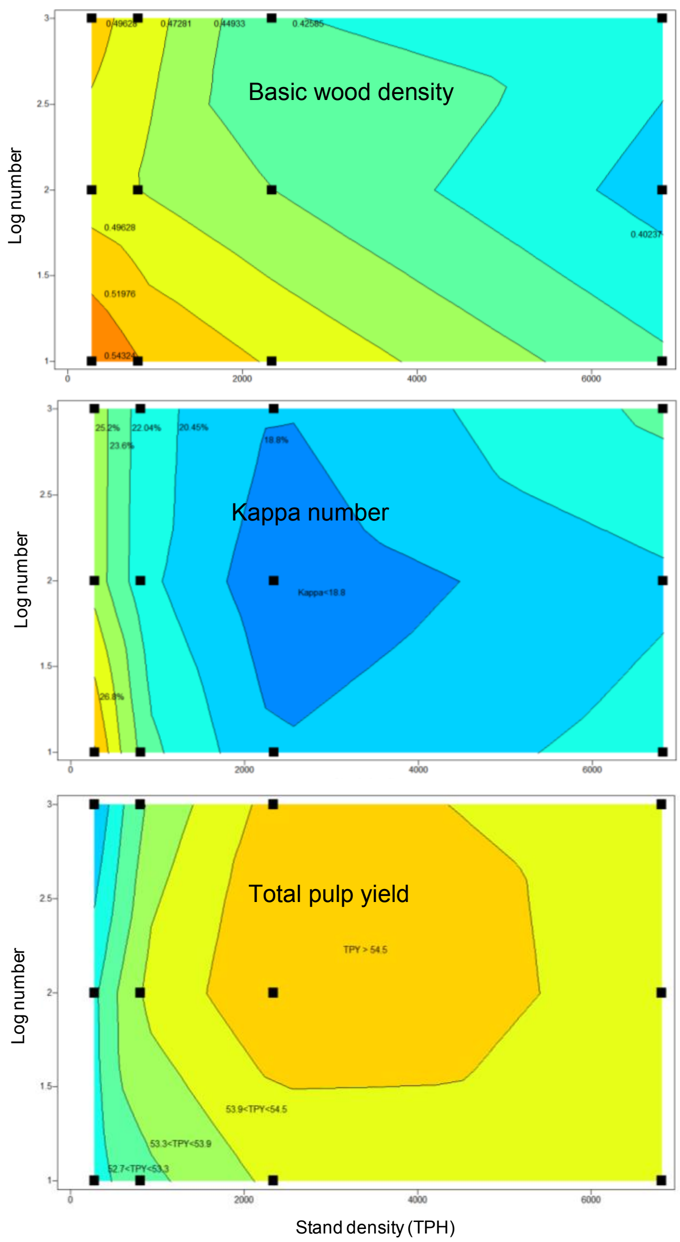

Figure 6-4: Basic wood density, kappa number and TPY contour plot displayed by planting density and log height position.

The relationships between kappa number, pulp yield and basic wood density will be considered as part of the fibre productivity index to describe optimum throughput in the integrated value chain.

6.3.5.1 Pulp chemical properties

Shown in Table 6-7 is a summary of the analyses of variance of the chemical properties developed from the HPLC from pulp samples. Notably, the HPLC chemical results are for pulped fibre and not wood. It is thus expected for the lignin and some hemicelluloses to be mostly washed from the samples. Included in the analysis of variance are only properties that were significant ($p < 0.05$). They are:

- glucose component which represents all the cellulose molecules
- the total amount of polysaccharides; as the complete sum of carbohydrates
- the total amount of acid insoluble lignin.

The acid insoluble lignin refers to the residual lignin in the pulp and not in the wood sample. It closely reflects kappa number when divided by 0.13 (J. Andrew, *pers. comm.*, CSIR 2011). The pulp samples contained 4.51 % insoluble lignin which falls within the same levels as *Eucalyptus* - clones tested in Brazil, reported as 3.1 - 5.1 % soluble lignin by Gomide et al. (2000).

Table 6-7: Summary on ANOVA testing differences in means of pulp chemistry.

Glucose (%)	**R^2**	**MSE**	**Pr > F**	**Means n = 60**	**Duncan group**			
					2336 TPH	**801 TPH**	**6809 TPH**	**275 TPH**
All	0.25	2.10	0.0011	80.14	81.18[a]	80.86[a]	80.37[a]	78.19[b]
Log 1	0.21	2.65	0.2825[ns]	79.91	79.93[a]	81.35[a]	80.45[a]	78.02[a]
Log 2	0.36	2.12	0.0580[ns]	79.70	81.83[a]	79.70[ab]	79.45[ab]	77.81[b]
Log 3	0.46	1.43	0.0154	80.80	81.75[a]	81.81[a]	81.22[a]	78.75[b]
Total Polysaccharides (%)	**R^2**	**MSE**	**Pr > F**	**Means n = 60**	**Duncan group**			
					2336	**6809**	**801**	**275**
All	0.16	1.29	0.0198	92.00	92.65[a]	92.16[a]	92.06[ab]	91.14[b]
Log 1	0.30	1.26	0.1314[ns]	91.58	91.52[ab]	92.35[a]	92.17[a]	90.45[b]
Log 2	0.28	1.47	0.1353[ns]	91.63	93.03[a]	91.45[ab]	91.19[ab]	90.85[b]
Log 3	0.44	1.42	0.0202	92.76	93.40[a]	92.71[ab]	92.83[ab]	92.10[b]
Total Lignin (%)	**R^2**	**MSE**	**Pr > F**	**Means n = 60**	**Duncan group**			
					275	**801**	**2336**	**6809**
All	0.57	2.66	<0.0001	31.11	33.89[b]	31.46[b]	29.78[c]	29.21[c]
Log 1	0.64	2.73	0.0012	32.51	35.07[a]	33.41[a]	31.08[b]	29.96[b]
Log 2	0.71	1.62	0.0001	30.59	33.42[a]	30.83[b]	28.88[c]	29.22[bc]
Log 3	0.74	1.36	<0.0001	30.32	33.18[a]	30.13[b]	29.37[b]	28.60[b]

All three models were significant when the means of glucose, polysaccharides and total lignin were compared with planting density. Glucose represented an average of 80.14 % of the total composition of the wood and total polysaccharides represented 92 %; the remaining portion was made up by 7.7 % total lignin (of which 4.5 % was insoluble and 3.2 % soluble) and a very small portion of extractives (not measured). Total wood lignin as seen in Table 6-7 was 31.1 %, highest in the DBH log and lowest in the 3rd log. Xylose was the main hemicellulosic sugar in the wood with an average content of 11.5 % per wood sample. The other carbohydrates including arabinose and mannose made up less than 1 % detectable of the wood. Glucose which is part of the total polysaccharides followed the same pattern as total pulp yield, i.e. 2336 TPH having the highest values (92.65 % polysaccharides) and 275 TPH the lowest values (91.14 %). The same inverse pattern emerges for acid insoluble lignin (from HPLC) and kappa number, the insoluble lignin highest in 275 TPH (5.24 %) and lowest in 2336 TPH (3.89 %). Noted from Table 6-7 is the lower coefficient of determination values and non-significance (tested at $p \leq 0.05$) when the main effect (planting density) was divided into logs and hence height position in the tree. Hexuronic acid was not non significant in the analysis of variance.

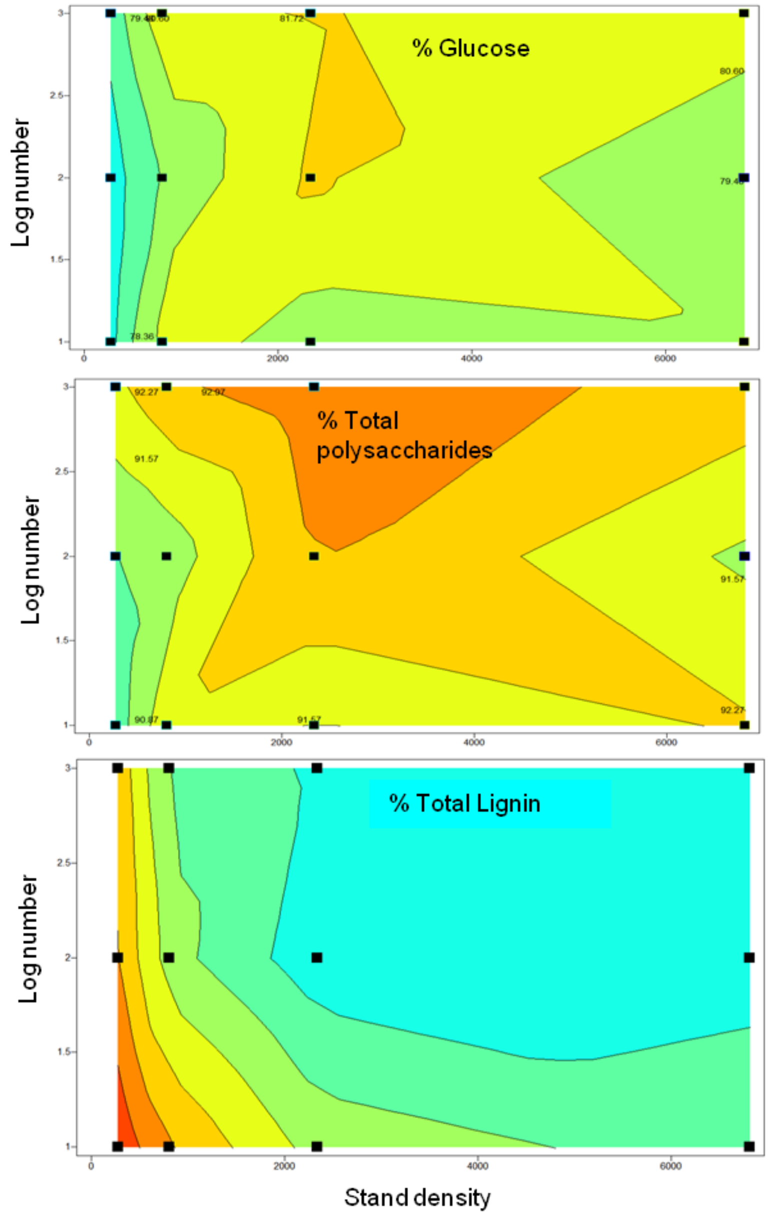

Figure 6-5: Contour plot displaying the relationships between %Glucose, %Polysaccharides and %Lignin with planting (stand) density and log height position.

Figure 6-5 is a contour map of % glucose, % total polysaccharides and % lignin sourced from the HPLC. These graphical representations were consistent with the ANOVA as summarised in Table 6-7 and can also be related back to total pulp yield and kappa number as displayed in the contour graph in Figure 6-4.

6.3.6 Paper properties

As suggested by a number of authors (du Plooy 1980, Malan 1988, Zobel and Van Buijtenen 1989, and Malan and Arbuthnot 1995), the three main linkages in the relationship between wood properties and paper properties are basic wood density, pulp fibre length, and fibre cell wall thickness. They were correlated with paper properties and those with high Pearson correlation (r) were entered into the analyses of variance to establish the influence of the main effect, planting density treatment and paper properties. In Table 6-8, a summary of the ANOVA is shown testing differences in individual log mean values at tree level (n = 60) by planting density treatments and paper properties at various beating levels.

Table 6-8: Summary on ANOVA testing differences in means of paper properties in individual logs and planting density.

Canadian Standard Freeness	**R^2**	**MSE**	**Pr > F**	**Means n = 60**	**Duncan group**			
					2336 TPH	**6809 TPH**	**801 TPH**	**275 TPH**
Rpm 0	0.27	31.31	0.0005	449.08	475.13^{a}	457.93^{a}	435.47^{b}	428.40^{b}
500	0.30	30.69	0.0002	390.61	418.13^{a}	400.21^{a}	373.07^{b}	371.67^{b}
1000	0.31	29.68	<0.0001	354.20	378.93^{a}	367.64^{a}	333.73^{b}	337.40^{b}
2000	0.27	24.97	0.0006	292.50	311.80^{a}	301.07^{a}	274.86^{b}	282.86^{b}
3000	0.25	19.01	0.0012	241.76	251.60^{a}	251.21^{a}	239.00^{b}	225.86^{b}
Brightness	**R^2**	**MSE**	**Pr > F**	**Means**	**2336**	**6809**	**801**	**275**
Rpm 0	0.54	1.53	<0.0001	30.48	32.16^{a}	31.40^{ab}	30.46^{b}	27.98^{c}
500	0.52	1.42	<0.0001	28.37	29.91^{a}	29.16^{ab}	28.37^{b}	26.10^{c}
1000	0.51	1.46	<0.0001	27.10	28.60^{a}	27.83^{ab}	27.23^{b}	24.80^{c}
2000	0.51	1.37	<0.0001	25.17	26.67^{a}	25.70^{ab}	25.33^{b}	23.03^{c}
3000	0.43	1.40	<0.0001	23.88	25.16^{a}	24.13^{a}	24.27^{a}	21.97^{b}
Tear	**R^2**	**MSE**	**Pr > F**	**Means**	**2336**	**801**	**6809**	**275**
Rpm 0	0.33	1.27	<0.0001	8.97	9.98^{a}	9.43^{a}	8.98^{a}	7.57^{b}
500	0.54	0.64	<0.0001	8.92	9.56^{a}	9.52^{a}	8.84^{b}	7.77^{c}
1000	0.52	0.69	<0.0001	8.79	9.36^{a}	9.43^{a}	8.66^{b}	7.70^{c}
2000	0.48	0.72	<0.0001	8.39	9.06^{a}	8.92^{a}	8.20^{b}	7.38^{c}
3000	0.48	0.65	<0.0001	8.13	8.59^{a}	8.75^{a}	7.97^{b}	7.20^{c}
Stretch	**R^2**	**MSE**	**Pr > F**	**Means**	**801**	**275**	**6809**	**2336**
Rpm 0	0.36	0.23	<0.0001	2.25	2.43^{a}	2.42^{a}	2.13^{b}	2.05^{b}
500	0.32	0.21	<0.0001	3.00	3.16^{a}	3.11^{a}	2.93^{b}	2.81^{b}
1000	0.28	0.20	0.0004	3.34	3.50^{a}	3.40^{ab}	3.29^{bc}	3.16^{c}
2000	0.23	0.18	0.0026	3.69	3.83^{a}	3.71^{ab}	3.63^{b}	3.58^{b}
3000	0.22	0.23	0.0170	3.95	4.06^{a}	3.88^{ab}	4.01^{ab}	3.84^{b}
Tensile stiffness	**R^2**	**MSE**	**Pr > F**	**Means**	**6809**	**2336**	**801**	**275**
Rpm 0	0.26	0.48	0.0006	8.43	8.77^{a}	8.65^{a}	8.23^{b}	8.09^{b}
500	0.32	0.57	<0.0001	8.68	8.78^{a}	8.70^{a}	8.15^{b}	7.86^{b}
1000	0.21	0.58	0.0042	8.22	8.44^{a}	8.53^{a}	8.14a^{b}	7.79^{b}
2000	0.10	0.63	0.1302^{ns}	8.15	8.38^{a}	8.32^{a}	8.03^{a}	7.90^{a}
3000	0.04	0.76	0.5611^{ns}	8.03	8.19^{a}	8.15^{a}	7.91^{a}	7.86^{a}

The CSF and Brightness showed values higher for the higher planting densities (6809 and 2336 TPH) and lower for the lower planting densities (801 and 275 TPH). Comparing paper strength properties, tear was the highest for the two intermediate planting density treatments (2336 and 801 TPH), and the lowest at the highest planting density and lowest planting density treatments respectively (6809 TPH and 275 TPH). Stretch was higher in the wider spaced treatments and lower in the narrow spacing treatments, whereas tensile stiffness was lower in the wide, and higher for the narrow spaced treatments.

6.3.7 Multivariate correlation analysis

A correlation analysis was conducted with individual log mean values at tree level for pulp physical, chemical, and paper properties that were significant in the ANOVA model as demonstrated in Table 6-6, Table 6-7 and Table 6-8. The Pearson correlation statistic was used to produce the graphical correlation path analysis shown in Figure 6-6 and Figure 6-7. The correlation matrix associated with Figure 6-6 shown in Annexure 6-1 and for Figure 6-7 is given in Annexure 6-2 .The correlation analyses are discussed below in terms of forestry factors, process, fibre quality, paper properties and chemical variables. It should be noted the p - values is an indication of the significance of the difference from zero, and does not the imply the practical importance of the correlation. The size of Pearson's correlation r - statistic is an indication of the usefulness of the relationship.

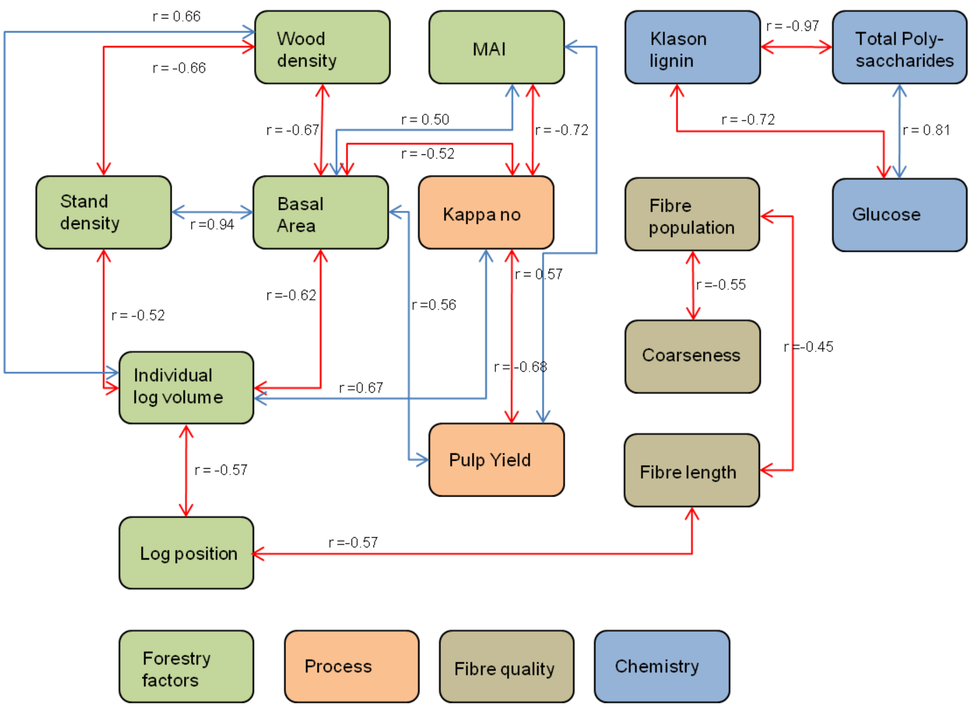

Figure 6-6: Graphic representation of correlation path analysis between forestry factors, process, fibre quality and chemical variables. Only highly significant values ($p \leq 0.0001$) are shown, n = 60.

