DEVELOPING A NON-DESTRUCTIVE SCREENING TOOL FOR PULP YIELD IN *ACACIA MEARNSII*
(BLACK WATTLE)

by

ROBERT WILLIAM DUNLOP

Submitted in fulfilment of the academic
requirements for the degree of
Master of Science in the
Discipline of Forestry
School of Agricultural Sciences and Agribusiness
Faculty of Science and Agriculture
University of KwaZulu-Natal

Pietermaritzburg
2009

Abstract

Acacia mearnsii (black wattle) is an important South African commercial forestry species, providing a source of high quality raw material (fibre) for both the domestic and international pulp and paper industries. Compared with many *Pinus* and *Eucalyptus* species, there has been very little research into the wood and pulping properties of black wattle. The ability to assess pulp yield in a non-destructive manner, using near infrared (NIR) spectroscopy, is vital from a tree improvement perspective. Destructive sampling and analysis, results in the loss of the genotype, while also being very expensive and time consuming. In order to assess some of the important characteristics that make the species desirable from a fibre perspective, this study investigates growth characteristics, wood density and pulp yield of ten trees grown on each of three different sites namely, Bloemendal, Glen Echo and Phoenix, and from each of three different age classes being 7- , 9- and 11-years-old. In total, 90 trees were sampled for this stage of the study. In general, physical characteristics such as utilisable height and diameter at breast height of the trees differed between sites and increased with age, this age effect trend was not reflected in the pulp yield or wood density results. Pulp yield measurements ranged from 52.61 to 59.91% across all sites and age classes, which, when compared to the pulp yield from many other forestry species, is relatively high.

Laboratory pulp yield data was used in conjunction with NIR spectra obtained from the same wood samples to calibrate a NIR spectrophotometer to predict pulp yield. Thirty 11-year-old trees were then chosen from the Bloemendal site and sampled extensively to investigate the within-tree variation in pulp yield. The NIR model developed was used to measure the pulp yield from the numerous samples taken from within the trees. In general, pulp yield decreased from pith to bark and from the base of the tree to about 20% of the tree height and then decreased towards the top of the tree. The within-tree variation data for pulp yield was analysed to identify the best position for non-destructive sampling, and a model was then developed to predict whole tree pulp yield based on this sample, which was taken at 1.4 m up the tree. The analyses of small samples of wood meal, using near infrared spectroscopy, enabled the prediction of whole tree pulp yield.

Declaration

This dissertation was supervised by Dr Peter Njuho, and co-supervised by Professor Colin Dyer.

I hereby declare that this dissertation, submitted for the degree of Master of Science at the University of KwaZulu-Natal, Pietermaritzburg, is the result of my own investigation, unless acknowledged to the contrary in the text.

Robert William Dunlop (candidate)
January 2009

We the undersigned certify that the above statement is correct:

Dr Peter Njuho (supervisor)

Professor Colin Dyer (co-supervisor)

Table of Contents

Acknowledgements

I would like to thank Prof. Colin Dyer (Director, ICFR) for his initial support of this project, his assistance in obtaining the considerable funding required for the project and also for his continued support for and interest in the project, even once I had left the employ of the ICFR. Thank you also for ultimately stepping in as a co-supervisor.

I owe a huge debt of gratitude to Central Timber Co-operative, Mondi Forests and Sappi Forests for funding this project.

I would like to thank Dr Peter Njuho, my principal supervisor, for his sound advice, extreme patience and understanding, enthusiasm and continued encouragement throughout the duration of this study. His excellent reviewing of this document is also greatly appreciated.

The following people also need special mention for the important parts they played in the success of this project.

- My original co-supervisors Prof. Philip Turner (CSIR-FFP) and Dr Charlie Clarke (Sappi Forests Research) for their advice, assistance and guidance in planning this study.
- Mr Micheon Ngubane (Manager of Bloemendal), Mr Ant Gibbs (Manager of Phoenix Wattle Farm) and Mr Randolf Keyser (Owner of Glen Echo), who allowed me to sample trees on their respective farms. Your support and interest in this project is greatly appreciated.
- Mr Tim Goodricke and Mr Darren de Leur for their hard work and help in collecting the samples and helping with all the density determinations. Mrs Sally Upfold for her untiring reviewing of my chapters at various levels of completion and for her help with the formatting of this document and Mrs Desiree Lamoral for her excellent support from the ICFR library.
- Mr Anton Wessels and Mr Antonio Mshengu (Sappi Forest Research) for their help in chipping the billet samples.
- The staff of CSIR-FFP for their assistance and patience, during the pulp yield and NIR laboratory work of this study. Dr Nelson Sefara (now employed by Sappi Forests), Mr Jerome Andrew and Dr Anton Zboňák need a special mention.

To my wife Vicky and three daughters Kayla, Jenna and Abbey, you have all had less of my attention than you deserved during the writing of this dissertation. Vicky thank you for all your wonderful and loving support, and kids I will make up for the lost time.

Conferences attended related to this dissertation

Southern African Plant Breeders Association Congress at San Lameer (KwaZulu-Natal) held from 15th to 17th March 2004. An oral presentation was made entitled: "Developing a non-destructive screening tool for pulp yield in *Acacia mearnsii* (black wattle) – Part 1.

Southern African Plant Breeders Association Congress at Club Mykonos (Western Cape) held from 13th to 15th March 2006. An oral presentation was made entitled: "Developing a non-destructive screening tool for pulp yield in *Acacia mearnsii* (black wattle) – Part 2.

List of Tables

List of Figures

List of Abbreviations

GLDUB	Ground line diameter under bark
DBHOB	Diameter at breast height over bark
DBHUB	Diameter at breast height under bark
TOTAL_HT	Total height
UT_HT	Utilisable height
SPY	Screened pulp yield
WMDSPY	Weighted mean disc screened pulp yield
WMTSPY	Weighted mean tree screened pulp yield

Chapter 1

Introduction

1.1 Overview

"Wood, a most useful substance, varies greatly", this is how Zobel and van Buijtenen (1989) described wood in the opening sentence of their book entitled "Wood Variation: Its Causes and Control". However, their publication does not feature *Acacia mearnsii* (De Wild) (black wattle) much. Taylor (1973) stated that knowledge of the variation in properties within a species is helpful in estimating the wood quality of the available timber supply and for intelligent planning of tree improvement programmes aimed at altering wood properties in future generations. This study will attempt to describe some of the variations that occur in black wattle wood.

Black wattle, a hardwood, is grown as a plantation species for the production of kraft pulp for paper and dissolving pulp for rayon, black wattle bark is also used in the production of vegetable tannin. As the raw material in these processes, the quality of the wood and bark plays an important part in the end-product quality and ultimate profitability. The role of wood quality in the profitability of kraft pulp production has been well established in various studies, and wood density and pulp yield are two of the important variables (Borralho *et al*., 1993; Greaves *et al*., 1997; Kube and Raymond, 2002). Wood density is important throughout the process of pulp manufacture. For timber growers higher density improves pulp yield per hectare, higher density also improves transport efficiency, which is a major economic component in the process. Higher density improves digester productivity in chemical pulping, however, there are limits to how high densities can be for different processes and products (Turner, 2001). Other important product quality criteria include brightness, opacity, stiffness, porosity and strength properties such as tear, tensile and burst (Turner, 2001). Density alone can be used to predict pulp yield per unit volume of wood and many other paper properties (Haygreen and Bowyer, 1996). Density is directly related to cell wall thickness and generally the lower the density, due to a lower proportion of thick-walled latewood cells, the better the wood as a raw material for paper-making (Haygreen and Bowyer, 1996).