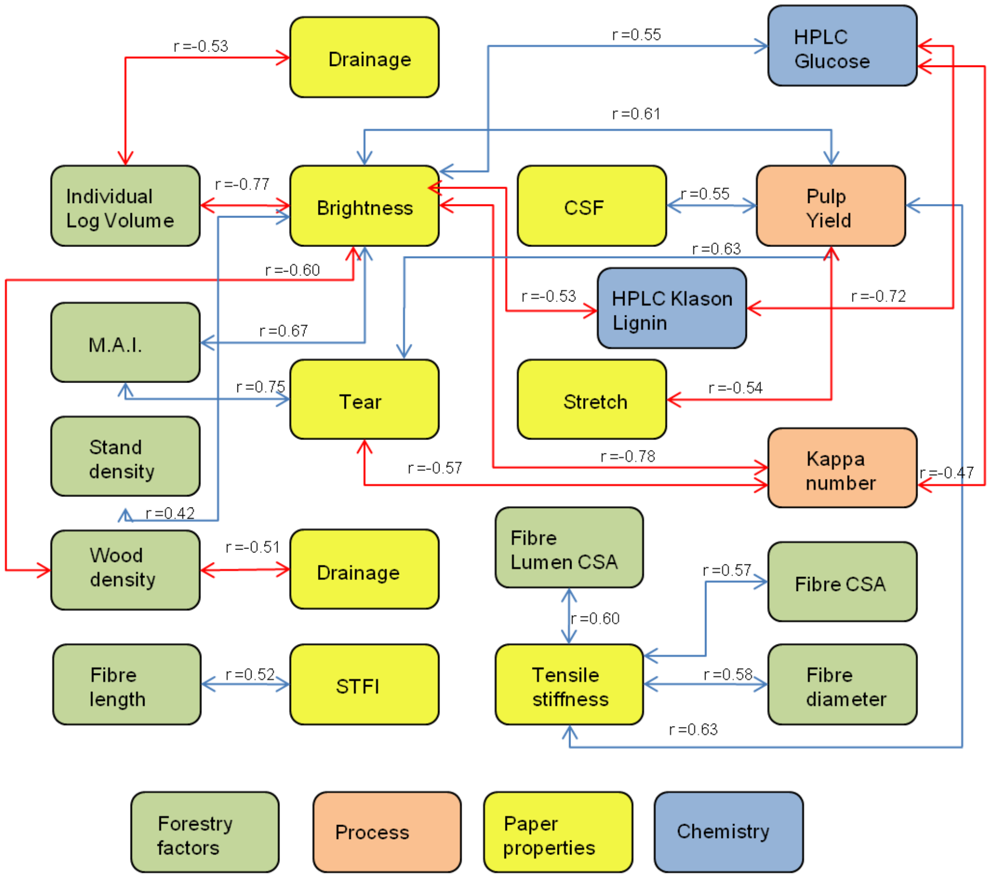

Figure 6-7: Graphic representation of correlation path analysis between forestry factors, process, paper properties and chemical variables. Only highly significant values are shown. Only highly significant values ($p \leq 0.0001$) are shown, n = 60.

6.3.7.1 Forestry factors

Planting density was well correlated with forestry variables, e.g. basal area, r = 0.94 (see du Plessis and Kotze 2011) and log volume, r = –0.52. Planting density was also well correlated with intermediate products from the Kraft pulping process, notably pulp yield (r = 0.40) and kappa number (r = –0.68). Planting density was highly correlated with basic wood density (r = –0.66) which explains the preference given to this characteristic by many researchers as a good indicator of quality, the high correlation and ease to measure. Basic wood density correlated with individual log volume (r = 0.66) indicating that the larger logs at low planting densities (r = –0.66) had higher basic wood densities. It is expected that basic wood density will contribute significantly as a fibre productivity indicator.

6.3.7.2 Wood as a raw material

Although basic wood density was highly correlated with planting density (r = –0.66, p < 0.0001), it had a low correlation with pulp yield (r = –0.38, p = 0.002), explaining that a decrease in planting density is associated with lower pulp yield as seen in the contour plot (Figure 6-4), and at the same time increased kappa number. The path analyses for paper properties (Figure 6-7) indicated significant negative relationships between basic wood density and drainage (r = –0.51) and brightness (r = –0.60), tear (r = –0.33, p = 0.0101) and small positive relationships with stretch, thickness and mass. Similar relationships were reported by (Wimmer et al. 2002). However, they reported a negative relationship for stretch in *E. globulus* and in the case of the *E. grandis* clone in this study (r = 0.28; p = 0.0299), it was positive.

Pulp fibre length was well correlated with the other fibre dimension variables, e.g. fibre width (r = 0.52), fibre cross sectional area (r = 0.52), lumen cross sectional area (r = 0.45), fibre wall cross sectional area (r = 0.53) and fibre cell wall thickness (r = 0.45). Cell wall thickness correlated well with other fibre measurements, e.g. coarseness (r = 0.61), fibre population (r = –0.60), fibre width (r = 0.71), fibre cross sectional area (r = 0.70) and fibre wall cross sectional area (r = 0.89). Similar to fibre length, these relationships were expected because of the shape and dimensions of the fibre.

6.3.7.3 Pulp properties

The correlation between pulp yield and kappa number was highly significant and negative (r = –0.68). This is confirmation of the contour pattern indicated in Figure 6-4 which depicts pulp yield and kappa number graphically as a reciprocal.

Pulp yield was highly correlated with all paper properties that were entered into the analyses; positive with CSF (r = 0.55), Brightness (r = 0.61), Tear (r = 0.63) and Tensile Stiffness (r = 0.62) and negatively correlated with Stretch (r = –0.54). Considering the chemical composition of the pulp samples, glucose which can be seen as a surrogate for cellulose, was negatively correlated with both insoluble lignin (r = –0.72; p < 0.0001) and kappa number (r = –0.47; p = 0.0001). This was expected and is also a good check; as cellulose content increase, lignin should decrease. Independent data from the HPLC correlated extremely well with one another, the highest of which is seen in Figure 6-6; insoluble lignin and total polysaccharides (r = –0.97; p < 0.0001), which confirmed the high trade-off between holocellulose and lignin; the one is always produced at the cost of the other. It was surprising that pulp yield and glucose content (r = 0.24) or total polysaccharides (r = 0.17) were not better correlated.

6.3.7.4 Paper properties

Paper brightness correlated well with the main effect, initial planting density (r = 0.42), with basic wood density (r = –0.59), with the resultant raw pulp produced (r = 0.61), with the process variable kappa number (r = –0.78) and with HPLC insoluble lignin (r = –0.52). The connection between pulp and paper brightness and lignin is well understood. It is negatively correlated explaining the fact that colour reversion takes place more easily in high lignin pulps when compared with low lignin or bleached pulps. This is often a commercial quality problem especially if paper products are left due to its usage in direct sunlight, where it almost always turns yellow.

When considering correlation analyses, caution must be exercised as correlation does not necessarily indicate causality. Variables may have underlying causal relation but this was not the purpose of correlation analysis. A good example is the high correlation between spacing treatment and paper brightness; it is obvious that planting density cannot cause high and low paper brightness but as explained, causality may be due to lignin content and beating levels. Although we know the correlation between variables, we do not know the form of the relationship between variables. These were further investigated by means of regression analysis.

6.3.7.5 Correlation monoplot

All the correlations given in the correlation matrixes in Annexure 6-1 and 6-2 can be optimally approximated and simultaneously displayed using the correlation monoplot described by Gower et al. (2011). All the correlations between the original variables i.e. stand density, fibre length, coarseness, fibre population, fibre diameter, fibre lumen cross sectional area (CSA), fibre wall CSA and fibre cell wall thickness (CWT) are shown in the monoplot in Figure 6-8.

Pulp fibre properties

The angle between two points (or arrows) in a correlation monoplot approximates the correlation between the two variables. With positive unit correlation between two variables, the two points (at the tip of the arrow) in the monoplot coincide while negative unit correlation generates points that are furthest apart. The following fibre properties which had Pearson correlation $r > 0.5$ and $p < 0.05$, were selected from Annexure 1: fibre coarseness, fibre cell wall thickness (CWT), fibre wall cross sectional area (CSA), fibre diameter (FD), fibre CSA, fibre length (FL), lumen CSA and fibre population. From Figure 6-8 it is construed that fibre diameter and fibre CSA are almost perfectly correlated while fibre population is highly negatively correlated with fibre coarseness. By plotting a unit circle (the green circle in the diagram), the degree of approximation (the length of the arrow) of a variable is visualized. It follows from Figure 6-8 that fibre population is negatively correlated with all the other variables but to a lesser extent than with fibre coarseness.

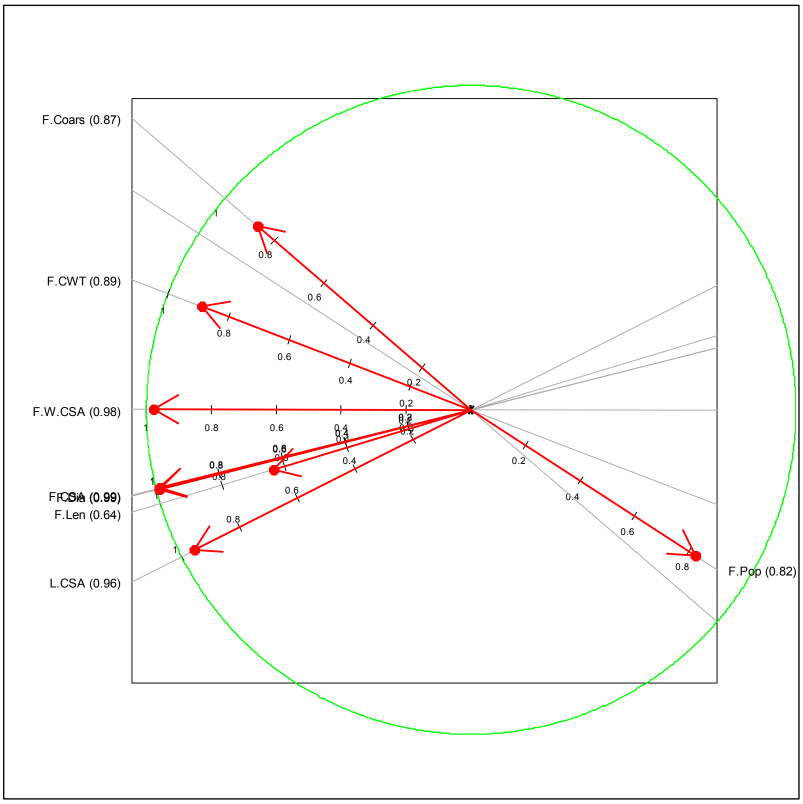

Figure 6-8: Correlation monoplot correlations between fibre variables.

Pulp chemical properties

Attention is now focussed at the pulp chemical variables. Variables with correlation r > 0.5 and p < 0.05 were selected from Annexure 6-1 and listed here: total polysaccharides, glucose, total pulp yield (TPY), residual black liquor, lignin and kappa number. The correlation monoplot for pulp chemical properties showed in Figure 6-9 shows strong negative correlations between lignin and total polysaccharides and glucose of the pulp. Kappa number as indication of residual lignin in the pulp is also strongly negatively correlated with total pulp yield which is consistent with the correlation graphic in Figure 6-6 and Annexure 6-1. Variables positioned at right angles are unrelated, e.g. kappa and glucose or total polysaccharides.

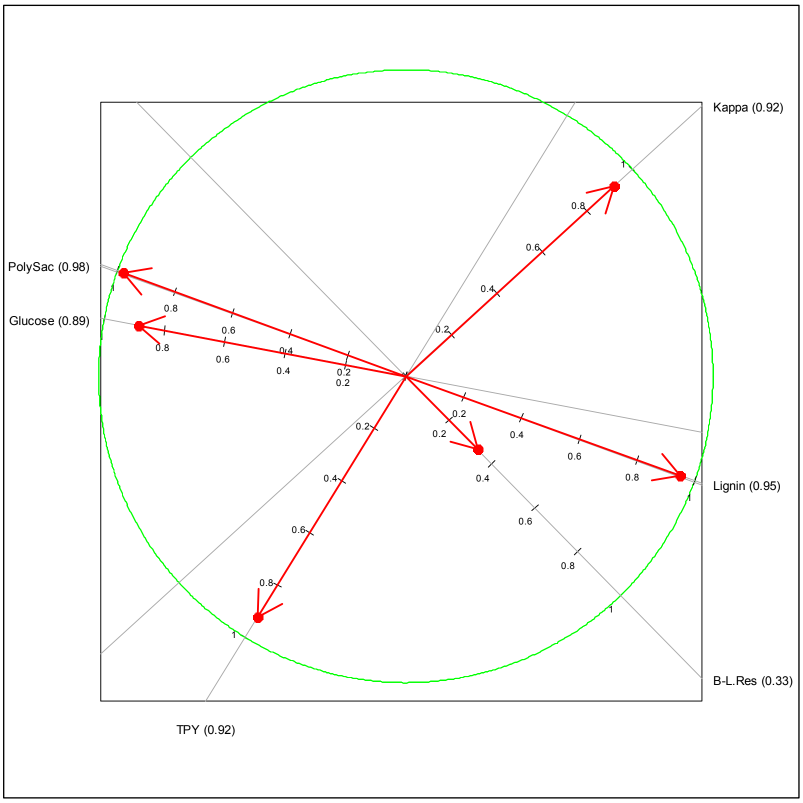

Figure 6-9: Correlation monoplot correlations between pulp chemical variables.

Paper handsheet properties

Paper handsheet variables selected ($r > 0.5$ and $p < 0.05$) from Annexure 6-2 were: thickness, Canadian standard freeness (CSF), brightness, smoothness, tear, tensile stiffness, burst, porosity and drainage, and fibre cell wall thickness (CWT), fibre length, fibre CSA and lumen CSA. It is noted from Figure 6-10 that porosity and burst at zero rpm beating levels, are highly correlated, together with tensile strength while all three these paper properties are negatively correlated with thickness. Fibre CWT thickness is perpendicular to these paper variables, indicating almost complete unrelatedness. Drainage and CSF are highly and negatively correlated which is an accepted paper making theorem. The two variables listed on the right (obscured by the fact that they are correlated by approximately 1) are burst and porosity at 0 rpm.

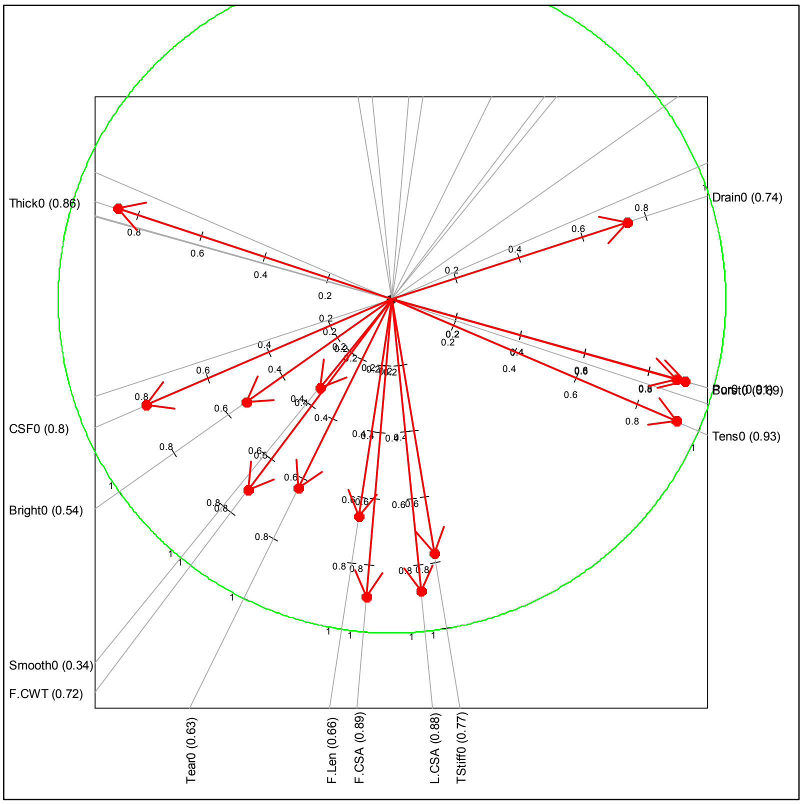

Figure 6-10: Correlation monoplot correlations between handsheet paper properties. The two variables listed on the right (obscured by the fact that they are correlated by *c.* 1) are burst and porosity at 0 rpm.

6.3.8 Principal Component Analysis (PCA)

Principal components were separately derived for fibre morphological data, chemical data and paper data. The main effect, planting density was used in each of the three analyses. Results are shown and discussed below.

6.3.8.1 Pulp fibre PCA

The fibre data of pulped fibre collected on the Kajaani Fibrelab was used to develop principal components. PCA worked well in this case as seen from Table 6-9 the four principal components that were chosen, collectively account for 95.7 % of the variation in the data set.

Table 6-9: Eigenvalue matrix for fibre data taken from Kajaani Fibrelab.

Eigenvalues of the Correlation Matrix				
No.	**Eigenvalue**	**Difference**	**Proportion**	**Cumulative**
1	5.4960	4.5348	0.6870	0.6870
2	0.9611	0.1944	0.1201	0.8071
3	0.7667	0.3338	0.0958	0.9030
4	0.4328	0.0191	0.0541	0.9571

The eigenvectors for the four eigenvectors of the correlation matrix are shown in Table 6-10 eigenvectors in the first column of Table 6-10 correspond with the first principal component in Table 6-9 which is a linear combination of the variables.

Table 6-10: Eigenvectors by principal components developed from variables used in analysis.

Eigenvectors				
Variable	**Principal 1**	**Principal 2**	**Principal 3**	**Principal 4**
F_coars	0.2806	–0.5770	0.3254	–0.1269
F_length	0.2597	0.1881	–0.8234	0.0835
F_pop	–0.2946	0.4570	0.3330	0.6154
F_diameter	0.4096	0.2487	0.1478	–0.0206
F_CSA	0.4092	0.2457	0.1606	–0.0482
F_Lumen_CSA	0.3641	0.4410	0.2225	–0.3210
F_Wall_CSA	0.4172	–0.0007	0.0738	0.2650
F_CWT	0.3536	–0.3253	–0.0494	0.6496

The first two principal components are defined in the following linear equations:

$PC_1 = 0.2805 \cdot (\text{F\_coarse}) + 0.2597 \cdot (\text{fibre length}) - 0.2946 \cdot (\text{F\_pop}) + \ldots\ldots$

$+ 0.4172 \cdot (\text{fibre wall CSA}) + 0.3536 \cdot (\text{fibre CWT}),$

$PC_2 = -0.5770 \cdot (\text{F\_coarse}) + 0.1881 \cdot (\text{fibre length}) + 0.4570 \cdot (\text{F\_pop}) + \ldots\ldots$

$- 0.0007 \cdot (\text{fibre wall CSA}) - 0.3253 \cdot (\text{fibre CWT}),$

and similar equations can be populated for PC 3 and 4.

The first principal component (PC_1) appears to be a weighted measure of fibre diameter (0.40), fibre wall CSA (0.41), Fibre cell wall thickness (0.35) and Fibre lumen CSA (0.36) and lower weights assigned to fibre length, fibre coarseness and fibre population. PC_2 is primarily related to fibre coarseness (–0.57), fibre population (0.45) and fibre lumen CSA (0.45), and less to other fibre morphological properties, whereas PC_3 is predominantly related to fibre length (–0.82). PCA analyses for chemical data and paper data are not shown.

The first two principal components form the framework of the biplot scaffolding for placement of the points and constructing the axes to represent the variables in the biplot (Gardner et al. 2005) as seen for pulp fibre properties in Figure 6-11 and Figure 6-12.

6.3.8.2 Graphical display of data in PCA biplots

Pulp fibre properties PCA

The PCA biplots for height position in the tree and planting density are shown below and discussed.

A short interpretation of the PCA biplots follows below:

- PCA for the purpose of being used in biplots acts as a dimension reduction technique.
- The PCA biplot approximates the distances between sample points.
- The approximate variable values associated with each sample point can be read from the calibrated linear biplot axes.
- Although the angles between biplot axes give some indication of the correlations between the respective variables these correlations are not optimally approximated in the PCA biplots. Therefore, the correlation monoplots should be used in conjunction with the PCA biplots for judging the correlations between the variables.

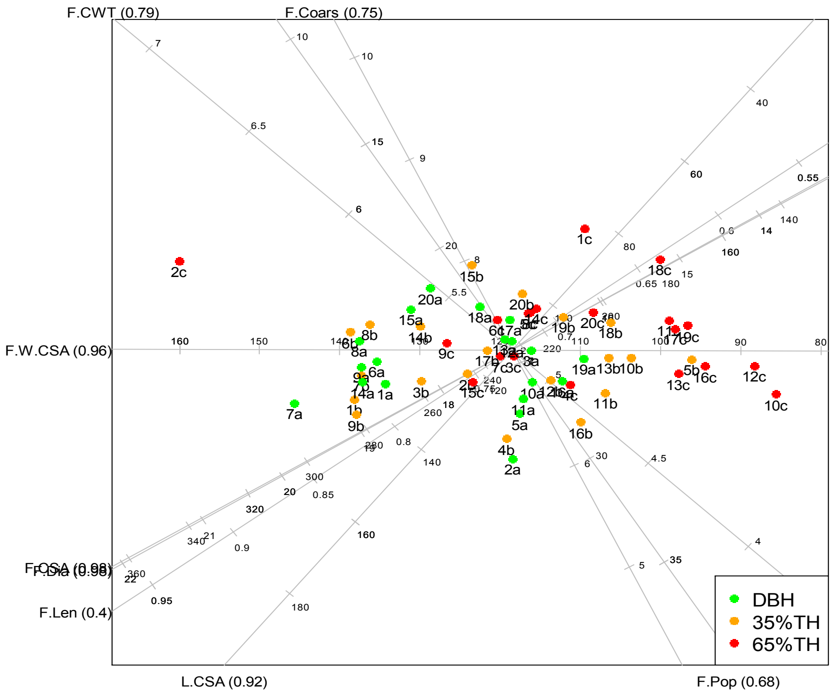

Figure 6-11: Biplot of pulped fibre physical properties with individual samples categorised in colour by the sample height position in the tree. The two biplot axes that almost coincide are those for variables fibre diameter and fibre cross sectional area respectively.

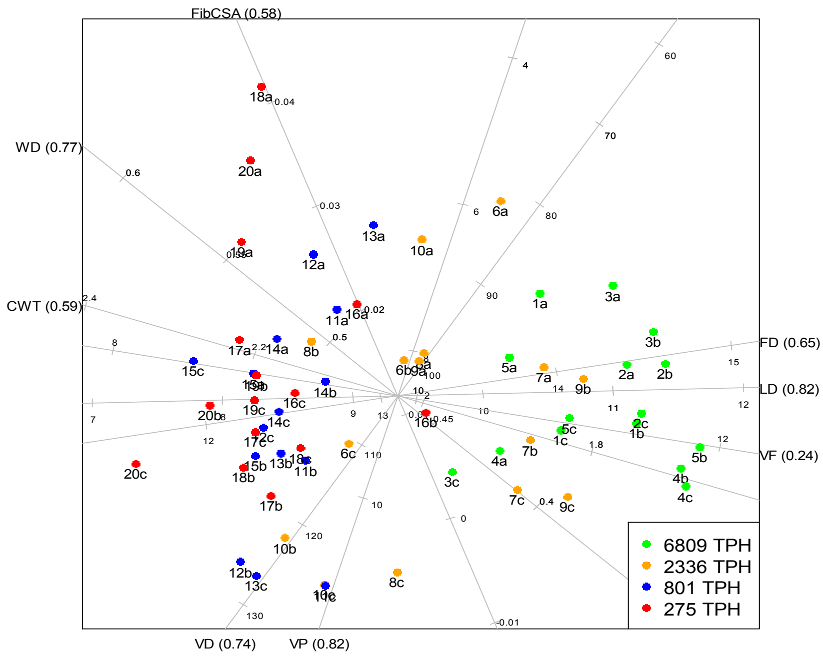

Figure 6-12: Biplot of pulped fibre properties with individual samples categorised in colour by planting density treatment.

From Figure 6-11 and Figure 6-12 the following key discussion points are relevant:

- The names of the variables are outside the plot and on the side with the highest value for that variable.
- There is no difference in distribution of pulped fibre data for tree positions at DBH and 35 % of tree height. However, the 65 % tree height position is shown clustering for low fibre wall cross sectional area, low fibre diameter and length and low fibre cross sectional area.
- Evaluating the planting density main effect on pulped fibre properties (Figure 6-12), there is no clear pattern emerging from the data points distribution but some structure in the positions of the data points is evident.

Pulp chemical properties PCA

The PCA biplots for tree position and planting density correlation with pulp chemistry are shown below and discussed.

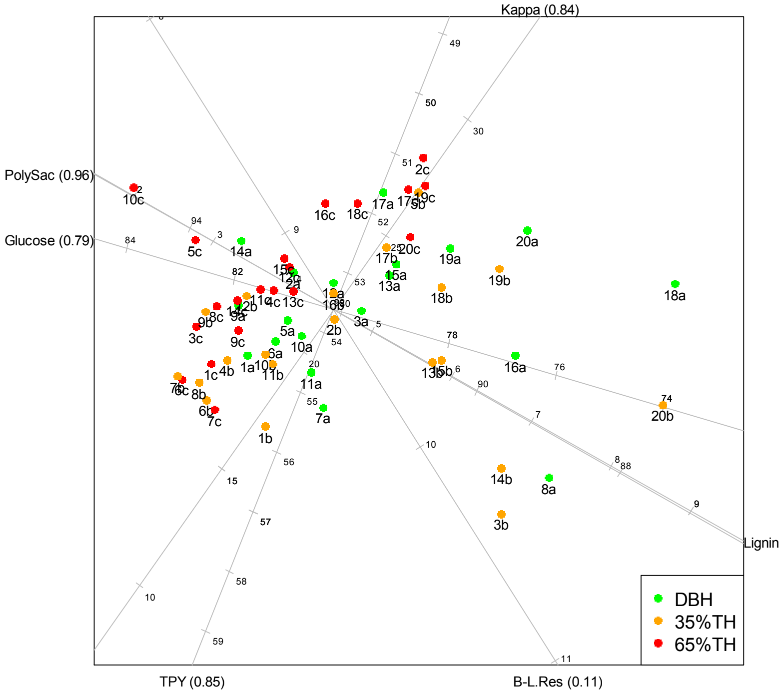

Figure 6-13: Biplot of pulped fibre chemical properties with individual samples categorised in colour by the sample position in the tree.

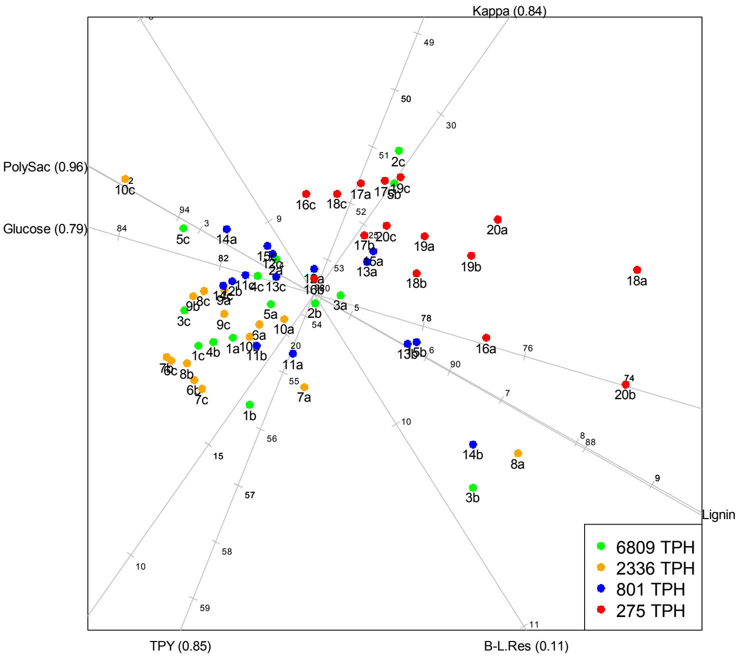

Figure 6-14: Biplot of pulped fibre properties with individual samples categorised in colour by planting density treatment.

From Figure 6-13 and Figure 6-14 the following key discussion points are relevant:

- Although lignin is strongly and negatively correlated with glucose and total polysaccharides, there seems to be a higher glucose and polysaccharide content in the 65 % logs than in the 35 % or DBH logs.
- Planting density (Figure 6-14) along the kappa number axis, is grouped for the low planting densities (275 and 801 TPH) on the high end of kappa and on the low end for total pulp yield; the 2336 TPH planting density does seem to cluster more on the high end of total pulp yield, particularly samples 6, 7 and 8 which, when the right angle projection is made were consistently between 55-56 % pulp yield.
- There is no clear pattern between planting density and glucose and total polysaccharides emerging from the PCA biplots.

Paper properties PCA

The PCA biplots for tree position and planting density correlation with paper properties are shown below and discussed. All values shown are at zero rpm beating levels.

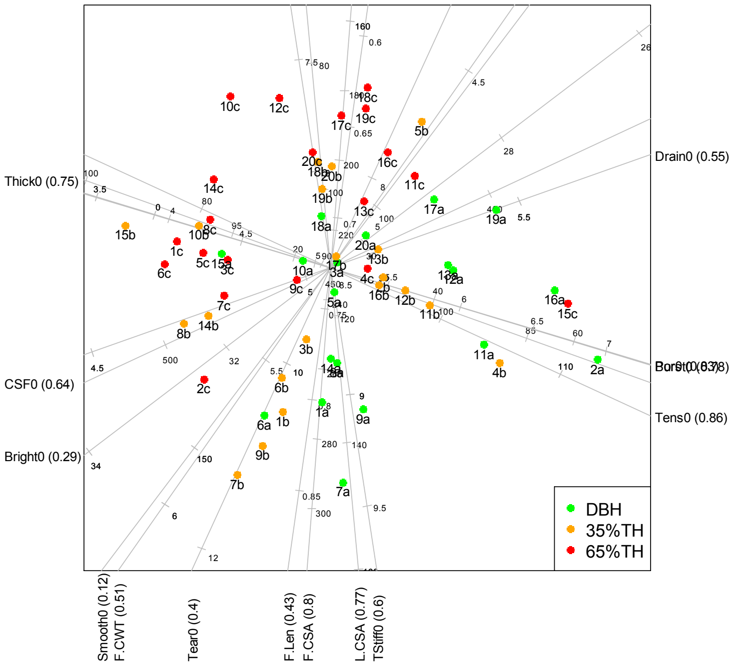

Figure 6-15: Biplot of paper properties categorised in colour by the sample position in the tree.

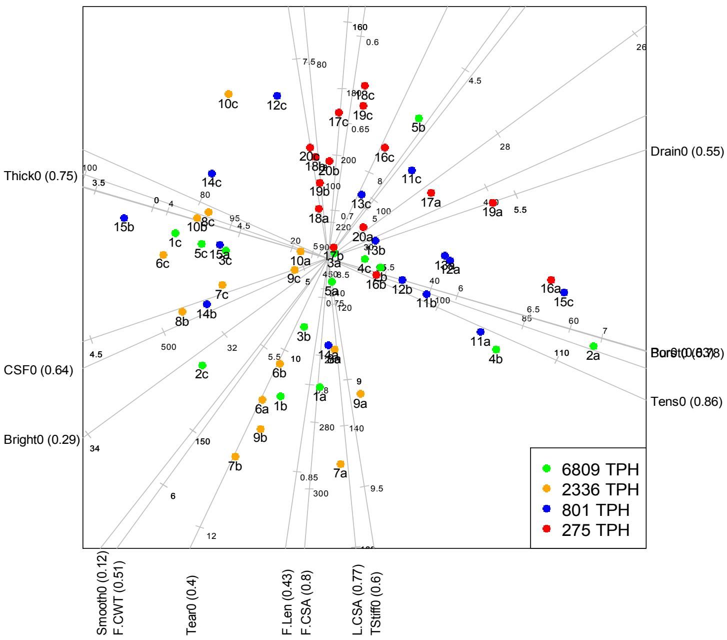

Figure 6-16: Biplot of paper properties with individual samples categorised in colour by planting density treatment.

From Figure 6-15 and Figure 6-16 the following key discussion points are relevant:

- Tensile stiffness which is strongly correlated with fibre properties, is highest in logs from the DBH position, similar to tensile strength which is higher in DBH and 35 % position, while paper thickness is higher in the 65 % height position.

- A very vague pattern is noted from Figure 6-16 for planting density treatments. However, it can be seen that tensile stiffness and tear is higher in high planting densities (2336 and 6809 TPH) and lower for the low planting densities (801 and 275 TPH).

6.3.9 Canonical Variate Analysis (CVA) biplots

CVA biplots were constructed from canonical variates to optimally separate the means of the three tree height positions and four planting density treatments with respect to the variables pulped fibre, pulp chemistry and paper data. These CVA biplots should shed more light on the structure found in the PCA biplots presented in section 3.8. Individual samples are colour coded in their respective groups and embedded into the biplot to give a graphical display of the overlap or separation. The calibrated biplot axes representing the variables are interpreted similar to the axes of an ordinary scatterplot, through projecting any point in the graph perpendicular onto an axis to read off the value for that particular variable; the inside axis with the units on, is known as the prediction axis. Each axis is calibrated in the original units of measurement; therefore it allows, similar to the PCA biplot, the reading-off of the value of the respective variable for a given point. Moreover, all the class means for all three variables can be determined graphically almost without error in this way.

6.3.9.1 Pulp fibre properties CVA

Following is a discussion of CVA biplots between tree height position and planting density and pulped fibre properties, pulp chemical properties and paper properties.

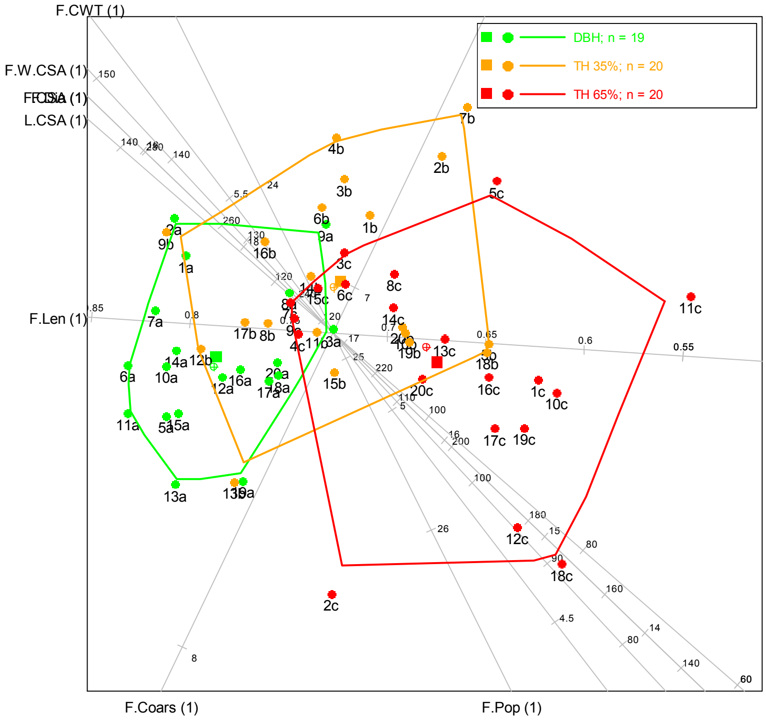

Figure 6-17: CVA Biplot showing data for tree position (DBH, 35 % and 65 %) of tree height position embedded in the pulped fibre data set. Group means are shown as solid squares and within group dispersion is shown as a series of solid circles. The two biplot axes that almost coincide are those for variables fibre diameter and fibre cross sectional area respectively.

Notes for interpretation of the CVA biplot:

- The coloured polygons about each group centroid denote the inner 95 % of the samples in the particular group.
- Group means are represented by the square block inside the polygon and correspond to the exact values.

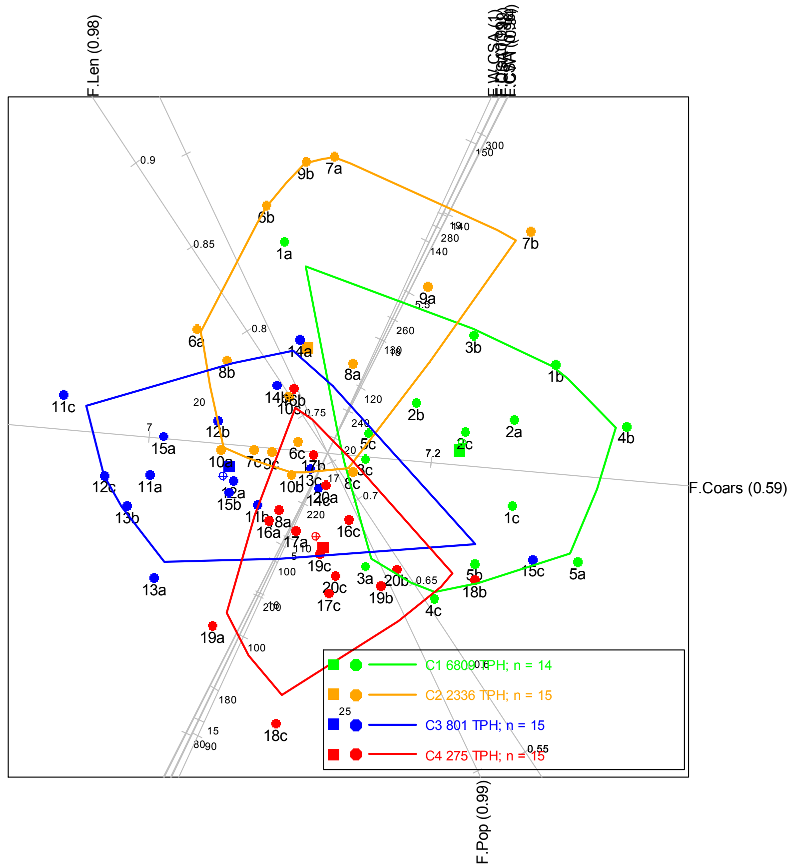

Figure 6-18: CVA Biplot showing the planting density treatments (main effects) embedded in the pulped fibre set. Group means are shown as sold squares and within group dispersion is shown as series of solid circles. The coloured polygons about each group centroid denote the inner 95 % of the samples in the particular group. A number of variables namely, fibre CWT, fibre wall CSA, fibre CSA, fibre diameter and lumen CSA aggregate on almost the same axes.

From Figure 6-17 and Figure 6-18 the following key discussion points are relevant:

- Groups for DBH and 65 % height are well separated for pulped fibre properties, showing clearly that fibre length is higher in the DBH than in the 65 % height positions.
- Fibre cell wall thickness is also higher for the DBH and 35 % height position than for the 65 % position.
- From Figure 6-18 it is noted that very little segregation had taken place between the planting density groupings. Two new groupings may be possible i) for low and ii) for high planting densities. The following fibre properties; fibre wall CSA, fibre lumen CSA, fibre CSA and fibre CWT are all highly correlated and clustered on a higher scale in the high planting density (6809 and 2336 TPH) and on the low scale in the low planting densities (801 and 275 TPH).
- The findings from Figure 6-17 and Figure 6-18 coincide with the ANOVA conducted and Chapter 5 and reported in Table 6-6 (this Chapter).

6.3.9.2 Pulp chemical properties CVA

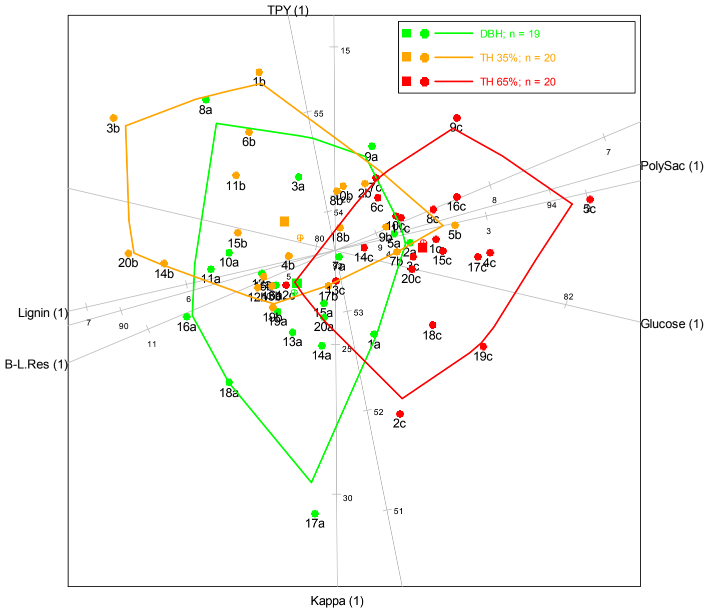

Figure 6-19: CVA biplot showing data for tree height position (DBH, 35 % and 65 %) embedded in the pulp chemistry data set. Group means are shown as solid squares and within group dispersion is shown as a series of solid circles.