Fibre wall thickness is important in factors such as burst and tensile strengths and resistance to tear. Thick walls result in paper with low burst and tensile strength but high resistance to tearing that are not conducive to folding. Burst and tensile strength depend on fibre-to-fibre bonding, as paper is manufactured by weight and the number of fibres in a sheet is inversely related to density of the fibre walls resulting in thick walled fibres having fewer fibre-to-fibre bonds per sheet. Thick walled fibres also have less surface area per unit weight compared to thin-walled fibres and together with fewer fibres reduce the chances of interfibre bonding (Malan *et al.*, 1994; Haygreen and Bowyer, 1996). Interfibre bonding is also important in tear strength. Fibre length also affects tear strength and is an important paper-making property of wood. In general the longer the fibre the higher the tear strength (Haygreen and Bowyer, 1996). In a specific study on *E. nitens*, in New Zealand, Jones and Richardson (1999) found that tear index increase with longer fibre length of the wood chips, burst, tensile, tensile energy stiffness indices and opacity increased with lower earlywood density and latewood percentage. Fibre dimensions affect the end product in the pulping process and the important fibre determinants are collapse resistance, fibre perimeter, wall thickness, relative number of fibres and fibre length (Kibblewhite, 1999). The properties that are important for the dissolving pulp process are wood density, viscosity of the pulp, brightness, K number, specific consumption and pulp yield (Dunlop *et al.*, 2000).

The ability to effectively improve the pulp yield and quality of commercial forestry plantations is becoming increasingly important due to rising establishment and transport costs, as well as negative publicity associated with exotic species used in plantation forestry (Clarke and Wessels, 1995). This increases the pressure on tree breeders to produce trees better suited to the end products they are used for. Improvement in the inherent pulp properties of timber is best effected by exploitation of the available genetic variation in tree populations (Clarke and Wessels, 1995). Timber growers, researchers and manufacturers have realised that the quality of the raw material being processed in pulp mills is as important as the quantity (Dadswell and Wardrop, 1959; Clarke and Wessels, 1995; Shaw *et al.*, 1998).

To measure wood and pulp properties, current technologies require sample trees to be felled in order to take large enough samples for basic density and pulp yield assessments. Basic density is generally measured by dividing the oven-dry weight of the sample (usually a cross-sectional disc) by the green (maximum swollen) volume (Tappi, 1988). Pulp yield is assessed in laboratory scale digesters, using wood chips from the tree as the sample. This process is costly and time consuming. Black wattle does not coppice or shoot once felled so destructive sampling leads to the loss of the genotype to the population and this is unacceptable from a tree breeding perspective. Furthermore, despite numerous efforts, vegetative propagation of selected mature individuals is not yet possible on a research or commercial level for black wattle. The species does not root easily when cuttings are taken, grafting is not successful at an acceptable level and tissue culture has only been successful with young material (Ledeboer, 1944; WRI, 1952; WRI, 1957; Beck, 2000).

The development of efficient screening tools for properties such as pulp yield depends to a large degree on the ability to non-destructively sample standing trees (Turner, 2001). Non-destructive sampling has been successful in pine, eucalypt, larch, spruce and other tree genera, to assess a range of characteristics, such as mechanical properties, chemical properties, density and pulp yield. Most of the analyses are carried out using Near Infrared spectroscopy (NIR) and multivariate analyses, such as partial least squares (PLS) regression and principal components analysis (PCA) (Birkett and Gambino, 1989; Wallbäcks *et al.*, 1991; Garbutt *et al.*, 1992; Michell, 1994; Schimleck *et al.*, 1996; Sefara *et al.*, 2000; Raymond and Schimleck, 2002; So *et al.*, 2004). Another non-destructive method to measure pulp yield would be to micropulp a core sample, however this method is slow and expensive due to the requirement that the pulp properties have to be determined at a constant state of delignification (Wright, 1987; Clarke and Wessels, 1995; Shaw *et al.*, 1998). However, for the scope of this study the focus was to use NIR spectroscopy. NIR spectroscopy allows breeders, in particular, needing large sample numbers, to relatively cheaply and quickly sample trials and populations that previously needed to be felled and analysed in laboratories by wet chemistry at high costs and with long time delays (Wright *et al.*, 1990; Kube and Raymond, 2002; Raymond and Schimleck, 2002). The simplicity of sample collection (described in Table 3.1) and preparation and the speed and ease of carrying out the analysis made NIR the method of choice for this study.

The use of NIR and the associated statistical tools to predict wood properties from destructive samples have not been exploited in black wattle as it is not a major plantation species on a world scale (Dunlop, 2002c), and the investment or need for this type of research has not been previously warranted. With the demand for black wattle timber increasing, and quality being imperative, this study is, according to the literature surveyed, the first of its kind for this species, and most definitely the first such study in South Africa. The use of these tools would allow breeders to rank individuals and families for pulp yield and select high quality parents for inclusion in breeding populations.

Measurements of other wood characteristics such as fibre morphology (cell wall thickness and fibre length) would certainly add to the understanding of the paper-making properties of black wattle, and could most definitely be the subject of future study. However, for the purposes of this study pulp yield and wood density were considered as the properties of focus.

If found to be successful, the breeding programme conducted at the Institute for Commercial Forestry Research (ICFR) for the entire South African black wattle industry, could in future, use these tools to select parent trees with higher pulp yield for inclusion in production seedling orchards (PSOs). These could supply growers with seed which produce trees with higher pulp yield. As is shown in the following chapter, black wattle already has acceptable to high pulp yield compared to other species competing for the same market share. If South African black wattle timber growers are able to continue to supply high quality raw material for pulp production, and to grow trees in future with even higher pulp yields, they will surely leverage continued sales of their timber.

1.2 Background

1.2.1 Commercial plantation forestry in South Africa

Commercial plantation forestry in South Africa comprises three main genera: *Eucalyptus*, *Pinus* and *Acacia*, as well as certain hybrids within these genera. The total area under plantation forestry in South Africa is 1.35 million hectares; softwoods (pines) make up 48.3%; eucalypt spp. 43.4%; and *Acacia* spp. 7.4% (FSA, 2002a). Although afforestation is governed by a permit or licensing system in South Africa (National Water Act, 1998), a total of 2 751 hectares was registered in the 1999/2000 season as new afforestation. Of this 46.9% was to the *Acacia* genus (FSA, 2002b). This highlights the important role and increased demand in South African forestry associated with this genus. The two *Acacia* species grown commercially in South Africa are *Acacia mearnsii* (black wattle) and *A. decurrens* (green wattle), with black wattle being the predominant species.