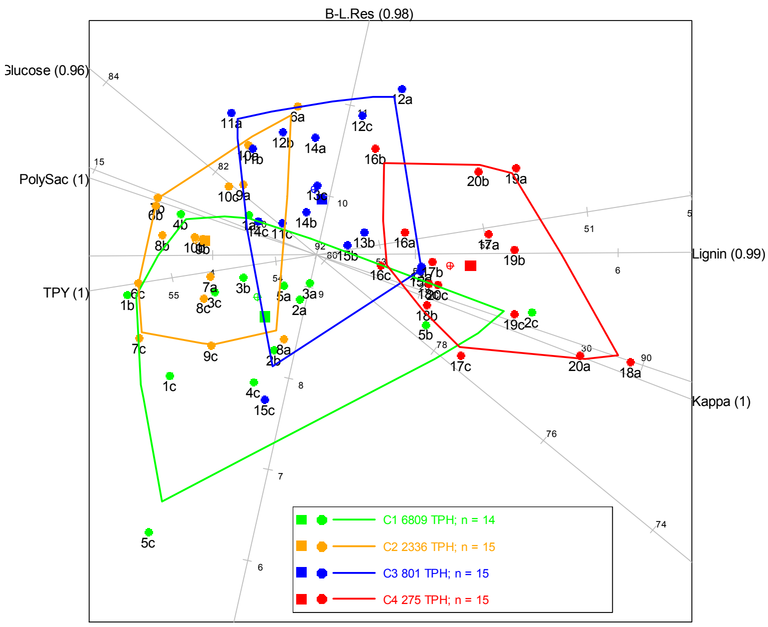

Figure 6-20: CVA Biplot showing the planting density treatments (main effects) embedded in the pulp chemistry data set. Group means are shown as solid squares and within group dispersion is shown as a series of solid circles.

From Figure 6-19 and Figure 6-20 the following key discussion points are relevant:

- Tree position did not separate into distinct groupings. When the groups means are considered it is noticed that very similar values are returned for various tree positions.
- There is better separation in planting density treatments, with clusters visible for the high planting density and low planting density groupings. With the exclusion of, e.g. sample 2c, the high planting density (6809 and 2336 TPH) groups will have much higher total pulp yield, total amount of polysaccharides and glucose than the lower planting densities found at 801 and 275 TPH. Moreover, for the latter, the lignin content and kappa numbers are high.
- The CVA biplot is a very good reflection of the ANOVA for pulp chemistry as seen from Table 6-7. Glucose in the pulp forms a cluster Duncan Multiple Range Test grouping "*a*" for 6809, 2336 and 801TPH and a separate grouping, "*c*", for 275 TPH. Similar results are seen in Table 6-7 for insoluble lignin and total polysaccharides.

6.3.9.3 Paper data

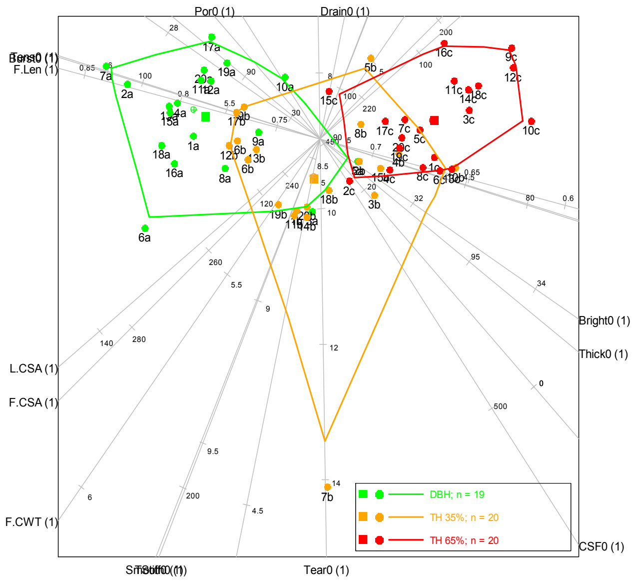

Figure 6-21: CVA Biplot showing data for tree position (DBH, 35 % and 65 %) of tree height embedded in the paper data set. Burst and Tensile strength coincides on the left axis and fibre CWT and tensile stiffness on the bottom axis.

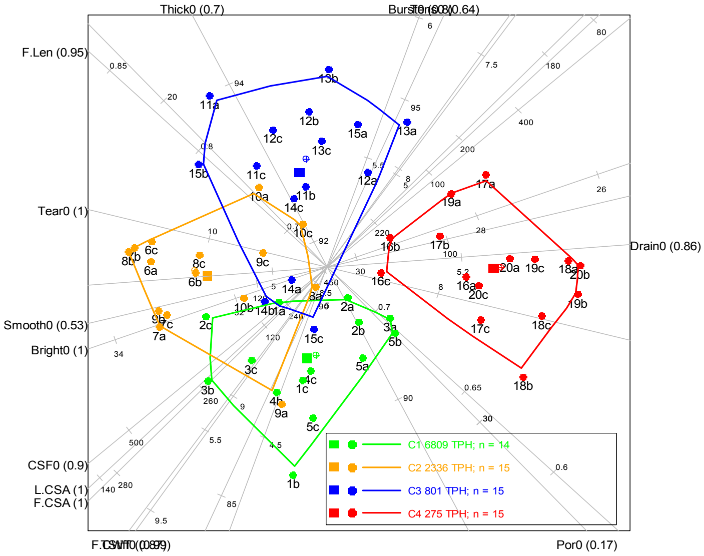

Figure 6-22: CVA Biplot showing data for planting density embedded in the paper data set. Burst and Tensile strength coincides on the left axis and fibre CWT and tensile stiffness on the bottom axis.

From Figure 6-21 and Figure 6-22 the following key discussion points are relevant:

- In Figure 6-21 clear separation between DBH and 65 % tree height for paper data is visible, while 35 % height position creates an overlap over the former groups.
- Figure 6-22 shows total separation between 275 TPH and the other three groups. Amongst the latter (6809, 2336 and 801 TPH), high levels of separation are also visible.
- Drainage for 275 TPH is much higher for the other groups while smoothness, tear and brightness are higher for the 6809, 2336 and 801 TPH than for the lowest planting density, 275 TPH.
- When Table 6-8 is considered together with the CVA biplots, the pattern of the Duncan groupings of planting density is repeated in both; CSF shows a separate grouping *"a"* for 6809 and 236 TPH and *"b"* for 801 and 275 TPH. Other patterns are also visible.

6.3.10 Curve fitting

6.3.10.1 Regression analyses

For purposes of developing regression models to assist in the development of a prediction system for a fibre productivity index, variables that revealed high levels of correlation shown in the monoplots (Figure 6-8, Figure 6-9 and Figure 6-10) and PCA biplots (Figures 6-11 to 6-16) and which are easily and cheaply acquired at high levels of accuracy, were chosen as the explanatory variables. Linear regressions were conducted on basic wood density and pulp yield. However, the regression lines did not match the data efficiently. Fit statistics are shown in Table 6-11.

Table 6-11: Linear regression statistics for wood bulk, pulp and process variables.

Variable	Model	β_1	β_2	n	R^2 adj	MSE
Basic Wood Density (gravimetric)	$BWD = \beta_1 + \beta_2 \cdot (TPH)$	505.88	–0.01559	60	0.44	41.5
Pulp Yield	$PY = \beta_1 + \beta_2 \cdot (TPH)$	52.17	0.0011	60	0.59	0.79
Lignin	$Lignin = \beta_1 + \beta_2 \cdot (TPH)$	32.87	0.0009	60	0.59	1.62

The basic wood density data (kg m^{-3}) was fitted to a non linear power function which described the data slightly better (R^2 comparison); the regression coefficients and statistics as shown in Table 6-12. The fitting procedure used the Marquardt iteration method and the convergence criterion was met. Pulp Yield was further fitted to a 2nd order polynomial function and is displayed with the linear function in Table 6-12.

Table 6-12: Non-linear regression coefficients for wood bulk, pulp and process variables.

Variable	Model	β_1	β_2	β_3	n	R^2adj	MSE
Basic Wood Density	$BWD = \beta_1 \cdot (TPH)^{\beta 2}$	752.80	–0.0663	–	60	–	1846.0
Pulp Yield	$PY = \beta_1 \cdot TPH^2 + \beta_2 \cdot TPH + \beta_3$	–1.9E-7	0.0016	51.96	60	0.61	1.618
Lignin	$Lignin = \beta_1 \cdot (TPH)^{\beta 2}$	43.92	–0.0481	–	60	–	2.76

The nonlinear model for basic wood density was displayed along the linear model and tested with independent data collected from the same Nelder 1a trial but not included in the development of the correlations and models. It is seen from Figure 6-23 that the nonlinear model (WDpower) follows the data used for modelling purposes better than the linear model. When compare to the test data set, it was noted that both models intersected the test data between the minima and maxima and can be recommended for implementation when basic wood density needs to be predicted from tree planting density data.

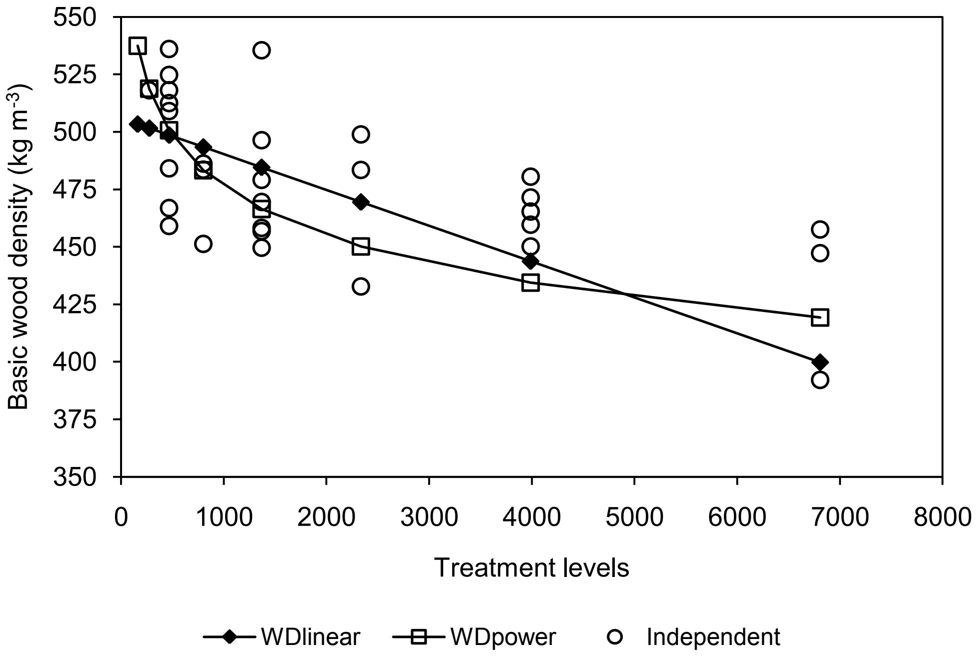

Figure 6-23: Basic wood density model prediction curves for linear and nonlinear functions plotted against test data.

In Figure 6-24, the polynomial curve and linear curve plotted for pulp yield against planting density is shown. The polynomial curve indicates that pulp yield starts off low in the low planting density and flattens off towards the high planting densities and intersects the test data as expected midway between the maxima and minima for the respective treatment test data. It is recommended that the polynomial function is used for further prediction of pulp yield with treatment data as the linear model keeps on increasing, not reflecting the measured or test data trends. Figure 6-25 shows the linear and nonlinear regression curves for total lignin.

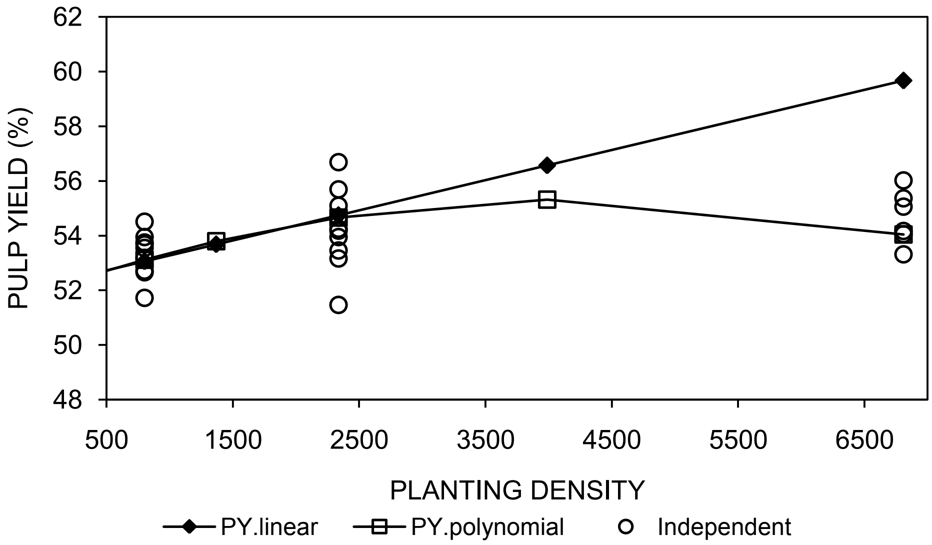

Figure 6-24: Pulp yield model prediction curves for linear and nonlinear functions plotted against test data.

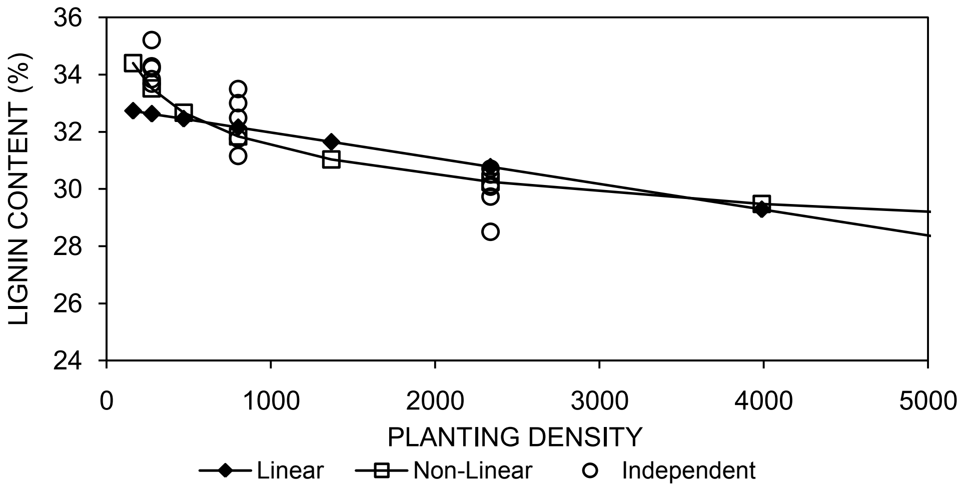

Figure 6-25: Total lignin prediction curves for linear and non-linear regression functions plotted against test data.

In order to predict paper properties, the correlation matrix (Figure 6-7) and monoplots (Figure 6-10) were used to identify significant correlations between wood product, chemical and paper data which were entered in multiple regression analyses. To enable the use of these functions from a planting-level to product-level approach, planting density treatment was statistically forced into the model. When tested, the variables that were not significant at the 5 % level were computationally forced out of the final equation. Table 6-13 gives the variable estimates; it is noted that only brightness as a characteristic of the visual impact of paper and tear and tensile stiffness as a strength characteristics were suitable for prediction from planting and process-level variables.

Table 6-13: Linear regression coefficients developed for paper properties that had correlation values.

Variable	Model	B_0	B_1	B_2	B_3	n	R^2adj	MSE
Freeness (CSF)	$CSF = B_0+B_1\cdot (TMT)+ B_2\cdot (PY)$	–108.157	–1.316	10.593		60	0.25	950.1
Brightness (B)	$B = B_0+B_1\cdot (TMT)+B_2\cdot (BWD)+ B_3\cdot (Kappa)$	42.956	–0.073	-0.008	-0.370	60	0.67	1.53
Tear (T)	$T = B_0+B_1\cdot (TMT)+B_2\cdot (PY))+ B_3\cdot (Fibre\ Length)$	–14.335	–0.026	0.417	1.359	60	0.78	0.50
Stretch (S)	$S = B_0+B_1\cdot (TMT)+B_2\cdot (PY)$	6.216	0.0176	–0.076		60	0.32	0.05
Tensile Stiffness (TS)	$TS = B_0+B_1\cdot (TMT)+B_2\cdot (PY)+B_3\cdot (Fibre\ Width)$	–2.662	–0.016	0.165	0.141	60	0.76	0.16

6.4 CONCLUSION

This investigation considered the vertically integrated forestry, pulp and paper value chain from the wood source (an experiment planted at different tree planting densities), Kraft chemical pulping and the manufacturing of nonwoven handsheets as final product. The results of this study showed the *Eucalyptus grandis* clone to be a very valuable resource, with high variability (as result of stand density and position in the tree) and highly versatile for its purpose as a quality paper product. Following is a summary of the findings of this integrated investigation.

6.4.1 Planting density as a forestry factor

Initial planting density, analysed as the main effect in this chapter, had an important effect on downstream products. Planting density variability affected the raw wood material especially timber yield and basic wood density. The effect of planting density was visible throughout the entire product value chain. Planting density correlated with basic wood density (r = –0.66) and individual log volume (r = –0.57) and basal area (r = 0.94). In the ANOVA, total pulp yield was well explained by planting density (R^2 = 0.44); the 2336 TPH treatment the highest and 275 TPH the lowest. Intra-specific tree variability of total pulp yield showed an increase from DBH to 35 % and then a decrease to 65 % of tree height. The influence was also significant in the secondary processing (paper manufacturing) stage, measuring strength and quality attributes of paper sheets such as tensile stiffness and paper brightness. Kappa number was influenced by planting density (R^2 = 0.57), the highest in 275 TPH and lowest in 2336 TPH, the inverse of total pulp yield. This phenomenon is well displayed in the contour plot in Figure 6-4. Individual log volume, an indication of tree size, impacted significantly on paper brightness (r = –0.77) and basic wood density also impacted on brightness (r = –0.66). The importance of this relationship is that trees with bigger logs or denser wood (found in planting densities less than 801 TPH), will in the case of the production of bleached pulp, possibly require more bleaching chemicals and hence incur more costs.

The breeding strategy in the 1980's and 1990's was to increase pulp yield at the Kraft mill from average (*c.* 48 %) to higher levels, which was fully achieved as shown in this study. Pulp yield was successfully regressed with spacing treatments and as a primary process product; this result can be used in an integrated fibre productivity index.

6.4.2 Wood and fibre as raw material

Basic wood density was a strong indicator of handsheet properties and was positively and significantly correlated with handsheet bulk properties such as mass and stretch but negatively correlated with indicators of strength such as tear, tensile stiffness and bending stiffness. A visual paper property, brightness, and basic wood density were strongly negatively correlated ($p < 0.0001$). Paper manufactured from the trees with higher density wood showed low levels of brightness when handsheets were evaluated. Basic wood density was modelled with planting density treatments and can form part of an integrated fibre productivity index which will be suggested in the next chapter.

Although some fibre properties were already discussed in Chapter 4, the data originated from the image analysis represented the radial plane only. Another data set of fibre properties was generated from individual fibres taken from the pulp samples through the Kajaani Fibrelab. This allowed properties of fibres such as fibre length to be observed three-dimensionally. The average fibre length in this study was 0.73 mm; higher in the DBH than in the logs from the 35 % or 65 % height positions. Although there was a weak correlation in the ANOVA and fibre length ($R^2 = 0.23$), the trend was consistent with pulp yield i.e. long fibres were found in stand densities of 2336 and 801 TPH. Fibre population and fibre length was correlated well with fibre population ($p < 0.0001$). In the PCA, fibre properties made significant contributions in elements of the latent variables Table 6-10 and as seen in the bi-plot (Figure 6-8).

Fibre length was highly related to tear index ($r = 0.77$) and as a result was used in a regression prediction. Other fibre geometrical properties, e.g. fibre width, lumen diameter and cell wall thickness, did not correlate well with process or product characteristics.

6.4.3 Pulp chemistry

Chemical data obtained from the HPLC analysis of pulp samples failed to show strong relationships with tree planting density in the analysis of variance (glucose, $R^2 = 0.25$; total polysaccharides, $R^2 = 0.16$ and Klason lignin $R^2 = 0.15$, all significant at $p < 0.05$). However, the information obtained was meaningful. As expected, arabinose and mannose were almost undetected, xylose (11.5 %) was the main hemicellulosic sugar component. Glucose content coincided well with high/low pulp yield on planting density level. Figure 6-5, the chemical constituents, showed much the same pattern as Figure 6-4, the components from the pulping process. When the biplot in Figure 6-13 was considered, it was noticed that planting density, total pulp yield and residual black liquor were not correlated with the HPLC assessed chemical components. However, glucose and total polysaccharides were well correlated (positively) and negatively with insoluble lignin.

6.4.4 Pulp and paper properties

Paper with higher bulk mass and thickness and more porous sheets are most likely to be made from 801 and 275 TPH, and stronger, smoother and denser paper is most likely to be made with trees grown at 6809 or 2336 TPH than the lower stand densities.

The mechanical strength properties of the handsheets such as burst (0-3000 rpm; 5.10 to 9.17 kPa m^2 g^{-1}) and stretch (0-3000 rpm; 2.25 to 3.95 %) increased with increased beating levels while some of the visual variables like brightness deteriorated (0-3000 rpm; 30.48 to 23.88 %) rapidly with increasing beating levels. Brightness and Canadian Standard Freeness were higher in the higher planting densities, while tear was high in the intermediate planting densities between 2336 and 801 TPH. Brightness values decreased with beating because the increase in the interface-bonded area resulted in fewer air pockets to scatter the light. Tensile stiffness, often used as a prominent paper quality indicator, was higher in the high planting density treatments. This was largely attributed to the beating process which caused the outer primary cell wall and the S1-layer to loosen and separate. Larger areas of the cellulosic material were exposed as hydrogen bonding zones during sheet formation and caused the strength properties to increase. Brightness (R^2_{adj} = 0.67), tensile stiffness (R^2_{adj} = 0.76) and tear (R^2_{adj} = 0.78) were modelled by making use of measured data elements such as planting density treatment, basic wood density, fibre length and width, pulp yield and kappa number.

6.4.5 The use of biplots

The use of biplots, demonstrated in the sections on PCA- and CVA biplots, was shown to have exceptional value as that they simultaneously provide information on both the samples and the variables of a data matrix in two or more- dimensional representations. The use of PCA and CVA biplots added substantially to the understanding to the data and its correlation and interaction with the wood fibre, pulp processing and paper product. A key in the interpretation of the data is the understanding of the behaviour of the data in analysis of variance.

An intimate understanding of materials, processes and products were defined by the outcomes of this materials investigation and are considered in the next chapter as constituents of a fibre productivity index.

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ANNEXURE 6-1: Correlation analysis associated with Figure 6.

Pearson Correlation Coefficients, N = 59
Prob > |r| under H0: Rho=0

	TPH	MAI	Wood_density	F_Length	F_Coars	F_pop	F_diameter	F_CSA	L_CSA	F_Wall_CSA	Fibre_CWT	Muhlsteph_Ratio	TPY	Kappa	Black_Liquor_res	HexA	Glucose	Polysaccharide	Klason_Lignin
TPH	1.00000	0.17691	-0.65844	-0.10091	0.04899	0.03264	0.33855	0.34337	0.35140	0.29823	0.20717	-0.10656	0.39998	-0.29842	-0.45538	-0.00764	0.16592	0.17153	-0.19637
		0.1801	<.0001	0.4470	0.7125	0.8062	0.0087	0.0078	0.0064	0.0218	0.1154	0.4218	0.0017	0.0217	0.0003	0.9542	0.2091	0.1939	0.1361
MAI	0.17691	1.00000	-0.25660	0.43807	-0.05852	-0.30280	0.31591	0.31954	0.31743	0.28836	0.18293	-0.13220	0.57486	-0.72345	-0.01954	-0.04502	0.49223	0.38314	-0.34304
	0.1801		0.0498	0.0005	0.6598	0.0197	0.0148	0.0136	0.0143	0.0268	0.1655	0.3182	<.0001	<.0001	0.8832	0.7350	<.0001	0.0027	0.0078
Wood_density	-0.65844	-0.25660	1.00000	0.15228	0.25939	-0.04482	-0.19340	-0.19931	-0.27516	-0.09265	0.05831	0.30278	-0.38389	0.46634	0.31198	-0.09142	-0.25200	-0.32907	0.34705
	<.0001	0.0498		0.2496	0.0473	0.7361	0.1422	0.1302	0.0349	0.4852	0.6609	0.0198	0.0027	0.0002	0.0162	0.4911	0.0542	0.0109	0.0071
F_Length	-0.10091	0.43807	0.15228	1.00000	0.19342	-0.45311	0.52760	0.51923	0.45734	0.53462	0.45730	-0.00368	0.37433	-0.19495	0.37050	-0.21133	0.18648	-0.02541	0.06028
	0.4470	0.0005	0.2496		0.1422	0.0003	<.0001	<.0001	0.0003	<.0001	0.0003	0.9779	0.0035	0.1390	0.0039	0.1081	0.1573	0.8485	0.6502
F_Coars	0.04899	-0.05852	0.25939	0.19342	1.00000	-0.55060	0.51988	0.52835	0.40476	0.61251	0.61343	0.23443	-0.08103	0.40000	0.00795	0.10147	-0.30055	-0.29368	0.24546
	0.7125	0.6598	0.0473	0.1422		<.0001	<.0001	<.0001	0.0015	<.0001	<.0001	0.0739	0.5418	0.0017	0.9523	0.4445	0.0207	0.0240	0.0610
F_pop	0.03264	-0.30280	-0.04482	-0.45311	-0.55060	1.00000	-0.52971	-0.53276	-0.41452	-0.61041	-0.59879	-0.20582	-0.35638	0.10178	-0.04906	-0.11237	0.07369	0.11754	-0.09267
	0.8062	0.0197	0.7361	0.0003	<.0001		<.0001	<.0001	0.0011	<.0001	<.0001	0.1178	0.0056	0.4430	0.7121	0.3968	0.5791	0.3753	0.4851
F_diameter	0.33855	0.31591	-0.19340	0.52760	0.51988	-0.52971	1.00000	0.99920	0.95198	0.94761	0.71162	-0.21376	0.43593	-0.20086	0.02480	-0.15635	0.01926	-0.09018	0.08683
	0.0087	0.0148	0.1422	<.0001	<.0001	<.0001		<.0001	<.0001	<.0001	<.0001	0.1040	0.0006	0.1272	0.8521	0.2370	0.8849	0.4970	0.5131
F_CSA	0.34337	0.31954	-0.19931	0.51923	0.52835	-0.53276	0.99920	1.00000	0.95651	0.94410	0.70255	-0.22497	0.42832	-0.20203	0.02154	-0.14231	0.02527	-0.08138	0.07773
	0.0078	0.0136	0.1302	<.0001	<.0001	<.0001	<.0001		<.0001	<.0001	<.0001	0.0867	0.0007	0.1249	0.8713	0.2823	0.8493	0.5400	0.5584
L_CSA	0.35140	0.31743	-0.27516	0.45734	0.40476	-0.41452	0.95198	0.95651	1.00000	0.80688	0.46536	-0.49639	0.36008	-0.23372	0.02387	-0.15282	0.08983	-0.03024	0.04769
	0.0064	0.0143	0.0349	0.0003	0.0015	0.0011	<.0001	<.0001		<.0001	0.0002	<.0001	0.0051	0.0748	0.8576	0.2479	0.4987	0.8202	0.7199
F_Wall_CSA	0.29823	0.28836	-0.09265	0.53462	0.61251	-0.61041	0.94761	0.94410	0.80688	1.00000	0.89680	0.10540	0.46045	-0.14498	0.01666	-0.11547	-0.05034	-0.13062	0.10351
	0.0218	0.0268	0.4852	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001		<.0001	0.4269	0.0002	0.2733	0.9003	0.3838	0.7050	0.3241	0.4353
Fibre_CWT	0.20717	0.18293	0.05831	0.45730	0.61343	-0.59879	0.71162	0.70255	0.46536	0.89680	1.00000	0.53293	0.43622	-0.04566	-0.00869	-0.06208	-0.14441	-0.17619	0.12117
	0.1154	0.1655	0.6609	0.0003	<.0001	<.0001	<.0001	<.0001	0.0002	<.0001		<.0001	0.0006	0.7313	0.9479	0.6404	0.2752	0.1819	0.3606
Muhlsteph_Ratio	-0.10656	-0.13220	0.30278	-0.00368	0.23443	-0.20582	-0.21376	-0.22497	-0.49639	0.10540	0.53293	1.00000	0.07872	0.17888	-0.06047	0.09897	-0.22133	-0.13783	0.06430
	0.4218	0.3182	0.0198	0.9779	0.0739	0.1178	0.1040	0.0867	<.0001	0.4269	<.0001		0.5534	0.1752	0.6491	0.4558	0.0921	0.2979	0.6285
TPY	0.39998	0.57486	-0.38389	0.37433	-0.08103	-0.35638	0.43593	0.42832	0.36008	0.46045	0.43622	0.07872	1.00000	-0.68049	-0.05703	0.09576	0.24947	0.17899	-0.20454
	0.0017	<.0001	0.0027	0.0035	0.5418	0.0056	0.0006	0.0007	0.0051	0.0002	0.0006	0.5534		<.0001	0.6679	0.4706	0.0567	0.1750	0.1202
Kappa	-0.29842	-0.72345	0.46634	-0.19495	0.40000	0.10178	-0.20086	-0.20203	-0.23372	-0.14498	-0.04566	0.17888	-0.68049	1.00000	0.03921	-0.04321	-0.47863	-0.39851	0.37604
	0.0217	<.0001	0.0002	0.1390	0.0017	0.4430	0.1272	0.1249	0.0748	0.2733	0.7313	0.1752	<.0001		0.7681	0.7452	0.0001	0.0018	0.0033
Black_Liquor_res	-0.45538	-0.01954	0.31198	0.37050	0.00795	-0.04906	0.02480	0.02154	0.02387	0.01666	-0.00869	-0.06047	-0.05703	0.03921	1.00000	0.01324	-0.14034	-0.16864	0.19078
	0.0003	0.8832	0.0162	0.0039	0.9523	0.7121	0.8521	0.8713	0.8576	0.9003	0.9479	0.6491	0.6679	0.7681		0.9207	0.2891	0.2017	0.1478
HexA	-0.00764	-0.04502	-0.09142	-0.21133	0.10147	-0.11237	-0.15635	-0.14231	-0.15282	-0.11547	-0.06208	0.09897	0.09576	-0.04321	0.01324	1.00000	-0.21429	0.09988	-0.20644
	0.9542	0.7350	0.4911	0.1081	0.4445	0.3968	0.2370	0.2823	0.2479	0.3838	0.6404	0.4558	0.4706	0.7452	0.9207		0.1032	0.4516	0.1167
Glucose	0.16592	0.49223	-0.25200	0.18648	-0.30055	0.07369	0.01926	0.02527	0.08983	-0.05034	-0.14441	-0.22133	0.24947	-0.47863	-0.14034	-0.21429	1.00000	0.81926	-0.72060
	0.2091	<.0001	0.0542	0.1573	0.0207	0.5791	0.8849	0.8493	0.4987	0.7050	0.2752	0.0921	0.0567	0.0001	0.2891	0.1032		<.0001	<.0001
Polysaccharide	0.17153	0.38314	-0.32907	-0.02541	-0.29368	0.11754	-0.09018	-0.08138	-0.03024	-0.13062	-0.17619	-0.13783	0.17899	-0.39851	-0.16864	0.09988	0.81926	1.00000	-0.97101
	0.1939	0.0027	0.0109	0.8485	0.0240	0.3753	0.4970	0.5400	0.8202	0.3241	0.1819	0.2979	0.1750	0.0018	0.2017	0.4516	<.0001		<.0001
Klason_Lignin	-0.19637	-0.34304	0.34705	0.06028	0.24546	-0.09267	0.08683	0.07773	0.04769	0.10351	0.12117	0.06430	-0.20454	0.37604	0.19078	-0.20644	-0.72060	-0.97101	1.00000
Lignin (Insol)	0.1361	0.0078	0.0071	0.6502	0.0610	0.4851	0.5131	0.5584	0.7199	0.4353	0.3606	0.6285	0.1202	0.0033	0.1478	0.1167	<.0001	<.0001	

ANNEXURE 6-2: Correlation analysis associated with Figure 7.

Pearson Correlation Coefficients, N = 59
Prob > |r| under H0: Rho=0

	TPH	MAI	Wood_density	F_Length	F_Coars	F_pop	F_diameter	F_CSA	L_CSA	Fibre_CWT	TPY	Kappa	Drain0	CSF0	Por0	Smooth0	Bright0	Tear0	Tens0	TStiff 0	Burst0	Thick0
TPH	1.00000	0.17691	-0.65844	-0.10091	0.04899	0.03264	0.33855	0.34337	0.35140	0.20717	0.39998	-0.29842	-0.08145	0.28417	0.14573	0.01277	0.42036	0.14769	-0.10565	0.44587	-0.20367	-0.15581
		0.1801	<.0001	0.4470	0.7125	0.8062	0.0087	0.0078	0.0064	0.1154	0.0017	0.0217	0.5397	0.0292	0.2708	0.9235	0.0009	0.2643	0.4258	0.0004	0.1218	0.2386
MAI	0.17691	1.00000	-0.25660	0.43807	-0.05852	-0.30280	0.31591	0.31954	0.31743	0.18293	0.57486	-0.72345	-0.34886	0.36718	-0.11442	0.20510	0.65377	0.57814	-0.07104	0.28247	-0.08084	0.17179
	0.1801		0.0498	0.0005	0.6598	0.0197	0.0148	0.0136	0.0143	0.1655	<.0001	<.0001	0.0068	0.0042	0.3882	0.1192	<.0001	<.0001	0.5929	0.0302	0.5427	0.1933
Wood_density	-0.65844	-0.25660	1.00000	0.15228	0.25939	-0.04482	-0.19340	-0.19931	-0.27516	0.05831	-0.38389	0.46634	-0.06863	-0.26409	-0.09124	0.07340	-0.59238	-0.33246	-0.02814	-0.46189	0.05261	0.20818
	<.0001	0.0498		0.2496	0.0473	0.7361	0.1422	0.1302	0.0349	0.6609	0.0027	0.0002	0.6055	0.0433	0.4919	0.5806	<.0001	0.0101	0.8324	0.0002	0.6923	0.1136
F_Length	-0.10091	0.43807	0.15228	1.00000	0.19342	-0.45311	0.52760	0.51923	0.45734	0.45730	0.37433	-0.19495	-0.36684	0.20444	-0.02942	0.28986	-0.01597	0.25500	0.25704	0.31434	0.20898	0.02744
	0.4470	0.0005	0.2496		0.1422	0.0003	<.0001	<.0001	0.0003	0.0003	0.0035	0.1390	0.0043	0.1204	0.8249	0.0260	0.9044	0.0513	0.0494	0.0153	0.1122	0.8366
F_Coars	0.04899	-0.05852	0.25939	0.19342	1.00000	-0.55060	0.51988	0.52835	0.40476	0.61343	-0.08103	0.40000	-0.17175	0.05523	-0.22732	0.13105	-0.17933	-0.02891	-0.23931	-0.17575	-0.25481	0.24986
	0.7125	0.6598	0.0473	0.1422		<.0001	<.0001	<.0001	0.0015	<.0001	0.5418	0.0017	0.1934	0.6778	0.0834	0.3225	0.1741	0.8279	0.0679	0.1830	0.0515	0.0563
F_pop	0.03264	-0.30280	-0.04482	-0.45311	-0.55060	1.00000	-0.52971	-0.53276	-0.41452	-0.59879	-0.35638	0.10178	0.38986	-0.30867	0.32051	-0.14951	-0.17065	-0.28351	0.16966	-0.10074	0.21126	-0.30089
	0.8062	0.0197	0.7361	0.0003	<.0001		<.0001	<.0001	0.0011	<.0001	0.0056	0.4430	0.0023	0.0174	0.0133	0.2584	0.1963	0.0296	0.1989	0.4478	0.1082	0.0206
F_diameter	0.33855	0.31591	-0.19340	0.52760	0.51988	-0.52971	1.00000	0.99920	0.95198	0.71162	0.43593	-0.20086	-0.17492	0.19480	0.16047	0.19203	0.13893	0.36113	0.17538	0.53208	0.06200	-0.12931
	0.0087	0.0148	0.1422	<.0001	<.0001	<.0001		<.0001	<.0001	<.0001	0.0006	0.1272	0.1851	0.1393	0.2247	0.1451	0.2940	0.0050	0.1840	<.0001	0.6408	0.3290
F_CSA	0.34337	0.31954	-0.19931	0.51923	0.52835	-0.53276	0.99920	1.00000	0.95651	0.70255	0.42832	-0.20203	-0.18004	0.20499	0.15290	0.19105	0.15154	0.36502	0.16823	0.53076	0.05511	-0.12567
	0.0078	0.0136	0.1302	<.0001	<.0001	<.0001	<.0001		<.0001	<.0001	0.0007	0.1249	0.1724	0.1194	0.2476	0.1472	0.2519	0.0045	0.2028	<.0001	0.6785	0.3429
L_CSA	0.35140	0.31743	-0.27516	0.45734	0.40476	-0.41452	0.95198	0.95651	1.00000	0.46536	0.36008	-0.23372	-0.04755	0.11348	0.29339	0.16265	0.17777	0.36423	0.29418	0.57421	0.19144	-0.25498
	0.0064	0.0143	0.0349	0.0003	0.0015	0.0011	<.0001	<.0001		0.0002	0.0051	0.0748	0.7206	0.3921	0.0241	0.2184	0.1780	0.0046	0.0237	<.0001	0.1464	0.0513
Fibre_CWT	0.20717	0.18293	0.05831	0.45730	0.61343	-0.59879	0.71162	0.70255	0.46536	1.00000	0.43622	-0.04566	-0.42328	0.34700	-0.23267	0.17645	0.02633	0.21697	-0.20027	0.23015	-0.29435	0.22116
	0.1154	0.1655	0.6609	0.0003	<.0001	<.0001	<.0001	<.0001	0.0002		0.0006	0.7313	0.0008	0.0071	0.0762	0.1813	0.8431	0.0988	0.1283	0.0795	0.0236	0.0923
TPY	0.39998	0.57486	-0.38389	0.37433	-0.08103	-0.35638	0.43593	0.42832	0.36008	0.43622	1.00000	-0.68049	-0.28833	0.51678	-0.07808	0.11386	0.61435	0.56751	-0.09233	0.62679	-0.17326	0.06631
	0.0017	<.0001	0.0027	0.0035	0.5418	0.0056	0.0006	0.0007	0.0051	0.0006		<.0001	0.0268	<.0001	0.5567	0.3905	<.0001	<.0001	0.4867	<.0001	0.1894	0.6178
Kappa	-0.29842	-0.72345	0.46634	-0.19495	0.40000	0.10178	-0.20086	-0.20203	-0.23372	-0.04566	-0.68049	1.00000	0.22811	-0.46182	0.02557	-0.15353	-0.78752	-0.54094	0.03413	-0.56419	0.06295	0.00733
	0.0217	<.0001	0.0002	0.1390	0.0017	0.4430	0.1272	0.1249	0.0748	0.7313	<.0001		0.0823	0.0002	0.8476	0.2457	<.0001	<.0001	0.7975	<.0001	0.6357	0.9561
Drain0	-0.08145	-0.34886	-0.06863	-0.36684	-0.17175	0.38986	-0.17492	-0.18004	-0.04755	-0.42328	-0.28833	0.22811	1.00000	-0.56341	0.56938	-0.25798	-0.21960	-0.26167	0.39763	-0.03910	0.40331	-0.49396
	0.5397	0.0068	0.6055	0.0043	0.1934	0.0023	0.1851	0.1724	0.7206	0.0008	0.0268	0.0823		<.0001	<.0001	0.0485	0.0947	0.0453	0.0018	0.7687	0.0015	<.0001
CSF0	0.28417	0.36718	-0.26409	0.20444	0.05523	-0.30867	0.19480	0.20499	0.11348	0.34700	0.51678	-0.46182	-0.56341	1.00000	-0.53201	0.20999	0.56409	0.41281	-0.46328	0.29303	-0.53269	0.36171
	0.0292	0.0042	0.0433	0.1204	0.6778	0.0174	0.1393	0.1194	0.3921	0.0071	<.0001	0.0002	<.0001		<.0001	0.1104	<.0001	0.0012	0.0002	0.0243	<.0001	0.0049
Por0	0.14573	-0.11442	-0.09124	-0.02942	-0.22732	0.32051	0.16047	0.15290	0.29339	-0.23267	-0.07808	0.02557	0.56938	-0.53201	1.00000	-0.10691	-0.22463	-0.14042	0.77313	0.33837	0.71524	-0.82621
	0.2708	0.3882	0.4919	0.8249	0.0834	0.0133	0.2247	0.2476	0.0241	0.0762	0.5567	0.8476	<.0001	<.0001		0.4203	0.0872	0.2888	<.0001	0.0088	<.0001	<.0001
Smooth0	0.01277	0.20510	0.07340	0.28986	0.13105	-0.14951	0.19203	0.19105	0.16265	0.17645	0.11386	-0.15353	-0.25798	0.20999	-0.10691	1.00000	0.03419	0.10949	-0.11428	0.06345	-0.05864	0.03820
	0.9235	0.1192	0.5806	0.0260	0.3225	0.2584	0.1451	0.1472	0.2184	0.1813	0.3905	0.2457	0.0485	0.1104	0.4203		0.7971	0.4091	0.3888	0.6331	0.6591	0.7739
Bright0	0.42036	0.65377	-0.59238	-0.01597	-0.17933	-0.17065	0.13893	0.15154	0.17777	0.02633	0.61435	-0.78752	-0.21960	0.56409	-0.22463	0.03419	1.00000	0.55811	-0.26528	0.40181	-0.30329	0.18392
	0.0009	<.0001	<.0001	0.9044	0.1741	0.1963	0.2940	0.2519	0.1780	0.8431	<.0001	<.0001	0.0947	<.0001	0.0872	0.7971		<.0001	0.0423	0.0016	0.0195	0.1632
Tear0	0.14769	0.57814	-0.33246	0.25500	-0.02891	-0.28351	0.36113	0.36502	0.36423	0.21697	0.56751	-0.54094	-0.26167	0.41281	-0.14042	0.10949	0.55811	1.00000	0.04364	0.42774	-0.00606	0.07899
	0.2643	<.0001	0.0101	0.0513	0.8279	0.0296	0.0050	0.0045	0.0046	0.0988	<.0001	<.0001	0.0453	0.0012	0.2888	0.4091	<.0001		0.7428	0.0007	0.9637	0.5521
Tens0	-0.10565	-0.07104	-0.02814	0.25704	-0.23931	0.16966	0.17538	0.16823	0.29418	-0.20027	-0.09233	0.03413	0.39763	-0.46328	0.77313	-0.11428	-0.26528	0.04364	1.00000	0.38042	0.92806	-0.75638
	0.4258	0.5929	0.8324	0.0494	0.0679	0.1989	0.1840	0.2028	0.0237	0.1283	0.4867	0.7975	0.0018	0.0002	<.0001	0.3888	0.0423	0.7428		0.0030	<.0001	<.0001
TStiff 0	0.44587	0.28247	-0.46189	0.31434	-0.17575	-0.10074	0.53208	0.53076	0.57421	0.23015	0.62679	-0.56419	-0.03910	0.29303	0.33837	0.06345	0.40181	0.42774	0.38042	1.00000	0.22168	-0.36627
	0.0004	0.0302	0.0002	0.0153	0.1830	0.4478	<.0001	<.0001	<.0001	0.0795	<.0001	<.0001	0.7687	0.0243	0.0088	0.6331	0.0016	0.0007	0.0030		0.0915	0.0043
Burst0	-0.20367	-0.08084	0.05261	0.20898	-0.25481	0.21126	0.06200	0.05511	0.19144	-0.29435	-0.17326	0.06295	0.40331	-0.53269	0.71524	-0.05864	-0.30329	-0.00606	0.92806	0.22168	1.00000	-0.70258
	0.1218	0.5427	0.6923	0.1122	0.0515	0.1082	0.6408	0.6785	0.1464	0.0236	0.1894	0.6357	0.0015	<.0001	<.0001	0.6591	0.0195	0.9637	<.0001	0.0915		<.0001
Thick0	-0.15581	0.17179	0.20818	0.02744	0.24986	-0.30089	-0.12931	-0.12567	-0.25498	0.22116	0.06631	0.00733	-0.49396	0.36171	-0.82621	0.03820	0.18392	0.07899	-0.75638	-0.36627	-0.70258	1.00000
	0.2386	0.1933	0.1136	0.8366	0.0563	0.0206	0.3290	0.3429	0.0513	0.0923	0.6178	0.9561	<.0001	0.0049	<.0001	0.7739	0.1632	0.5521	<.0001	0.0043	<.0001	