1.2.2 Black wattle (*Acacia mearnsii* (De Wild))

Black wattle occurs naturally in south eastern Australia. Its range includes southern New South Wales, Victoria, Tasmania and the south eastern part of South Australia between latitudes 24 ^{o}S and 43 ^{o}S and longitudes 138 ^{o}E and 151 ^{o}E (Sherry, 1971). The species has been introduced into the tropics and subtropics with large plantations established in Kenya, South Africa, Zimbabwe, Brazil and India. Other smaller introductions have also been reported, but not all have been successful (Dunlop, 2002a). Black wattle is grown for both its timber and bark. It is one of the principal sources of vegetable tannin, the bark containing up to 40% tannin which, when extracted, is used for leather tanning in the manufacture of heavy leather goods. In addition, the powdered bark extract is used in the production of formaldehyde adhesive for the manufacture of exterior grade plywood, particleboard and laminated timbers. The demand for black wattle timber by the international pulp and paper industry has increased substantially in recent years. It is used in combination with other woods in both the kraft and dissolving pulp industries. Japan, in particular, is a large importer of black wattle chips from South Africa. Other uses for the wood include charcoal, rural construction material, mine props, wooden tools, joinery, parquet flooring and hardboard (Dunlop, 2002b).

1.2.3 Introduction of *Acacia mearnsii* into South Africa

Black wattle was reportedly first introduced into South Africa by the Vanderplanck brothers in 1864 as a shade tree for stock, for windbreaks and as a source of fuel on farms (Sherry, 1971). Twenty years later sufficient wattle bark was available to conduct the first tannery tests in Pietermaritzburg, and for the next seventy years the bark industry developed into a large export initiative (Sherry, 1971). By 1960, approximately 300 000 hectares were planted to black wattle in South Africa. Today this figure is about 130 000 hectares (SAWGU, 2001), the decline due largely to the loss of international markets for wattle bark extract.

1.2.4 Uses of black wattle wood in South Africa

Historically, black wattle timber has been used for firewood, building and fencing poles, or has been disposed of by burning (Dunlop and Hagedorn, 1998). More recent uses include mining timber, pulpwood for the production of paper, rayon or hardboard, charcoal and parquet flooring (Sherry, 1971). In the last decade wattle timber has risen in importance, both locally and internationally, as a source of pulpwood. South Africa produces approximately 1 000 000 tons of wattle timber per annum, most of which goes into pulp production, with a small percentage being used in the manufacture of charcoal. Approximately 16% of the timber is processed in South Africa at the Sappi Saiccor factory at Umkomaas, for the manufacture of dissolving pulp, while 82% is exported to Japan by Silvacel and CTC for processing in kraft pulp mills. Few pulp studies have been undertaken on wattle in South Africa (Dunlop *et al.*, 2000).

1.2.5 Black wattle research in South Africa

In 1947 the Wattle Research Institute (WRI), now the ICFR, was established to conduct research into wattle growing with the aim of reducing the cost of growing the trees and improving bark yields. Research efforts focussed on tree breeding and genetic studies of the species. In order to provide the Industry with improved genetic material, the breeding programme concentrated on selecting disease-tolerant trees with the highest bark yields. These were then used to establish PSOs to supply the Industry with improved seed. Entomology and plant pathology researchers studied the major pests and diseases affecting black wattle, while silvicultural research efforts concentrated on problems related to growing the trees.

During the past 50 years, many recommendations have been made with respect to tree improvement, nursery management, establishment and re-establishment, land preparation, planting practice, nutrition, weed control, slash management, entomology, plant pathology, water use, and yield and growth predictions. This knowledge has enabled wattle growers to maximise yields more cost-effectively.

Research into uses for wattle bark extract was carried out for many years, locally at the WRI/ICFR in Pietermaritzburg, the Leather Industries Research Institute (LIRI) in Grahamstown (established in 1941), and at National Timber Research Institute (NTRI) of the CSIR, as well as abroad. In 1978, the Applied Research Technical Services (ARTS) section was established at the WRI to co-ordinate the development and application of alternative uses of wattle bark extract (WRI, 1980). Three years later, this section moved to the Wattle Industry Centre (WIC), where this research continues today. The WIC performs the administrative, research and marketing functions of the wattle bark industry. One of the main areas of ongoing research is in thermosetting industrial adhesives used in the manufacture of products such as particleboard, plywood, medium-density fibreboard, and corrugated cardboard. This area of research was extensively studied at the NTRI and researchers such as Pizzi, amongst others, made many advancements in the domain of joining wood for particleboards and structural timber. Pizzi (1978) described how wattle-base adhesives were modified to make them more suitable for use in the manufacture of particle boards and another improvement was in the area of finger joints in structural timbers where short lengths of timber are joined to produce longer boards. The use of tannin based rather than synthetic phenols in the compounds used to glue finger joints allowed shorter setting times and therefore more efficient processing (Pizzi *et al*., 1980). The low formaldehyde emissions from the natural adhesives make these products more environmentally friendly than synthetic alternatives (Dunlop, 2002b).

In the past black wattle bark quality and yield were characteristics of importance, and wood quality and yield were given little attention. Today, these wood characteristics are as important as bark quality and yield, and funds are being made available for relevant research. This study is hopefully the first of many to enlighten scientists and growers alike with data describing the variation in pulp yield of black wattle trees across a range of environments, at a single location and within single trees. Variation in wood density will also be described. A summary of some of the research already directed at black wattle wood is given in Chapter 2.

1.3 Aims and scope of this study

This study is the first of its kind in South Africa, and has taken the initial steps towards developing a tool that will enable tree breeders to non-destructively, cost effectively and quickly evaluate the pulp yield of standing black wattle trees. In future, a NIR spectrophotometer could be calibrated for other analyses such as lignin and cellulose content, as has been done for many eucalypt species (Garbutt *et al*., 1992; Shimleck *et al*., 1996), and for chemical and mechanical properties of pine wood (Kelley *et al.,* 2004a; Kelley *et al.,* 2004b and So *et al.,* 2004). If enough interest is evoked by this study, it could lead to further investigations into other wood, pulp and paper-making properties of black wattle.

The main aim of the study is to calibrate a NIR spectrophotometer to measure kraft pulp yield of *Acacia mearnsii*. NIR spectroscopy is a powerful analytical technique used widely in agriculture and industry for rapid determination of various chemical constituents (Henry, 1999; Sefara *et al*., 2000). NIR spectroscopy is based on the absorption of electromagnetic radiation at wavelengths in the range 780 – 2500 nm (Osborne, 2000; So *et al*., 2004) and the resultant reflectance spectra are calibrated against measurements obtained using conventional analytical techniques (Mark, 2000; Sefara *et al*., 2000). Various researchers have already shown that it is possible to predict pulp yield using NIR spectroscopy for a number of tree species. To investigate this, the relationship between the pulp yield and the spectra obtained from a small sample of wood is established.