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Abstract

Forestry decision system methodologies were evaluated to assist with the compilation of a fibre productivity index. Much work in the literature has been done to demonstrate decision tools available in the industry, such as green productivity, life cycle analysis, multi criteria decision analysis, Malmquist index and stochastic frontier analysis, to name a few. It was decided that the approach to measure gains achieved from a forest relative to the population mean, for example the mean wood density in a breeding population, described the change in productivity the best. Demonstrated in this chapter is the simplistic way of the determination of fibre throughput from a forest into a mill, however, as indicated by Lopez et al. (2009) and Hodge (2011), the accurate way to use indicators required economic weights to be assigned to them. A financial sensitivity analysis method developed by Turner et al. (2005) was used to assign economic weights to evaluate the impacts of properties on the mill throughput. For any pulp mill, when the throughput or demand is increased, a bottleneck appears which puts a constraint on manufacturing. It was shown through this sensitivity analysis for a 2.5 million tons size intake pulp mill, that cooking time had 3.8 times higher impact on profitability than wood density had in a situation where the recovery boiler was constrained. If the cooking time needed to increase by 5 % (from 140 to 147 minutes) due to slow throughput of the recovery boiler, it was shown that the profitability of the mill was reduced by 32 % (from R512m to R345m). Moreover, an increase of 5 % in wood density could increase the profit by R42m (8.4 %). Fibre productivity, calculated as the product of mean annual increment, basic wood density and pulp yield (PY) resulting in the highest value of 11,282 tons fibre ha^{-1} yr^{-1} produced in the 2336 TPH planting density. Due to the scale of economics of growing timber at the range between 6809 and 161 TPH, the delivered cost of timber was calculated for each planting density. The financial model, with this and other inputs, assisted to determine the profit/loss of a tonne of pulp produced.

The index derived through this work, termed the Fibre Productivity Index at the *Mill* (FPMill) is suggested as a product between fibre productivity and the profit/loss made on each tonne of pulp produced. The planting density at 1368 TPH had the highest calculated FPMill or, R9,297.92 pulp produced ha^{-1} yr^{-1}. It is anticipated that this index can be used to a) plan the delivery of consistent quality wood to the pulp mill and b) to differentially pay suppliers of timber for the inherent wood quality and not for mass of timber delivered.

Keywords: Fibre productivity index, Kraft mill, *E. grandis* clones, economic weights, financial sensitivity

7.1 INTRODUCTION

To manufacture products with greater added value is increasingly viewed as a strategic goal of forest products industries. Added value is defined as the difference in economic value between the physical inputs and outputs of a production process, and is generally analysed at the company or national economy level.

Substantial improvements in management practices must be made to increase forest volume and pulp yields. One way of increasing yields per unit area of land is to increase tree volume by enhancing growth rate, or by increasing wood density, often through genetic selection.

The net effect of such enhancements is most often translated into economic terms, in particular the increased efficiency of genetic selection. The combination of economics and genetics to describe financial gains from fibre yield, dominates literature with regards to increased productivity throughput in the production environment, e.g. a Kraft pulp mill (Borralho et al. 1993, Lowe et al. 1999, Lopez et al. 2009 and Hodge 2011). Most often the assignment of economic weights to properties such as forest volume (Mean Annual Increment; MAI) in $m^3\ ha^{-1} yr^{-1}$, basic wood density in kg m^{-3} and pulp yield in %. Bridgewater et al. (1983) defines economic weights as the value of a unit change in a property, e.g. monetary value change, measured in Rand/cents, per increase in 1 m^3 of wood per hectare. In order for economic weights to be successfully applied, the cost structure of the production of wood and pulp must be known; the accuracy of the use of economic weights depends on the availability and accuracy of costs of i) plantation establishment, ii) management, iii) harvesting and transport, and iv) mill production costs.

The objective of this study was to evaluate the indicators or parameters that could contribute to the components of a fibre productivity index, to use the data and models from the Nelder materials study to predict the indicator properties and to simulate a testing scenario by applying the fibre productivity index to the Nelder data. The outcome will be proposed as an index suitable to categorise stand density treatments into technical and economical classes for the consideration of a forestry manager.

7.2 EVALUATION OF PRODUCTIVITY MANAGEMENT DECISION METHODOLOGY

Following is a summary of a number of productivity indices used in industries where efficiency or change is monitored. Much work has been done to ensure environmentally sound production processes (Green Productivity - GP), to complete life cycle assessment(LCA) on products from a multiple of manufacturing backgrounds, facilitate multi-criteria decision analysis (MCDA) especially on the interaction between product, environment and social aspects, the facilitation of complex decision making requirements for example in complex land use scenarios in natural forests, the process of analytical hierarchy processes (AHP) with all of these integrated to some level with the Malmquist Index or using techniques such as stochastic frontier production function (SFPF). Most of these tools as described in literature consider production or technical efficiency change on the global level and on a long term basis. Moreover, none of the techniques considered from literature, focuses on wood material use efficiency, e.g. fibre optimisation, and hence will not be considered to assist in the compilation of a vertically integrated fibre optimisation index. The exception is the Gains-approach as described by Borralho et al. (1993).

7.2.1 Green Productivity

The growing outcry for environmentally sound products and processes poses a challenge to industries that are trying to address environmental issues in addition to quality and productivity concerns to achieve competitive advantage. Many concepts and strategies of manufacturing performance have evolved over time with the increased importance of environmental and resource concerns in product development, process technology, and systems management. For inclusivity of the environmental economy, the term ‘green productivity’ (GP) was adopted (Pineda-Henson et al. 2004) and used for brevity to refer to the combined concept of environmental and productivity performance of manufacturing processes. Based on the experience of Pineda-Henson et al. (2004) in an Asian production and packaging sector, environmental protection measures have to be linked to productivity and quality improvements to gain acceptability and to rationalize their implementation. This gave rise to the new paradigm called ‘green productivity’ in which environmental protection provides the foundation for sustainable development. Furthermore, productivity enhancement serves as the framework for continuous improvement (Madu et al. 2002). Green productivity emerged gradually from the basic aim of increasing production with the minimum utilization of raw materials and resources to the application of appropriate technologies and sound management techniques in order to produce environmentally compatible goods for enhanced productivity. The GP model provides an open framework that can incorporate several strategies that leverage the benefits of the various concepts of sustainable manufacturing like resource productivity, cleaner production, pollution prevention and eco-efficiency. It is an innovative way of integrating the perceptions of stakeholders, decision makers and experts on environmental and productivity issues in the design of products and manufacturing processes.

7.2.2 Life Cycle Assessment

The life cycle or 'cradle-to-grave' concept dominates many approaches in assessing and improving environmental performance of products and processes like design for environment, cleaner production and total quality environmental management (Pineda-Henson et al. 2004). Life cycle assessment (LCA) as embodied in ISO 14040, and is defined as a technique for assessing the environmental aspects and potential impacts associated with a product throughout its life cycle (i.e. cradle-to-grave) from raw materials acquisition through production, use, and its disposal (ISO 1997). LCA is implemented as a system analysis of industry where the system begins with all the raw materials taken from the environment and ends with the outputs released to the environment (Besnainou and Coulon 1996).

7.2.3 Multi-Criteria Decision Analysis

The need for participation and communication in forest management decision processes, such as regime selection (e.g. planting density options), strongly relates to aspects of decision analysis. Decision-making not only requires quantitative facts and data but also information about values, as well as a process for integration of management and productivity for example (Gregory et al. 2006). Facilitating such integration, Multi-criteria Decision Analysis (MCDA) comprises a set of methods which are specifically designed for: (i) taking explicit account of multiple, conflicting indicators, criteria or objectives, (ii) structuring a decision problem, (iii) providing a formal model for such problems, and (iv) offering a process that leads to rational, justifiable, and explainable decisions (Pukkala 2006).

Multi-criteria decision-analysis methods have been applied in strategic, tactical and operational forest planning and management (Pukkala 2006). In particular, MCDA techniques have been adapted to structure and implement indicator-based assessments of Sustainable Forest Management (Wolfslehner et al. 2005). MCDA methods are used to accommodate complexity and enhance structural understanding in indicator frameworks. They create combined and preference-based rankings for management alternatives while analysing the trade-offs among indicators. MCDA is predominantly decision analysis based and as such not suitable to evaluate quantitative indicators of process and product throughput to compile an optimisation index.

7.2.4 Analytic Hierarchy Process

Forest management decisions are often characterised by complexity, irreversibility and uncertainty. Much of the complexity arises from the multiple-use nature of forest goods and services, difficulty in monetary valuation of ecological services and the involvement of numerous stakeholders (Ananda and Herath 2003). Under these circumstances, conventional methods such as cost-benefit analysis are ill-suited to evaluate forest decisions. The Analytic Hierarchy Process (AHP), can be useful in regional forest planning as it can accommodate conflicting, multidimensional and incomparable set of objectives. The decision analysis tool, AHP, was originally developed by Saaty (1977) and Saaty (1980) as a method for obtaining and quantifying preferences. AHP is a general theory of measurement based on mathematical and psychological foundations. It has been found to be a useful decision-analysis technique and it has been applied in cases dealing with strategic planning, including marketing applications, design and evaluation of business and corporate strategy (Wind 1987). AHP is a widely used method also in forestry and forest management planning. A list of applications from a variety of areas of decision making is reported (Zahedi 1986). Forest certification has rapidly become a major topic in the debate dealing with the issue of how to improve the ways in which the world's forests can be sustainably managed and the method has been viewed as reasonably objective (Mikkila et al. 2005).

The AHP provides a systematic method for comparison and weighting of these multiple criteria and alternatives by decision-makers. The steps in the AHP method are as follows (Saaty 1980): (i) structure a problem in the form of a hierarchy with objectives, criteria and alternatives, (ii) elicit judgments regarding a decision-maker's relative preferences for criteria and alternatives and represent those judgments with numbers, (iii) use the numbers to calculate the priorities of the criteria and alternatives in the hierarchy and (iv) complete the synthesis of these results to determine the 'best' alternative. The AHP is also useful when many interests are involved and a number of people participate in the selection process (Saaty, 1980) and as such is not the ideal method to determine the input values of a fibre optimisation indicator.

7.2.5 Malmquist Total Factor Productivity index

The Malmquist Total Factor Productivity (TFP) index methodology is popular amongst resource economists because it does not need costs of the input factors to calculate the weights of individual inputs. The Malmquist TFP index can be defined as a measurement of the productivity change between two data points achieved by calculating the ratio of the distances of each data point in relation to a common technology (Coelli et al. 1998). The Malmquist index has been used widely in agriculture (Fulginiti and Perrin 1997) and other natural resource environments, e.g. the investigation of global carbon emissions (Zhou et al. 2010).

However, most of the studies used long term data (Hseu and Shang 2005) and were often spread geographically over a continent, e.g. involving 18 developing countries in the case of Fulginiti and Perrin (1997) when they investigated the change in agricultural productivity. In most instances the method involves global indexing, e.g. Pastor and Knox-Lovell (2005) evaluating trends in the global economy and Siry and Newman (2001) evaluating the forest resources on basis of productivity and technical efficiency of the whole of Poland. The Malmquist index does not have a local empitus and was not considered for developing an index for the forest-pulp-paper value chain in Mondi Forests.

7.2.6 Stochastic Frontier Analysis

Much work has been done by Helvoight and Adams (2009) to demonstrate the use of the stochastic frontier production function (SFPF) to estimate technical change, efficiency change, and productivity growth for the Northwest sawmill industry. SFPF allows the direct estimation of technical efficiency at a point in time, as well as technical and efficiency change through time. By definition (Helvoight and Adams 2009), technical efficiency is a measure of a production unit operations relative to its competitors and can, e.g. a pulp mill be regarded as technically efficient if it operates close or above the frontier, or if it operates below the frontier, regarded as having some degree of technical inefficiency. Although this approach is suitable to evaluate a whole industry, especially over a number of years (decades) on basis of its productivity growth, technical change and other economic measures as indicated by (Siry and Newman 2001), it does not focus on material use efficiency, e.g. fibre optimisation and hence will not be considered to assist in the compilation of a vertically integrated fibre optimisation index.

7.2.7 The Gains approach

Most often on the operational level, to describe improvements in yield, density or product throughput, the approach of describing *gains* are followed (Borralho et al. 1993, Lopez et al. 2009 and Hodge 2011). These are most frequently linked to the genetic improvement of trees, however, it was shown by du Toit et al. (2010) that the gains of good silviculture (especially improved stand density) together with genetics, species choice and wood density, is measurable and additive. The gains approach is based on the estimation of economic weights which considers plantation establishment, management thereof, harvesting and transport costs and costs of production at the pulp mill. In a landmark study by Borralho et al. (1993), conducted in Portugal, it was demonstrated that selection of best regime options based on indices which included volume, wood density and pulp yield, gave the greatest expected gains in the breeding or silvicultural objectives and costs savings per ton of pulp produced from eucalyptus species.

The methods that were described above all have low focus on material optimisation, they address environmental processes such as the green productivity or life cycle analysis, they assist in solving decision making problems and almost all require inputs on the global scale. This clearly would not suffice for the purpose of developing a fibre productivity index and since the "Gains-approach" with its indicators as suggested by Borralho et al. (1993) has local consideration (material-process-product value chain), the ease and relative low cost of measurement as indicated in Chapters 5 and 6, have high correlation values with product quality (measured in terms of physical and chemical properties), can be predicted (NIR) or modelled (regression, PCA, CVA) and evaluated, this approach is therefore selected to describe and develop a fibre productivity index.