This thesis provides a review of some of the literature available on studies related to: a) wood and pulp properties of paper-making species; b) within-tree variation of some of these properties; c) NIR calibration and analysis of these properties from non-destructive sampling techniques; and d) models to predict important wood, paper-making and pulping properties in Chapter 3. This literature review positioned the author in such a way that a critical and structured approach could be followed in this study. The available information pertaining to similar work carried out on other forest tree species allowed for a focussed assessment of some of the important issues and characteristics related to pulp yield and the non-destructive screening thereof. Although on a global scale, black wattle is not a major plantation species, it does provide a highly sought after niche raw material. Any relevant advancement and improvement in the species will help to maintain its position as a sought after raw material in the global forest sector.

The materials and methods used in the experimental work, presented in Chapter 4, follow a strategy designed to look, firstly, at the growth characteristics, density and pulp yield of black wattle at a macro scale incorporating three different ages and plantations. This was aimed at evaluating the variation in these characteristics as well as correlations between the different ages and plantations. A total of 90 trees were sampled for that part of the study, the hypothesis being tested is based on the assumption that tree age and plantation (incorporating site factors) do not affect these characteristics. It is important, at the outset to mention that when referring to age, the author is referring to tree age and not the age of the wood that is being sampled at various positions in the tree, unless otherwise stated. It is well understood that wood found closer to the bark is more juvenile than wood at the same height that is found closer to the pith. The same 90 samples were also used to calibrate a NIR spectrophotometer to analyse pulp yield from small samples of black wattle wood meal. An important point to note is that for the NIR model to be useful the samples used for the calibration need to cover the full range of measurements as the model does not support any extrapolation beyond the values used in the calibration (Mark, 2000)

Secondly, the study focussed on 30 trees from one site and age class of trees investigating the within-tree variation in pulp yield. The null hypothesis being tested was that the position within a tree has no effect on screened pulp yield. Again, it is important to stress that the variation being studied here is purely viewed from a positional point of view (horizontally from pith to bark or vertically from the base of the tree to the top of the tree) and no attempt is made to define the changes in pulp yield, if any, from a wood-age perspective. Thirdly, at a more micro level, a model was developed capable of predicting the pulp yield of the tree from samples taken from a single sampling point. The hypothesis being tested here is that whole tree pulp yield can be predicted from a predicted pulp yield value of a small sample of wood, obtained using a non-destructive sampling method at a fixed height from the ground. The results obtained from analysing the data are presented and discussed in Chapter 5. In Chapter 6 conclusions are drawn around the usefulness and practicalities of using the knowledge and techniques established during this study, especially from a tree breeding perspective.

The technology under investigation in this study is used in other genera of forest trees, and allows tree breeders to successfully analyse large numbers of samples for various characteristics quickly and cost effectively (Michell, 1994; Schimleck *et al*., 1996; Sefara *et al*., 2000; Edlund, 2003; Hintertoisser *et al*., 2001; Kelley *et al*., 2004a).

The results from this study are the first steps towards allowing researchers to calculate the heritability for pulp yield, and assess the feasibility of increasing pulp yield through classical tree breeding techniques and strategies in black wattle in South Africa.

Chapter 2

Black Wattle

2.1 Black wattle site requirements

As stated previously, black wattle occurs naturally in south eastern Australia. In South Africa, black wattle plantations are predominantly situated in the summer rainfall region between latitudes 25 °S and 33 °S and longitudes of 27 °E and 30 °E. This encompasses south eastern Mpumalanga, northern and southern KwaZulu-Natal, and the KwaZulu-Natal Midlands (Figure 2.1).

Rainfall, and the risks associated with frost, snow and disease, are among the factors limiting the geographic distribution of commercial cultivation. The altitude, mean annual temperature (MAT) and mean annual precipitation (MAP) for optimum growing conditions of black wattle throughout the summer rainfall regions of South Africa are given in Table 2.1. Most plantations occur in the warm temperate climate of the summer rainfall region where the MAP exceeds 750 mm at higher altitudes (corresponding to 16 °C to 18 °C) and 850 mm at lower altitudes (corresponding to 18 °C to 20 °C). Black wattle grown in areas with a MAP greater than 1200 mm suffers unacceptably high levels of a disease complex known as gummosis. It is usually grown in areas where the MAT ranges from between 16 °C to 20 °C (Herbert, 1993).

The species does not thrive in warm humid coastal climates and the lower altitudinal limit in southern KwaZulu-Natal is about 400 m, and in northern KwaZulu-Natal about 500 m (Table 2.1). Trees are easily damaged by snow, either snapping or becoming bent over and crooked, and planting should be limited to altitudes below 1250 m in KwaZulu-Natal. The species is also sensitive to frost, and therefore topographic depressions must be avoided in cooler areas. Although black wattle has proven to be one of the most drought resistant of the commercial hardwoods in South Africa (Herbert, 2000) the species has suffered badly from drought conditions when planted in KwaZulu-Natal below 900 metres on low rainfall sites (< 850 mm per annum), especially on soils derived from sandy parent materials (Natal Group sandstones) (Smith, 2002).