7.3 GAINS-INDEX FOR A FORESTRY-PULP-PAPER VALUE CHAIN

7.3.1 Fibre gain

A definite goal of a modern forest research program is to produce more value for the business. This is achieved with elements and combinations of a tree breeding program, effective silviculture (e.g. forest nutrition and vegetation management), efficient forest management regimes (e.g. manipulation of planting density and rotation age) and sound harvesting and transport practice (e.g. minimum timber damage and moisture control, phasing). In a vertically integrated forestry-pulp-paper business enterprise like Mondi South African Division (MSAD), this goal translates into the production of more pulped fibre per unit area (hectare). Theoretically this goal can be achieved through (i) producing more timber volume per hectare (ii) more wood (cellulose) per volume and/or, (iii) more fibre yield per unit of wood (Hodge 2011). The available fibre yield (pulp fibre produced per hectare) is equal to the product of volume, density and pulp yield and can be calculated (in kg pulp fibre produced ha^{-1} yr^{-1}). These variables are analogous to indicators in the index and defined in Equation 1:

$$Pulp\ Fibre\ ha^{-1} = Volume\left(\frac{m^3}{ha}\right) \cdot Wood\ density\left(\frac{kg}{m^3}\right) \cdot Pulp\ yield\left(\frac{kg_{pulp}}{kg_{wood}}\right)$$

Equation 1

To illustrate fibre/ha gain, the following examples are used:

- Assume a base scenario of Mean Annual Increment (MAI) = 45 m^3 $ha^{-1}yr^{-1}$, wood density = 490 kg m^{-3} and pulp yield = 50 %; then fibre produced = 11,025 kg $ha^{-1}yr^{-1}$.

  - Fibre ha^{-1} = 45 m^3 $ha^{-1}yr^{-1}$ · 490 kg m^{-3} · 0.5 kg_{pulp} kg_{wood}^{-1}
    = 11,025 kg $ha^{-1}yr^{-1}$

- Assume a volume gain ha^{-1} of 10 % through a forest management intervention, e.g. improved breeding selection efficiency, optimum spacing regime, improved forest nutrition, etc. leading to a 10 % gain in both density and pulp yield. The base for each of the three properties in the "gains" calculation changes to MAI = 49.5 m^3 $ha^{-1}yr^{-1}$ (45 · 1.1), wood density = 539 kg m^{-3} (490 · 1.1) and pulp yield = 55 % (50 · 1.1) respectively; then fibre produced is 14,674 kg $ha^{-1}an^{-1}$, which constitutes a 33 % fibre gain ha^{-1} (FG).

  - Fibre ha^{-1} = 1.1(Volume) · 1.1(density) · 1.1(pulp yield)
    = 1.1(45 m^3 $ha^{-1}yr^{-1}$) · 1.1(490 kg m^{-3}) · 1.1(0.5 kg_{pulp} kg_{wood}^{-1})
    = 49.5 m^3 $ha^{-1}yr^{-1}$ · 539 kg m^{-3} · 0.55 kg_{pulp} kg_{wood}^{-1}
    = 14,675 kg $ha^{-1}yr^{-1}$

Applying a 10 % improvement in each component, FG can be calculate in two ways:

- FG = 1.10 · 1.10 · 1.10 = 1.33, or ,
- FG = (14,675-11,025)/ 11,025 = 0.33

In both examples the resultant Fibre Gain (FG) = 33 %

It is noted that comparing both scenarios, the FG is 33 % by using the raw values to calculate kilograms of fibre produced per hectare or using the product of the individual gain percentages directly.

An important consideration of the two scenarios was that the economic weights given to each of the three components in the equation were chosen to be the same (10 % improvement); the 33 % FG is equally attributable to a 10 % gain in MAI, 10 % in wood density and 10 % in pulp yield. Put differently, the value to the company could have been the same if the 33 % gain was made in volume growth (MAI) only, while no resultant improvements in wood density and pulp yield materialised. Wood density and pulp yield can be inter-dependent and at the same time independent from volume, it is thus a more complex calculation and an economic weight approach is required to make optimal decisions for the selection of, e.g. superior genotypes or optimum silvicultural regimes.

The economic value in this context is defined as the combination of technical and business aspects of producing wood pulp, it thus illustrates the ability of an enterprise to do something technically-correct and cost-effectively at the same time. The combined result is measured as a profit or loss.

7.3.2 Economic weights

Whether developing a selection index for genetic improvement or developing an index to describe fibre productivity in a value chain, to assign an economic weight to a variable is most often understood as a linear function of different properties used to rank various forestry regimes for selection (Hodge 2011). In the case of a fibre productivity index, that accounts for different economic weights assigned to indicators and that combines volume, density and pulp yield, an economic index would have the following form:

$$W = a_V V + a_d D + a_p P \qquad \text{Equation 2}$$

where:

W = aggregate value,

V = volume value,

D = density value,

P = pulp yield value, and

a_i = economic weight for the variable considered in an index.

Conceptually, the equation is straightforward, however, it gets complicated when the equation is populated with actual values for each of the indicators. Typically change in MAI-values can result in a positive or negative gain value when the age at a given planting density is altered (Figure 7-1); observing a rise in MAI to age 8 and then a decline in MAI towards age 10. Moreover, the indicator values (volume, density and pulp yield) can have a mean gain of zero, i.e. there will be positive and negative values expressed as gain, or deviations from the population mean for a given trait, e.g. wood density. Typically, genetic gains in a breeding population aggregates around zero, i.e. with as many positive gains as negative gains.

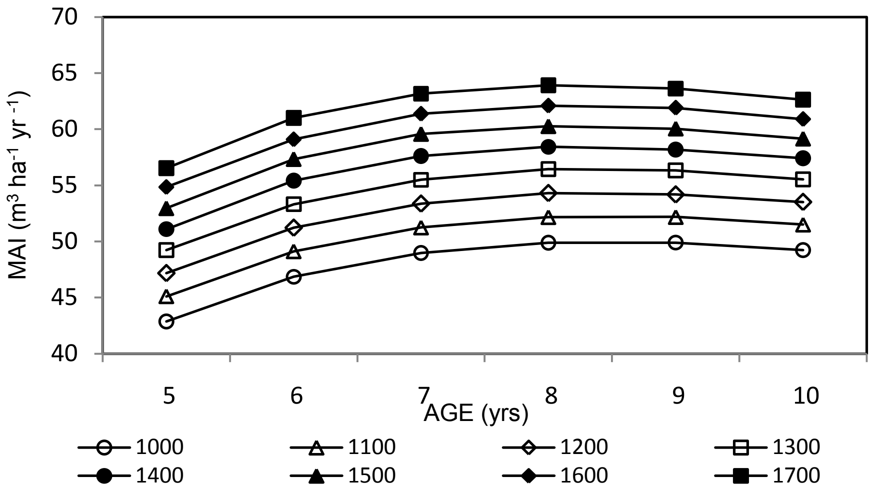

Figure 7-1: Mean annual increment development for planting densities typically found in the commercial range plotted against age.

Technically, the economic weights, a_i, are defined as the relative value of one unit increase in i^{th} indicator, holding other values constant. The units on the economic weights must match the units on the indicator values, otherwise the equation will return nonsensical results (Hodge 2011). For illustration, the result of a forest management intervention, e.g. changing planting density is considered. Characteristically volume values are calculated in $m^3\ ha^{-1}yr^{-1}$ unit gain, density values in units of kg m^{-3}, and pulp yield values in units of percent pulp yield. A planting density treatment with a pulp yield value of +1.0 in the equation (measured as kg pulp produced per kg wood), will have a PY of 51 % relative to a population mean of 50 %). For the fibre productivity equation with the units of measurement added, Equation 2 is transformed into (Equation 3):

$$Rc(W) = a_v\left(\frac{Rc}{m^3ha^{-1}yr^{-1}}\right)\cdot\frac{V(\%)}{1} + a_d\left(\frac{Rc}{kg\ m^{-3}}\right)\cdot\frac{D(kg\ m^{-3})}{1} + a_y\left(\frac{Rc}{\%}\right)\cdot\frac{P(\%)}{1}$$

Equation 3

where:

Rc	=	Aggregated value (W) in South African Rand,
V	=	volume value expressed in MAI (m^3 ha^{-1} yr^{-1}),
D	=	density value expressed in basic density (kg m^{-3},),

P = pulp yield value expressed in pulp yield (%), and

a_i = economic weight for the particular property.

It is described by Hodge (2011) that the challenge is the assigning of appropriate economic weights to the different properties. The question that arises is: What is the relative economic value of an increase in volume growth (expressed in %, or m^3 per tree, or, m^3 ha^{-1} $year^{-1}$) compared to an increase in density of 1 kg m^{-3} or an increase in pulp yield from 50 % to 51 %? To calculate appropriate weights, the costs for all forest operations need to be known including nursery, planting and maintenance, harvesting and transport to the mill, processing and manufacturing and price earned for the final product.

7.3.3 Recent work on economic weights

There have been a number of papers on economic weights and breeding objectives for eucalyptus pulpwood production published in recent years (Aubry et al. 1998), most with Nuno Borralho as one of the authors (See Borralho et al. 1993). A recent publication by Lopez et al. (2009) looked at the relative values of different *Eucalyptus* wood properties for a Brazilian pulp mill example. Essentially, the paper attempted to establish the economic values on gains (or reduction) in tree volume growth, wood density and lignin (which is inversely related to pulp yield) for a pulp mill, accounting for all forestry, harvesting, and mill costs. In a Kraft pulp mill, depending on the specific manufacturing process, one, or more, of the digester, recovery boiler or pulp dryer often is constrained when an increased throughput is required. It was shown by Lopez et al. (2009) that *Eucalyptus*-clones with the lowest mean annual increment, the lowest density and the lowest pulp yield would be the worst economic performers, and clones with the highest values for all these properties would be the best economic performers, when profitability is used as the measure. The situation is not that obvious when you have clones with high values for some properties and low values for other properties, or clones with intermediate values for all the properties. There might be cases when there is a clone with the highest pulp yield and lowest wood density as the best economic performer. It is possible that a clone with very high wood density, moderate pulp yield and low volume growth could also be the best financial performer.

When a sensitivity analysis was done by Lopez (2009), varying one of three components (volume, density and lignin) in the aggregated value equation (Equation 3) while keeping the values of the other two components constant, the economic impact may be very large, depending on the pulp mill constraint in the manufacturing process. In other words, the proper economic weight of the indicators in the selection of clones depends on the manufacturing constraint. For mills where the recovery boiler was the constraint, the most important factor was wood or lignin content. Fibre gains from decreasing wood lignin and increasing pulp yield at the same time were approximately 3.4 times as valuable as the same fibre gain from growth.

Economic weights in breeding objectives have traditionally been derived using profit equations or bio-economic models to study the effect of genetic changes on profit. In the planting density experiment, economic weights will be determined for indicators of productivity throughput by making use of financial analysis.

7.4 GAINS IN *EUCALYPTUS GRANDIS* CLONES IN A PLANTING DENSITY EXPERIMENT

The approach followed in this study to derive the economic weights and populate a fibre productivity index, is summarised as follows:

- Calculate volume and mean annual increment by making use of models developed in Chapter 4.
- Determine basic wood density and pulp yield making use of regression models developed in Chapters 5 and 6.
- Calculate the fibre productivity index.
- Carry out an integrated financial analysis to determine the profit/loss per ton of pulp produced. Inherent to this process is the calculation of different impacts (economic weights) on the aggregated value of the gain of the various planting density treatments used in the Nelder 1a experiment.
- Determine the differential cost of growing and delivery of wood grown under different planting density regimes.
- The suggested fibre productivity index at the mill will be populated by the multiplication of the fibre productivity index with the profit/loss per ton of pulp produced per hectare per annum.

7.4.1 Forest yield

Mean Annual Increment (MAI; $m^3\ ha^{-1}\ yr^{-1}$) was modelled from the Basal Area model developed in Chapter 4 and described by du Plessis and Kotze (2011). Volume was determined by i) calculating DBH from the basal area ($m^2\ ha^{-1}$) values and ii) by using the MMRC *E. grandis* volume model as parameterised by Chiswell (1998) for *E. grandis* plantations in the Mpumalanga province of South Africa. The models are shown below:

Basal area

$$\ln(\mathrm{BA}_1) = \beta_0 + \beta_1 \cdot \frac{1}{Age_1} + \beta_2 \ln(TPH) + \beta_3 \cdot \ln(HD_1) + \beta_4 \cdot \frac{\ln(TPH_1)}{Age_1} + \beta_5 \cdot \frac{\ln(HD_1)}{Age_1}$$

where:

BA_1 is the predicted basal area per hectare ($m^2\ ha^{-1}$) at Age_1,

HD_1 is the predicted dominant height (m) at Age_1,

$ß_1$ to $ß_5$ are estimated parameters,

$\beta_0 = -3.8246$, $\beta_1 = -7.4535$, $\beta_2 = 0.3798$, $\beta_3 = 1.3362$, $\beta_4 = 0.7181$, $\beta_5 = 0.9181$

(du Plessis and Kotze, 2011)

Volume

The segmented polynomial Volume (V_t) equation as suggested by Max and Burkhart (1976) and parameterised by Chiswell (1998) was applied as indicated in the following equations:

$$V_t = \left(\frac{\pi}{40000}\right) \cdot k \cdot DBH^2 \cdot HD$$

where:

$$k = \left(\frac{\beta_1}{3} + \frac{\beta_0}{2}\right) - (\beta_0 + \beta_1) + \left(\frac{\beta_2}{3}\right) \cdot a_1^3 + \left(\frac{\beta_3}{3}\right) \cdot a_2^3$$

where:

$a_1 = \beta_4$; $a_2 = \beta_5$, and $\beta_0 = -3.2510$, $\beta_1 = 1.5295$, $\beta_2 = -1.3530$, $\beta_3 = 36.6070$, $\beta_4 = 0.7909$, $\beta_5 = 0.0838$ (Chiswell, 1998)

7.4.2 Pulp yield

Pulp yield (PY) was predicted with the model developed in Chapter 6. The basic form was a 2nd order polynomial as shown:

$$PY = \beta_1 \cdot TPH^2 + \beta_2 \cdot TPH + \beta_3$$

where:

$\beta_1 = -1.9E-7$, $\beta_2 = 0.0016$, $\beta_3 = 51.96$

The model was applied to a series of stand densities as indicated in Table 7-1.

7.4.3 Basic wood density

Basic wood density was predicted with the power function developed in Chapter 6 and given below:

$$WD = \beta_1 \times TPH^{\beta_2}$$

where:

$\beta 1 = 752.80$, $\beta_2 = -0.0663$

The volume, pulp yield and wood density models were applied to a series of stand densities with the predicted values shown in Table 7-1. The fibre (pulp) in kg produced per hectare as calculated by using Equation 2, is found in Table 7-1.

Table 7-1: Modelled indicator properties of *E. grandis* at various planting densities.

TPH	6 809	3 988	2 336	1 368	801	469	275	161	Average
MAI $m^3 ha^{-1} yr^{-1}$	38.88	43.59	45.85	42.55	34.92	29.54	24.27	20.11	34.96
% PY	54.05	55.32	54.66	53.79	53.12	52.67	52.39	52.21	53.53
Density kg m^{-3}	419.32	434.46	450.14	466.40	483.25	500.70	518.74	537.49	476.31
Fibre kg $ha^{-1} yr^{-1}$	8 811	10 477	11 282	10 675	8 964	7 791	6 594	5 644	8 914

Noticeable is the ranking change in stand density treatments when the product of MAI, density and pulp yield is calculated. The highest fibre production was 11 282 kg ha^{-1} yr^{-1} which is in a stand density of 2236 TPH at planting.

The data from Table 7-1 is displayed graphically in Figure 7-2 and is discussed below:

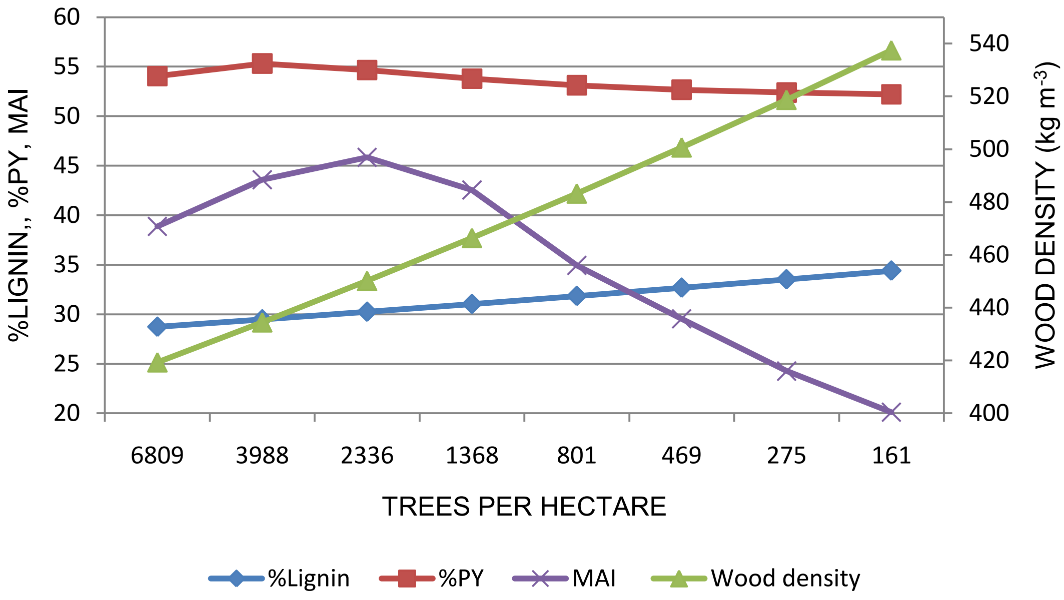

Figure 7-2: Variation in lignin content, pulp yield, MAI and wood density for eight selected planting density treatments.

It is observed from Figure 7-2 that pulp yield declines steadily from high to low planting density, at the same time lignin content is increasing. The inverse relationship is consistent with the correlation analyses conducted in Chapter 5 ($r = -0.72$, $p < 0.0001$). The MAI follows a typical pattern for stand density (Clutter et al. 1983); MAI increases steadily to *c*. 2336 TPH and thereafter declines rapidly. Wood density increases sharply towards low planting density ($r = -0.69$, $p < 0.0001$). Each planting density treatment showed a mixture of characteristics, making the prediction of its financial superiority difficult without undertaking a totally integrated forest-pulp mill analysis.

7.5 INTEGRATED FINANCIAL ANALYSIS

The strategy of any pulp mill to add more value to the resource should be to focus on the most important parameters driving profitability in the pulp mill. This requires *inter alia* the assessment of which wood or pulp properties are of greatest value and/or economic impact. As part of the process a basic spreadsheet-based model was developed by the CSIR Eucalypt Cooperative to investigate economic scenarios (Turner et al. 2005).

7.5.1 A Kraft pulp mill model

The cost of capital employed is an essential measure in the pulp and paper industry, and to maximise the return thereon, pulp mills need to maximise throughput (Diesen 1998). The Kraft pulp mill model explores scenarios in which wood properties were varied to allow an assessment of economic impact on a green fields mill, i.e. a new mill with appropriate levels of capital investment. The following assumptions were made with the design of the financial model:

- The model takes in account all fixed cost elements (cost of capital, infrastructure, salaries, etc.) and variable costs, mainly process costs such as chemicals, utilities (water and electricity), and very important - the cost of wood.
- The model assumes 50 % pulp yield from the tonnage to determine chemical costs and utilities. When pulp yield exceeds 50 %, the relative costs of pulp production is reduced, also the fixed costs allotment to a ton of pulp reduces when the pulp yield increases; more pulp is produced from the same fixed cost element. An increase in density would also have an effect on the fixed costs per ton produced as these costs are based upon volume of wood processed. Higher density wood would also increase the total amount of pulp that the mill could process leading to a reduction in fixed costs per ton of pulp produced.
- Along with pulp yield, one of the important variables that has been included is rate of delignification. The base line assumption is that cooking time is 140 minutes (once the digester is loaded). If the cooking time is shorter than this it would mean that a greater number of cooks would be possible for the same period, thus increasing the productivity (throughput) of the mill. This increased productivity would result with the same fixed overhead costs thus reducing the fixed costs per ton of pulp produced (Turner et al. 2005).
- The model requires an input cost of timber, however, in the planting density experiment with the range of densities between 6809 and 161 TPH, it is clear that the cost of timber varies because of different input costs discounted over time. A Mondi SAD proprietary spreadsheet model was used to calculate delivered cost of timber per planting density. Silviculture input costs (establishment, vegetation management, etc.) and harvesting costs (felling and loading) varied over stand densities. Moreover, the area of land required to sustain a pulp mill with 2,5 million tonnes intake per annum for the different stand densities varied considerably, hence fixed plantation costs were adjusted accordingly and delivered cost to the mill are displayed in Table 7-2.

Table 7-2: Delivered cost per ton of timber calculated per planting density treatment.

TPH	**6 809**	**3 988**	**2 336**	**1 368**	**801**	**469**	**275**	**161**
Delivered cost to mill (R ton^{-1})	R757.76	R504.53	R494.40	R378.07	R422.10	R430.53	R482.06	R514.44

Shown in Table 7-3 are the costs and parameters associated with the growing and production of timber in an integrated forest company like Mondi SAD.

Table 7-3: Input parameters and set values to the financial analysis model.

Parameter / Assumption	Unit of measure	Base
Average distance to mill	km	350
Annual incoming volume of timber	m^3 $year^{-1}$	2 500 000
Chipper efficiency	Available %	98 %
Delivered cost of timber	R ton^{-1}	R variable
Pulp price	R ton^{-1}	R 4 900
Estimated fixed costs	R ton^{-1}	R 1 250
Estimated variable costs	R ton^{-1}	R 500
Interest rate (prime)	%	10.0 %
Average moisture loss	%	35 %

Following from this input, in Table 7-4, a cost analysis for the manufacturing of pulp of stand density treatment for a baseline case is shown. The "base line-case" that was selected incorporated the properties for a 801 TPH stand (Table 7-1) with a wood density of 483.25 kg m^{-3} and 53.12 % pulp yield when pulped at 140 °C to a set kappa number and with active alkali consumption of no less than 80 %. The delivered cost per ton was R422.10. The moisture content was set at 35 % at roadside and was used to calculate the mass of wood consumed in tonnes per annum.

Table 7-4: Stand density base line case modelled manufacturing cost analysis based on wood properties and forest growth volume with a required profit to total cost ratio of 19.9 %.

Cost element	Unit of measure	Base	% of total cost
Relative timber cost	R ton^{-1}1 of pulp	R 795	19.5
Adjusted fixed costs	R $ton^{-1}$of pulp	R 1 250	30.6
Adjusted variable costs	R ton^{-1} of pulp	R 500	12.2
Transport cost (product)	R $ton^{-1}$of a.d. pulp	R 447	10.9
Interest cost	R ton^{-1}1 of pulp	R 1 093	26.8
Total cost	R $ton^{-1}$of pulp	R 4 085	100.0
Profit/ (Loss)	R $ton^{-1}$of pulp	R 815	19.9

Wood cost is still an advantage for South African pulp manufacturers. However, it does account for 20 % of the cost of manufacturing as seen in Table 7-4. It is further observed from

Table 7-4 that adjusted fixed costs, which encapsulates overheads and other costs regardless of operation of the pulp mill, accounts for 30.6 % of total wood cost, a function of the cost of new technology in the South African pulp industry. Fixed costs are assumed to decrease per ton of pulp produced, when throughput increases. Variable costs are all those costs associated with the production of pulp and increases when more timber is pulped. The profit realizable is R815.03 per air dry (ad) ton pulp produced. Profit/loss per ton is calculated by subtracting the sum of all costs from the international pulp price in the local currency.

7.5.2 Trends associated with this model

In any pulp mill, with increased throughput of volume of wood, or a significant change in wood properties, at least one of the main process components can become a limiting factor. In a Kraft pulp mill this is most often the recovery boiler, the volumetric feeding capacity into the digester or capacity of the pulp dryer that becomes limiting. The mill sensitivity model (Turner et al. 2005) allows to test for the sensitivity of four parameters i) pulp yield, ii) density, iii) cooking time and, iv) active alkali consumption. It is assumed that the pulp dryer at this point is not a constraint. A scenario of limiting recovery boiler capacity and volumetric feed rate constraints at the Mondi SAD Richard's Bay mill was investigated further, assuming that the capacity of the pulp drier could not be constrained in this example.

7.5.2.1 Recovery boiler capacity

Recovery boiler capacity is often constrained by hearth heat release, expressed as Gj m^{-2} hearth cross sectional area. Hearth heat release can be affected by the ability to combust organic materials fired at 75-80 % black liquor solids content, the total black liquor solids content throughput per hour or inadequate steam flow (Lopez et al. 2009). If the baseline conditions of 801 TPH are used again, as explained in Table 7-3, (pulp yield 53.21 %; wood density 483.25 kg m^{-3}; cooking time 140 minutes; AA consumption of 80 %), and at the given financial rates as shown (Table 7-3 and Table 7-4), the 801 TPH produced wood in a hypothetical pulp mill generates an estimated annual profit of R512 million. This scenario is displayed as 0 % base in Figure 7-3.

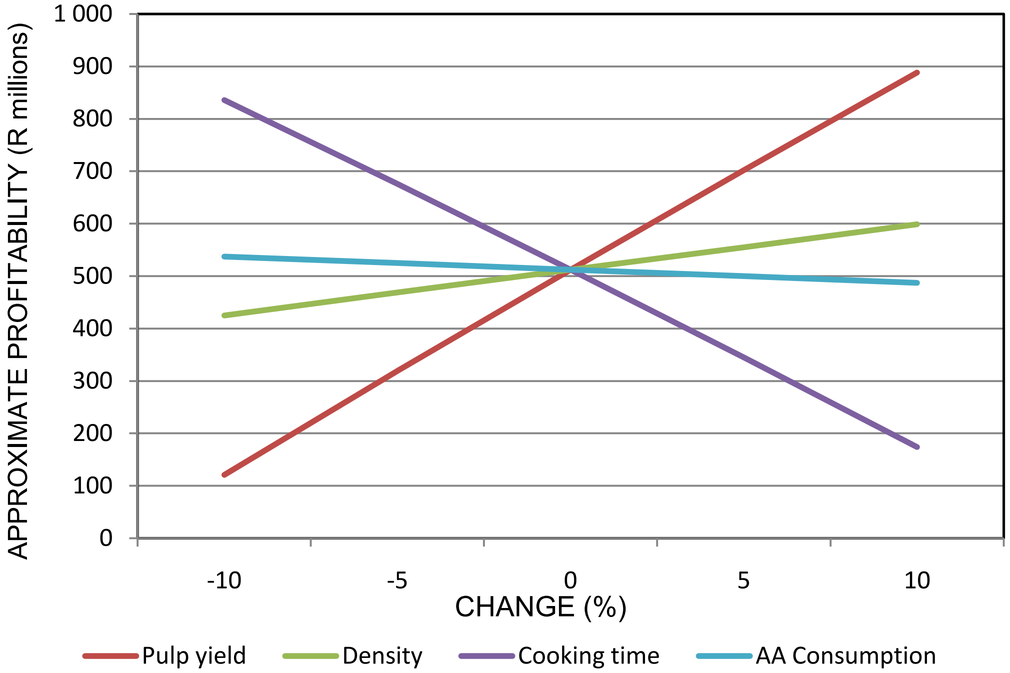

Figure 7-3: Estimated impact on the profitability of a mill when each of the properties for 801 TPH were changed with +10 % to -10 % from the base line of *c*. R512 million.

The gradients of the lines, as they divert from this base line value, give an indication of the sensitivity of the mill to each variable. Pulp yield and cooking time showed the steepest changes in profit or loss when wood properties were altered individually. Both these variables had a comparable level of impact, followed by density and lastly by AA consumption, which had limited effect on profitability.

In a recovery boiler constrained scenario as indicated by Lopez et al. (2009), the rate of delignification (ROD), denoted by cooking time (minutes) in this example, and wood density, would impact on profitability. From Figure 7-3, it is construed that cooking time had 3.8 times the impact on profitability than which wood density had. In the Lopez (2009) study it was shown the impact of lignin content to be 1.7 times bigger than the impact of wood density. The consequence of the calculated ratio between cooking time and wood density is explained as follows:

- If the cooking time needs to increase by 5 % (from 140 to 147 minutes) due to slow throughput of the recovery boiler, in other words, the process time is delayed by 5 % for the recovery boiler's inability to handle the black liquor solids load, the profitability of the mill can reduce from R512m to R345m (a reduction in profit of 32.6 %).
- If the recovery boiler is fed with wood which is 5 % less dense (from 483 to 456 kg m^{-3}) to allow the recovery boiler to handle the throughput of black liquor solids

load, the negative impact on the profitability is on R43m in this case, or a reduction of 8.4 %.

Pulp yield and lignin content are negatively and strongly correlated as described in Chapter 6. It is postulated that by increasing pulp yield, lignin content will reduce and assisting the recovery boiler to be less constrained. Since the Turner model (Turner et al. 2005) does not accept lignin content as input like the Lopez model (Lopez et al. 2009), it is assumed that an increase in lignin will increase the pulp production costs and hence lower the profit.

7.5.2.2 Digester chip feed volumetric capacity

A continuous digester feeder is a volumetric device and, therefore, the capacity is set by revolutions per minute x volume of chips fed per revolution. This in turn is dictated by the wood density (Lopez et al. 2009). It is assumed that high wood density is favourable for the process and low wood density thus the bottle neck.

- From Figure 7-3 it is construed that an increase of 5 % in wood density and thus a reduction in the amount of wood fed into the continuous digester, can increase the profit of this pulp mill (based on wood from 801 TPH quality) with R43m, or by 8.4 %.

7.5.2.3 Summary of financial analysis

The study illustrates the principle that the reduction in cooking time or ROD and an increase in pulp yield can lead to the greatest economic gains. From this model (Turner et al. 2005), it is also noted that active alkali consumption and wood density had limited impact on the mill profitability. A further note however is that faster cooking material (less cooking time) might not be realisable as indicated due to constraint on the recovery boiler and may necessitate an increase in cooking time to handle the black liquor solids. The value of an analysis that emphasises the limitation of the recovery boiler can easily be used to motivate for capital expenditure, given the enhanced throughput by increasing pulp yield of the raw material. By iterating the stand density treatments keeping cooking time and active alkali consumption constant, the profit/loss per ton of pulp produced per treatment, is given Table 7-5.

Table 7-5: R/c Profit (loss) per ton of pulp produced by stand density treatment. Note: The delivered cost per tonne of timber was used in the financial analysis model to determine profit/loss.

TPH	**6 809**	**3 988**	**2 336**	**1 368**	**801**	**469**	**275**	**161**
Profit (Loss) R 1000kg^{-1} pulp	R3.40	R592.78	R638.44	R871.00	R815.03	R801.22	R702.15	R639.88

The highest profit in the pulp mill per ton is in the intermediate stand densities (*c.* 1000 - 2300 TPH). The delivered cost per tonne of wood had an impact on the profitability as previously explained.

7.5.3 Fibre Productivity Index at the mill

When the product of fibre produced per hectare per year (equation 1) and the profitability (loss) of one tonne of pulp is calculated, this product has a unit of R/c (profit (loss)) of pulp produced per hectare per year (R_{pulp} ha^{-1} yr^{-1}). This is illustrated in Table 7-6.

Table 7-6: Product of fibre productivity and profit (loss) of ton of pulp produced per hectare per year, proposed as an inclusive index of measuring the forest-pulp value chain.

TPH	**6 809**	**3 988**	**2 336**	**1 368**	**801**	**469**	**275**	**161**
Fibre kg ha^{-1} yr^{-1}	8 811	10477	11282	10675	8964	7791	6594	5644
Profit R $1000kg^{-1}$ pulp	R3.40	R592.78	R638.44	R871.00	R815.03	R801.22	R702.15	R639.88
R_{pulp} ha^{-1} yr^{-1}	R299.57	R6210.55	R7202.88	R9297.92	R7305.93	R6242.31	R4629.97	R3611.48

The Fibre Productivity Index (FPI) at the *Mill* (now denoted as FPMill), is best described by the following relationships:

$$FPM = (mai \cdot density \cdot pulpyield) \cdot (net\ pulp\ profit)$$

$$= \left[\frac{m^3}{ha} \cdot \frac{1}{yr} \cdot \frac{kg}{m^3} \cdot py(\%)\right] \cdot \left[\frac{R}{1000kg}\right]_{TPH}$$

$$= R_{pulp} \cdot ha^{-1} \cdot yr^{-1}$$

The highest FPMill value of R9,927.92 ha^{-1} yr^{-1} is found in the 1368 TPH planting density treatment. This value is 22.5 % higher than 2336 TPH and 21.5 % higher than the 801 TPH treatment.

7.6 DISCUSSION

The following elements of the FPMill that were of material or processing character were taken into account with the development of the FPMill. Their significance for inclusion is explained below:

- **Mean annual increment:** the rate at which yield increment is achieved per year; an excellent indicator of growth potential under any give regime. Stand volume was effectively described in Chapter 4 and by du Plessis and Kotze (2011) and has shown the effect of planting density on survival/mortality of trees planted, their height development and the development of basal area over time. The survival, height and basal area functions performed well when scrutinized for their goodness of fit. They were also found to be consistent with forest growth theory when their logical behaviour was tested over the range of planting densities. High predictive ability was observed when the Nelder models were compared with the Langepan model.
- **Wood density** was described in detail in Chapters 5 and 6 and has a strong relationship with stand density (r = -0.67). Furthermore, the significant variation in wood density is well described over all stand density treatments and positions in the tree when an ANOVA was conducted. The variation in wood density was also addressed in Chapter 2a when a technique to separate growth rings on basis of density differentiation was described. The relationship between wood density and fibre tracheid characteristics (i.e. lumen and fibre diameter and cell wall thickness), also showed significance. Wood density can be accurately predicted with principal components in a regression analysis (R^2 = 0.76). Moreover, wood density was a strong indicator of handsheet paper properties as seen from Chapter 6. It was positively correlated with especially bulk properties such as mass and paper stretch, and negatively correlated with paper strength indicators such as tear, tensile and stiffness.
- **Pulp yield** is the product of the Kraft pulping process and has been a selection variable in tree improvement programs for decades. Pulp yield showed good response with planting density (R^2 = 0.44) in analysis of variance; it is positively correlated with basal area (r = 0.56) and MAI (r = 0.57) and negatively correlated with kappa number (r = -0.66). The pulp yield measured in this study was highest for the 2336 TPH and lowest for 275 TPH. Physical properties of pulp (fibre tracheids mainly) showed a pattern of distribution across planting density and position in the tree when PCA and CVA biplots were drawn. When regressed with latent variables or principal components, a high

coefficient of variation was achieved (R^2 = 0.85) and R^2 = 59 % when regressed with stand density.

A NIR model for pulp yield that was developed had high calibration statistics (R^2 = 0.80, SEC = 0.55) and had high prediction potential. When tested against an independent data set, pulp yield of NIR predicted and laboratory measured data had a high correlation (R^2 = 0.73). Pulp yield has a large lever on profitability in the pulp mill as shown in the mill profitability model by Turner et al. (2005).

These elements were linked with the financial components of a vertically integrated mill to describe a productivity index that has relevance both in technical and economical terms.

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CHAPTER 8: Concluding remarks

Throughout the study, the investigation focussed on the identification of wood, cellular, pulping and product properties that could be used in a productivity index and that would highlight the quality aspect of the material or product quality. In order to be considered for inclusion in such an index, properties had to be clearly identified, relatively easily and cheaply assessed and have high correlations with downstream paper properties, and in themselves have predictive ability with statistical methods such as regression analysis.

8.1 SUMMARY

An abbreviated summary follows to illustrate the study succeeded to identify variables to populate a fibre productivity index:

- Successful development of a technique to differentiate growth rings by means of wood density peaks from gamma-ray densitometry to *inter alia* describe the variability in **wood density** on an intra- and inter-specific basis. The results indicated that tree spacing at establishment as a management intervention did not influence the variability of wood density but that it is rather a micro-environmental function of individual rainfall events, the intensity and spread, and thus available soil water. However wood remains a highly variable resource in terms of its density and as was seen in Chapters 4 and 5, have significant influences on pulp and paper properties.
- Successful development of **NIR models** to assist in rapid and reliable assessment of wood properties on a non-destructive basis. The calibration models for i) wood properties: *air dry* wood density (R^2 = 0.81, SEC = 23.30), ii) pulp properties: total pulp yield (R^2 = 0.80, SEC = 0.55), kappa number (R^2 = 0.95, SEPC = 0.83) and for iii) pulp chemistry: insoluble lignin (R^2 = 0.82, SEP = 0.22) returned good calibration values. When validated with the external validation procedure, with 30 % of the samples excluded from calibration, similar high R^2 and SEP - values were returned.
- Successful modelling of **growth and yield** development with regards to its survival, height and basal area development across planting density treatments was demonstrated by their goodness of fit and consistence with forest growth theory when their logical behaviour was tested over the range of planting densities. High predictive ability was observed when the Nelder models were compared with the Langepan model. The model

forecasted an accurate growth and yield scenario for trees of variable stand densities that can be used in a fibre productivity index.

- Successful study of **wood bulk, and fibre and vessel properties** across four distinctly different planting density treatments was conducted. Planting density means was significantly different from zero in all instances when weighted mean tree values were analysed with wood, fibre tracheid and vessel element properties ($p < 0.0001$). PCA was effectively used to develop principal components and when regressed with wood properties, high R^2-values were obtained. When the most extreme stand density treatments; 275 TPH and 6809 TPH, were evaluated, it was evident that larger trees, grown at 275 TPH, produced wood of better quality for pulp processing (basic wood density at 0.520 g cm^{-3} was 21 % higher, fibre cell wall thickness at 2.10 µm was 18.6 % thicker and fibre lumen diameter at 8.16 µm was 9.9 % lower than for 6809TPH). Canonical variate analysis (CVA) which is a widely used method for analysing group structure in multivariate data was used to construct biplots from the data. The data analyses suggested basic wood density to be a suitable property for a Fibre Productivity Indicator (FPI) due to the high correlation with stand density, ease of measurement and modelling success.
- Successful study of **pulp and paper properties** to describe the effects of planting density. Extensive use was made of monoplots, PCA-biplots and CVA-biplots to illustrate relationships between data elements as well as the size and significance thereof. Kappa number, as an indication of residual lignin in pulp, was highly significant to explain the variation in paper product quality, e.g. brightness ($r = -0.78$) and tear ($r = -0.57$).

Elements taken from the materials study to populate the fibre productivity index at the mill (FPMill) were: **Mean annual increment (MAI)** as a forestry growth indicator which takes into account, diameter and height growth and the effect of planting density, **wood density** as a bulk property summarising in many respects the composition of wood and **pulp yield**, the indicator of the amount of fibre processed through a Kraft cooking process which all met the requirements as set out for inclusion into a fibre productivity index. Furthermore, the product of these variables as suggested by Borralho et al. (1993), does not take into account the cost of production of pulp and therefore an economic component was added to the index.

The economic component included elements of fixed costs, variable costs, mill efficiency and relative importance of wood density, pulp yield, cooking time and the consumption of active alkali in the process, as the economic weights suggested by Lowe (1999) and Hodge (2011). The calculation of wood delivered cost was calculated by economics of scale allocating high establishment costs to, e.g. 6809 TPH and high land cost to, e.g. 161 TPH, this variable was added to the mill financial analysis model, developed by Turner et al. (2005).

The product of the fibre productivity and the economic analysis which culminated in profit/loss of producing 1 ton of pulp was deemed the best index to describe the entire and integrated value chain. This index, named Fibre Productivity Index (FPI) at the *Mill,* denoted as **FPMill**, is an integrated index that is easy to interpret in the realms of a forestry - kraft pulp mill enterprise like that of Mondi SAD.

The implementation of the **FPMill** will involve the non-destructive sampling of the compartments of the felling plan and the calculation of delivered cost per ton of wood to the mill. Further work in Mondi SAD is required on the latter, however, the business has positioned itself to be able to assess growth and yield and wood properties from its raw wood resource and will follow a path of implementation of the **FPMill**.

Furthermore, FPMill can be used to differentially pay suppliers of timber for the inherent quality thereof and not for that mass of wood delivered.

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