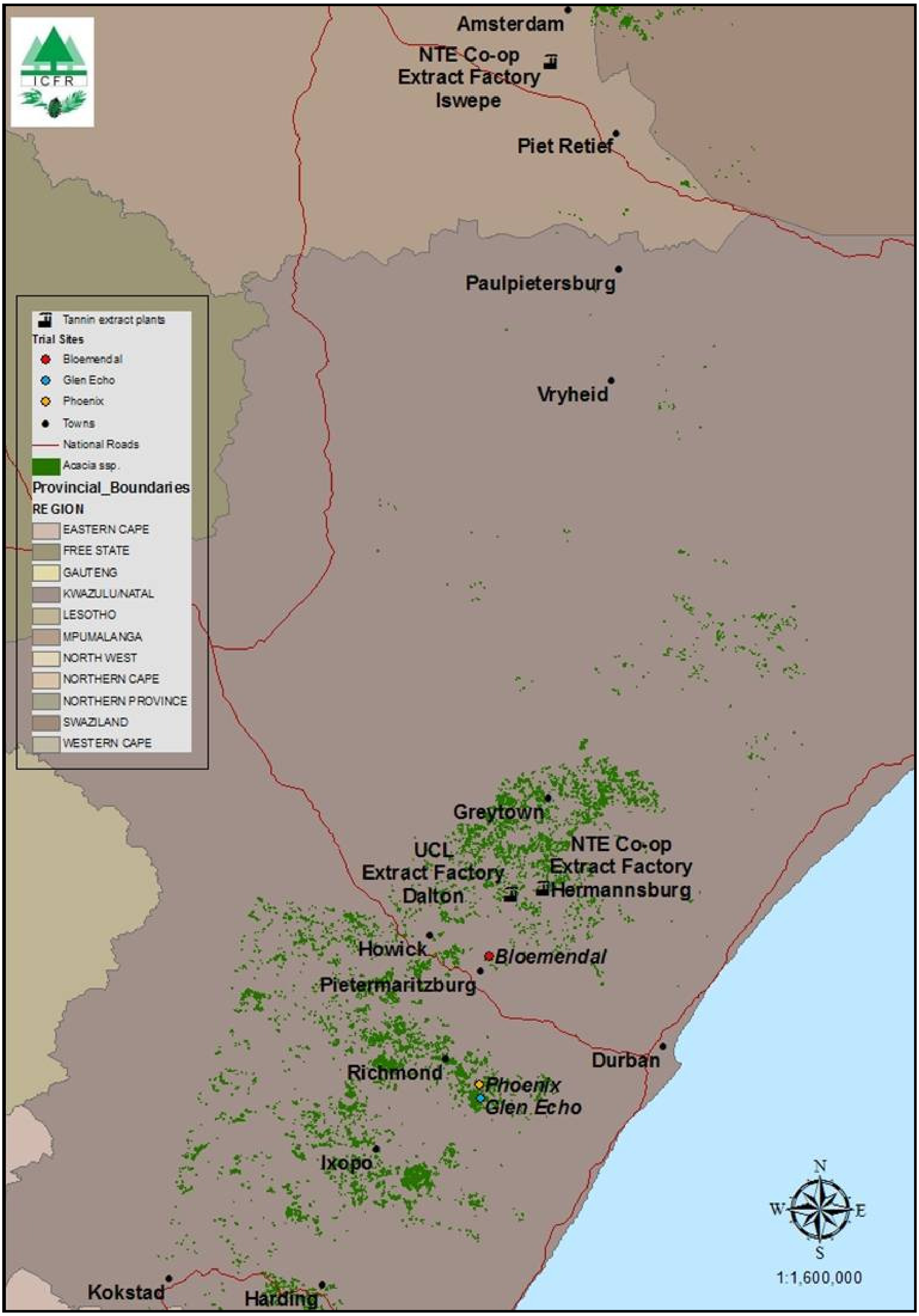

Figure 2.1 Location of sample sites in KwaZulu-Natal along with the wattle growing areas and bark processing plants in the provinces of KwaZulu-Natal and Mpumalanga.

Table 2.1 Optimum growing conditions and geographical range for black wattle in the summer rainfall regions of South Africa (Smith, 2002).

Region	Latitude	Approximate location range	Approximate altitude range (m)						
KwaZulu-Natal Midlands	30°30' - 29°00' S	Harding - Kranskop	800 – 1350			350 – 950			
Northern KwaZulu-Natal	29°00' - 27°00' S	Kranskop - Piet Retief	950 -1450			500 – 1050			
South Eastern Mpumulanga	27°00' - 26°00' S	Piet Retief - Jessievale	1050 – 1550			600 – 1100			
			Mean annual temperature (°C)						
			16 – 18			18 – 20			
			Mean annual precipitation (mm)						
			< 750	750 - 1250	> 1250	< 800	800 - 900	900 - 1300	> 1300
Optimum range (shaded) and Potential problems stated			Too dry		Gummosis	Too dry	Dry[a]		Gummosis

[a] On sandy or shallow soils black wattle may be subject to drought stress and higher mortality in this category.

Black wattle grows on a wide range of soil types in the summer rainfall areas, and it is more tolerant of poor soil conditions than *Eucalyptus* spp. for example (Schönau and Fitzpatrick, 1981). Optimum growing conditions are found on soils greater than 30 cm deep, well drained, with textures ranging from sandy loams to clays, and with moderate to high organic matter content (organic carbon > 1.8%). The species tolerates soils with a fluctuating water table (E and soft plinthic B horizons) but growth may be negatively affected if trees are grown on very poorly drained soils (Herbert, 2000). Nevertheless, Schönau and Fitzpatrick (1981) suggested that black wattle is one of the more tolerant commercial species of poorly drained soils. Planting on shallow soils less than 50 cm deep increases the chances of black wattle being affected by wind throw, especially in older trees, and particularly if planted as seedlings rather than directly sown seed, due to poor tap root development (Smith, 2002).

2.2 Growth of black wattle

The growth of most tree species is influenced by environmental variation and these influences are likely to affect the wood, pulp and paper-making properties (Clarke *et al.*, 1999). Variability in growth rate and related characteristics in black wattle is well known, and observations regarding differences in vigour, shape, foliage, fruit and bark have been documented (Osborn, 1931; Sherry, 1971). According to local knowledge of the species, growth differences occur on the same site between trees of the same age, and differences in vigour are evident, even after years of tree breeding, in plantations grown from genetically improved seeds. This indicates potential for further genetic improvement of the species. Disease resistance has been a trait of major importance in the breeding programme of black wattle at the WRI and ICFR. Improvements in disease resistance have resulted in better survival of the crop and therefore a final stocking closer to the ideal situation of 1500 stems per hectare (sph) at full rotation age (Dunlop, 2002c). The number of stems per hectare at felling or rotation age is a major driver of, wood and pulp, yield. Improvements in yield presented by WRI and ICFR tree breeders have been largely dependent on having a disease-free crop, at the optimum stocking at the time of felling. In general, progeny from genetically improved seeds have shown superior height, diameter, volume and bark yield. Compared to commercial seedlots, improved progeny have been reported to be 8.5% taller, have 19% larger diameters, 112% greater volume, 85% greater bark yield and 10% more trees are alive at the time of felling (ICFR, 1989).

Determining rotation length for any forestry species depends mainly on the characteristics of tree growth, stand density, site conditions and current markets (Smith, 2002). Historically, in South Africa, the rotation age of black wattle was dictated by the bark industry, and it was suggested by Schönau (1979) that bark from eight-year-old trees was acceptable for high quality tannin extraction. In general, before the 1950s, rotation age was between eight and ten years, but in 1971 it increased to between ten and twelve years due to an oversupply of bark (Sherry, 1971). Today, black wattle is felled between eight and twelve years, depending on whether it is being grown for its bark or wood, or both (Smith, 2002). The decision on the exact rotation age is often a cultural one, and many growers persevere with methods that have been practiced on their farms for generations.

2.3 Black wattle wood research

Internationally, there has been work undertaken on black wattle wood properties and quality, generally in conjunction with eucalypt species (Hannah *et al.*, 1977; Clark *et al.*, 1992; Fang *et al.*, 1994). These studies have been aimed at assessing the suitability of black wattle and other *Acacias* to be grown as plantation species as a source of raw material for the production of pulp. .Generally black wattle has been found to have very good screened pulp yield and to be suitable as a source of wood for pulp production. Locally the research has been of an *ad hoc* nature, and some of this work is described in this section. Taylor (1973), working on *E. grandis*, stated that variations in wood properties within and between trees were being studied to a greater extent in recent years, and summarised the importance of this type of work by saying “A knowledge of the variation in properties within a species is useful for estimating the wood quality of the existing timber supply and for intelligent planning of tree improvement programmes aimed at altering wood properties in future generations”. To emphasise this point Shaw *et al.* (1998) suggested that the forestry and pulp and paper industries are entering a new age in which they will need to have a better understanding of the quality of the timber entering the mills on more than volume, tonnage and moisture content.

The ability to non-destructively screen for kraft pulp yield would be a considerable improvement on the current destructive, labour intensive and expensive methods. Successful tree breeding programmes rely heavily on the assessment of large numbers of samples for the trait of interest. When the trait is kraft pulp yield, large-scale assessments are impractical (Schimleck and Michell, 1998). A non-destructive method of kraft pulp yield assessment for black wattle would allow tree breeders to directly select superior genotypes for the desired characteristic, and has the added benefit of conserving genotypes for later experimentation, further research and breeding.

2.3.1 Anatomy and general properties

Hannah *et al.* (1977) reported the fibre length of sixteen-year-old black wattle (syn. *Acacia mollissima*) trees to be 0.88 mm measured using a projection microscope. This figure places black wattle within the range of other hardwood species' fibre lengths reported by Taylor (1973); Hannah *et al*. (1977), Bamber *et al*. (1982) Bamber (1985) and Kibblewhite (1999) measured using a range of methods and tools including the graduated bull's eye method, a measuring wheel (map measurer) and a Kajaani FS 200 instrument. Many of the species tested are major contributors of raw materials to the pulp and paper industries. Although not a focus of this study, the chemistry and morphology of the fibres in wood and pulp ultimately determine pulp quality and end use (Kibblewhite, 1999). In another study, fibre diameter was measured with an average 14.2 µm (Bhat and Virmani, 1953, cited by Hillis, 1997). Black wattle has fairly numerous vessels (13 vessels/1000 fibres) when compared to *Eucalyptus fastigata* (8 vessels/1000 fibres), *E. nitens* (4 vessels/1000 fibres) and *E. regnans* (10 vessels/1000 fibres) (Hannah *et al*., 1977). Growth rings are indistinct, the sapwood is a pale straw colour and the heartwood is light brown with reddish markings. At ten years of age, commercially grown black wattle trees in South Africa seldom have stems larger than 23 cm in diameter and the tree stems are relatively straight (Hillis, 1997).

2.3.2 Mechanical properties

Hillis (1997) summarised figures obtained by various authors from air dry (12.5% moisture) wood for (Figures in italics are specifically from Banks (1954) describing black wattle grown in South Africa):

- Static bending (modulus of rupture 124 – 139 (*119*) MPa, modulus of elasticity 18 (*16*) MPa x 10^3);
- Compression parallel to the grain (stress at limit of proportionality) 35.1 MPa;
- Maximum crushing strength 41 – 59 (*63.1*) MPa, modulus of elasticity 14.3 MPa x 10^3;
- Maximum shear strength (on radial face 12.2 – 19.9 (*13.9*) MPa and on tangential face 15.7 – 21.1 MPa;
- Impact (Izod radial 25.9 N.m, Izod tangential 23.7 N.m,
- Toughness value radial 35.7 N.m, toughness value tangential 40.1 N.m);
- Cleavage (66.8 Nm m^{-1}); and
- Hardness (radial 6316 N, tangential 7074 (*7632*) N and end 8853 (*9038*) N).

2.3.3 Density

As previously mentioned, tree breeding programmes have, in the past, generally selected trees based on volume, stem form and branching habit. However, the situation is changing with the realisation that wood properties are also important (Raymond *et al.*, 1998). This was the situation in the case of black wattle until recently. With black wattle bark being the primary forest product during the expansion of the industry, it is notable that bark quality and tannin yield, over and above bark yield, were being assessed from as early as 1951 (WRI, 1951).

Smith (2002) reappraised some of the work done by Stubbings and Schönau (1972) and reported that the density of black wattle varied depending on where the trees were grown. The study included assessments in KwaZulu-Natal and south eastern Mpumalanga. The average oven-dry density of black wattle ranged from 682 kg m^{-3} in the KwaZulu-Natal midlands to 701 kg m^{-3} in northern KwaZulu-Natal, and peaked at 767 kg m^{-3} in south eastern Mpumalanga. The density seems to increase with decreasing latitude and this is a trend also found in *P. patula*, *P. elliottii* and *P. taeda* (Boden, 1982). The KwaZulu-Natal midlands measurement was confirmed in a subsequent density study of a progeny trial including 60 families of black wattle, where the mean density was recorded as 675 kg m^{-3} ([1]Hagedorn, 2003 *pers. comm.*). Dunlop *et al.* (2000) found the mean basic density of 30 families of black wattle to be 642 kg m^{-3}. In their study carried out in New Zealand, Hannah *et al.* (1977) found the mean basic density of five black wattle trees to be 593 kg m^{-3}. These results confirm that density varies with site within this species.

---

[1] Mr S. F. Hagedorn, Institute for Commercial Forestry Research, P O Box 100281, Scottsville, 3209.

2.3.4 Pulp yield

Historically, it was believed that eucalypts were unsuitable for pulp and paper manufacture. Extensive research has lead to the acceptance of many eucalypt species for commercial utilisation in the production of raw material for newsprint, magazine grade paper, writing paper and packaging materials (Logan, 1986). Plantation-grown eucalypts are now used commercially for pulp production in many countries around the world. Similarly, studies with other fast growing hardwoods have identified some of the Australian *Acacias* as promising for pulp production (Logan, 1986). In this study Logan (1986) compared six *Acacias*, including *A. mearnsii*, with *E. deglupta* and *Gmelina arborea*, two commercial pulpwoods from the tropics. All of the *Acacias* had higher screened pulp yields than *E. deglupta* and *G. arborea*, with black wattle having a screened pulp yield of 52.4%. Logan (1986) also pointed out that plantation-grown black wattle in South Africa, was used in blends with other hardwood species in kraft and soda-AQ pulp production and that black wattle woodchips were being exported to Japan for pulp production.

Few pulp studies have been undertaken on black wattle in South Africa. However, the mechanical pulp and bleaching properties are thought to be equivalent to *E. grandis* (Nicholson, 1991). In a study carried out on black wattle trees from Zimbabwe, Muneri (1997) found that black wattle produced 323 kg of pulp per m^3 of wood compared with 224 kg per m^3 for *E. grandis,* however, in this comparison the difference in wood densities of these species should also be taken into account, considering that black wattle has a higher wood density than *E. grandis* then their pulp yields are similar. This is due to a higher mass per volume of wood in the case of black wattle gives rise to more pulp but when expressed as a percentage the values obtained from the two species are similar, as pulp yield is defined as the percentage of the original dry mass of wood fibre remaining after pulping to a given content of residual lignin (Schimleck and French, 2002). In a study comparing several eucalypt species with black wattle, pulp yields of 57.9, 53.6 and 49.6% at 20 kappa were reported for black wattle, *E. fastigata* and *E. nitens* respectively (Hannah *et al.*,1977). Clark *et al.* (1992) compared the pulpwood potential of some tropical and temperate *Acacias*, including black wattle. From these few studies carried out on black wattle wood properties and market trends it is obvious that black wattle is a valuable pulpwood species

There have been no prior published studies dedicated to determine the variation in pulp yield of black wattle over a number of sites from a range of age classes, nor have any researchers tried to calibrate a NIR spectrophotometer to analyse pulp yield in this species. Therefore, there has also been no need to model the within-tree variation to establish a correlation between whole tree pulp yield and the value obtained from NIR using material from a single sampling point. From the literature it is very clear that even within a hardwood genus such as *Eucalyptus,* unique calibrations are necessary for each species and the within-tree variation of pulp yield differs from species to species (Birkett and Gambino, 1989; Michell and Schimleck, 1996; Schimleck and Michell, 1998; Sefara *et al*., 2000; Kube and Raymond, 2002; Clark and Hicks, 2003). Shaw *et al*. (1998) summarised the situation, stating that variation in important pulping properties have been demonstrated in wood from trees of different genera, species within a genus, between provenances of the same species, families and clones of individuals from a family. As black wattle belongs to the hardwood genus *Acacia,* it is fair to say that the variation in pulp yield within this species, and within individual trees could be different to other species, especially those from another genus. Therefore, this project could not simply use models developed for another species but rather had to follow a similar series of studies used in other species. The intention was to use the knowledge obtained by other researchers in this field, learn from their experience and apply the most acceptable protocols to achieve the aims of this study.

Chapter 3

Literature Review

3.1 Wood

There are various definitions of wood, but Zobel and van Buijtenen (1989) settled on the definition of Webster and McKetchnie (1980) which stated that wood is “the hard fibrous substance beneath the bark in the stems and branches of trees and shrubs: called xylem “. Despite the many definitions, wood is an extraordinary material that is variable and flexible and can be used to produce many kinds of products. Wood is made up of two types of sugars cellulose and hemicellulose, lignin, numerous types of extracts and other organic and inorganic substances and is used as a raw material in paper production, building materials, chemicals, energy and sometimes even food (Zobel and Buijtenen, 1989). The use of wood as a raw material has and will continue to be important in the fulfilment of human needs into the future. Globally the industrial use of wood equates to that of cement and steel and exceeds the use of plastics (Haygreen and Bowyer, 1996). Wood has many advantages over other raw materials some of which are: wood is a very versatile raw material, value can be added to wood to produce finished products with low energy inputs, the production of wood is more eco-friendly than other raw materials such as metals, plastics and cements, and wood is a renewable resource (Zobel and Buijtenen, 1989; Haygreen and Bowyer, 1996).

The use of wood as a paper-making fibre began in 1840 when non-woody sources of fibre became scarce (Britt, 1965; cited by Bamber, 1985), prior to this time cotton and linen had been used (Haygreen and Bowyer, 1996). The fibrous nature of wood was not readily perceived because the cells are bonded together into a compact mass (Hill, 1770 cited by Bamber 1985). It was not until the invention of the microscope in the 17th century that the cellular nature of wood was revealed, and only in the 18th century when techniques to macerate wood were developed, that the morphology of wood and its potential as a source of paper-making fibres could be appreciated.

3.2 Wood as a raw material for pulp

In the manufacture of pulp the composition of the raw material affects pulp yield and quality (Taylor, 1973; Shaw *et al*., 1998; Corson, 1999; Kibblewhite, 1999). Many tree species, both hardwood and softwood, grown in all parts of the world, are used extensively in the production of pulp. Hardwoods and softwoods differ greatly and are classified as angiospermae and gymnospermae respectively. They differ in reproductive structure with angiosperms having seed within ovaries and gymnosperm seed do not have a covering layer. Softwoods have needle-like leaves and hardwoods have broad leaves. Not only do hardwoods and softwoods differ in appearance but their wood also differs structurally (Haygreen and Bowyer, 1996). Under a microscope wood is seen to be made up of tiny cells or fibres. The types of cells, their relative numbers and their arrangement differ between hardwoods and softwoods, with hardwoods containing a type of cell called a vessel element which is seldom found in softwoods (Haygreen and Bowyer, 1996). Softwoods are made up of a few main cell types, with hardwoods having many cell types. 90-95% of softwood volume is made up of long cells called longitudinal tracheids, with ray cells making up the remainder. Hardwoods consist of four major cell types: fiber tracheid (15-60%), vessel elements (20-60%), longitudinal parenchyma (0-24%), and ray parenchyma (5-30%) (Haygreen and Bowyer, 1996). With these inherent differences between hardwoods and softwoods, compounded with differences between species, differences between trees and the influence of environment, it is clear that wood as a raw material is highly variable. This variability gives wood a great range of utility but it also detracts from it as an efficient raw material and this variability is also a reason why wood performance will never be precisely predictable (Zobel and Buijtenen, 1989; Haygreen and Bowyer, 1996). In the South African forestry industry the biggest single constraint in available commercial resources is the variation, which impacts both technically and economically and only through effective management and understanding can the true potential of the plantation resources be realised (Turner, 2001).

The relationships between wood quality and profitability of kraft pulp production are well documented (Borralho *et al.*, 1993; Greaves *et al.*, 1997), with wood density and pulp yield being two of the more important characteristics. For consistency within this study, the conventions as described by Zobel and Buijtenen (1989) defining wood properties and wood quality will be used. Wood properties will refer to cellular, anatomical and chemical characteristics of the wood within and among trees and wood quality will refer to the cumulative effect of the wood properties on some specified product or products.

3.3 Wood density and pulp yield in paper-making

Basic density and pulp yield combine to determine the mass of pulp available for the production of paper from a given volume of wood. Basic density is simply defined by the oven dried mass divided by the green or wet volume (Downes *et al.*, 1997). Specific gravity is another term that is used by many authors when referring to the density of wood but it must be clarified that specific gravity is a dimensionless value that expresses the ratio of the weight of a given volume of wood to the weight of an equal volume of water at 4°C (Zobel and Buijtenen, 1989; Haygreen and Bowyer, 1996; Downes *et al.*, 1997). The term basic density will be used in this dissertation and is viewed as the most important physical property of wood, with most mechanical properties of wood correlated to density

(Zobel and Buijtenen, 1989; Haygreen and Bowyer, 1996). Basic density is an important parameter when assessing raw material for pulping (Miranda *et al.*, 2001) and authors such as van Buijtenen (1982) state that “of all wood properties density is the most significant in determining end use”. Kube and Raymond (2002) emphasise this point by mentioning that not only does density affect the end product but also the profitability of any operation using wood as the raw material. More specifically density impacts on the financial success of pulp manufacture, expressed as tonnage, affecting transport costs, digester throughput and chemical consumption (Clarke, 1995; Zboňák, 2002). This is of particular importance to the black wattle chip export industry of South Africa, where the relatively high density of the chips makes them suitable for transport by ship to overseas customers and end users where the sellers of the chips are paid for tons and not for volume. Basic density assessments, therefore, formed an important part of this study.

Many pulp mills need to accept wood from various tree species and genera to maintain a steady supply of raw material into the mills. This is the case in South Africa, in that, a certain pulp mill accepts various eucalypt species as well as *Acacia*, *Populus* and *Casuarina* wood (Arbuthnot, 1991). In such cases certain criteria need to be met to ensure the production of consistent high quality pulp. In listing these criteria Arbuthnot 1991 mentions basic wood density first followed by pulping yield and other characteristics such as cellulose and lignin content, extractives, fibre length, fibre coarseness, cell wall thickness and other paper strength properties. In a study aimed at investigating the relationship between wood density and pulp and paper properties of some eucalypt species Arbuthnot (1991) concluded that the basic wood density of the species studied was the major determinant of pulp and paper-making properties. He found the relationship to be of particular interest due to the high degree of correlation found because the relationship seemed to be independent of species or tree age. These result supported those published by Hillis and Brown (1978). Furthermore, Barefoot *et al.* (1966) and Artuz-Siegel *et al.* (1968) refer to the important relationship between wood density and pulp and paper properties. Pulp yield is the other important component of this study.

Density is also related to the strength and quality of solid wood products which are important in lumber (Pearson and Gilmore, 1980), energy yield is also dependent on specific gravity (Goldstein, 1980). These two properties are not discussed in this study but black wattle is used to a limited degree in furniture manufacture and is used extensively in South Africa for firewood and charcoal (Sherry, 1971).

Density is affected by many factors through their effect on growth patterns which affect cell morphology and chemistry. Silviculture, including fertilization, site quality and stocking, growth rate and genetics can also influence density (Zobel and Buijtenen, 1989). There is also large variation in density within trees of the same species (Higgins, 1970; Taylor, 1973; Downes *et al*., 1997; Clark, 2001). Hall *et al*. (1973) make the significant statement that low density woods generally produce superior pulp to that of high density wood.

Sampling trees for basic density can be achieved by taking discs from the tree (destructive sampling) or by taking increment cores or by using a pilodyn (non-destructive sampling) (Schimleck and French, 2002). Basic density is often used as a relatively cheap and easily measurable indicator of wood quality, in the evaluations of forest resources (Downes *et al*., 1997).

The separation of wood into its constituents by the destruction of the bonds between the cells is called pulping and can be achieved mechanically, chemically or semi-chemically (Bamber, 1985). The kraft pulp process used in this study is the world's predominant chemical pulping process and was developed in Germany in 1884 (Haygreen and Bowyer, 1996) and the process involves cooking (digesting) wood in an alkaline solution (liquor) made up of sodium hydroxide and sodium sulphide for several hours, during which time the chemicals attack the lignin in the wood, which bonds the fibres together, fragmenting it into smaller segments. The dissolved lignin is later removed leaving behind the cellulose fibres or pulp. The liquor and dissolved lignin is burnt and the expensive alkaline chemicals recovered for re-use. Kraft pulp is dark brown and is bleached before being used in paper-making (Martin, 1994; Pulpwatch, 2003).

3.4 Pulp yield

Pulp yield is an important parameter in the paper industry and relates to cellulose, extractives and lignin content of the tree as well as its density (So *et al*., 2004). It can also be defined as the percentage of the original dry mass of wood fibre remaining after pulping to a given content of residual lignin (Schimleck and French, 2002). Pulp yield is normally quoted at a constant kappa number or state of delignification. However, standard kappa numbers are rarely used in the literature and it is therefore difficult to compare pulp properties from different studies (Clarke, 1995). Along with stem volume and density, pulp yield is important in the economics of pulping because wood is the predominant cost of kraft pulp production (Clark *et al*., 1992; Downes *et al*., 1997). Considerable work has been done on pulp yield within the *Eucalyptus* genus and has been found to vary between and within species depending mostly on age and on climatic and site factors. The differences between species in pulping characteristics is exerted mainly through the wood properties such as basic density, extractives content and vessel number. These characteristics are under genetic control but are also highly dependent on the age of the tree and to a lesser extent on the environmental factors (Higgins, 1970). Hall *et al.* (1973) studied eleven eucalyptus species in their natural habitat in Australia and found that stand characteristics, apart from age, did not significantly affect kraft pulp properties.

However, South African researchers place some emphasis on the concept of Site Index (SI). SI is calculated as the mean tree height attained at a reference age of five or 10 years (Schönau, 1969), for the area being evaluated, and the general consensus is that as SI increases so does pulp yield (Shaw *et al.,* 1998; Megown *et al.*, 2000; Turner, 2001). Megown *et al.* (2000) studied a single *E. grandis* clone (Tag 5) and found that SI was more important than age when describing the variation in pulp yield of this clone. Hannah *et al.* (1977) measured the basic density and assessed the pulp yield of three eucalypt species (*E. fastigata*, *E. regnans* and *E. nitens*) and two *Acacia* species (*A. decurrens* and *A. mollissima*) and found a range of basic densities from 380 to 460 kg m^{-3} for the eucalypts and the *Acacias* had basic densities of 457 and 593 kg m^{-3}. The three eucalypts produced pulp yield of 50.5 to 54% and the *Acacias* produced about 56% pulp yield. Shaw *et al.* (1998) refer to work done by various authors looking for variation in eucalyptus species that can be exploited from a tree breeding perspective. They state that these studies have demonstrated large differences in the pulping properties between eucalypt species. Clarke *et al.* (1999) examined nine eucalypt species of the same age and seedlots planted at two different sites that differed mainly in altitude, MAT and MAP. Growth rate was 20% higher at the warmer, lower site but the trees had significantly more lignin. However, they delignified more easily, consumed less alkali and produced higher pulp yields. Farrington and Hickey (1989) demonstrated that felling age strongly influenced pulp yield in three eucalyptus species (*E. globulus*, *E. regnans* and *E. nitens*) although these researchers were using very old trees. The effects of age and site on pulp yield have been observed in the *Acacia* genus (Fang *et al.*, 1994; van Wyk and Gerischer, 1999, unpublished), where these authors reported that age did not significantly affect screened pulp yield in trees between eight and ten years of age.

3.5 The within-tree variation of basic density and pulp yield

A key in the development of efficient screening tools is the use of non-destructive sampling of standing trees (Turner, 2001). When attempting to non-destructively sample a whole tree to get a representative figure of either density or pulp yield, or any other characteristic of importance, a sound understanding of the within-tree variation of the characteristic is important. Due to the large variation in wood properties from pith to bark, and from the base of the tree to the tip, the type of sample and its position in the tree is critical to ensuring that a true representation of the whole tree can be extrapolated from the sample (Clarke and Wessels, 1995). Knowledge of variation between trees and across sites is also important when trying to predict the value of a plantation. Once all the sources of variation are known, it is possible to quantify the value of the available plantation resource (Downes *et al.*, 1997). Corson (1999) pointed out that wider international attention is now being given to paper quality differences resulting from wood quality differences within a species due to age, site as well as position in the tree effects.

In general, density increases from pith to bark, and from the base of the tree to the top in eucalypts (Unkalkar *et al.*, 1975; Downes *et al.*, 1997). Batchelor *et al.*, (1970, 1971) studied the within-tree variation in basic density and soda pulp yield of the wood from five major eucalypt species (*E. delegatensis*, *E. obliqua*, *E. amygdalina*, *E. viminalis* and *E. regnans*). They found that the basic density variation in trees was not similar for all of the species, *E. delegatensis*, *E. obliqua* and *E. amygdalina* showed a rapid increase in basic density with height to 30% of the merchantable height and then no further increase with height, *E. viminalis* and *E. regnans* exhibited a steady increase in basic density from the base to the top of the tree. For all of the five species pulp yield increased rapidly from the base of the tree up to 10 to 20% of height, with maximum yields at about 30% height and then decreased up the tree.

Crawford *et al.* (1972) sampled two trees of *E. delegatensis* with similar girth and height but with differing growth rates at various heights and from sapwood to pith. These samples were pulped by the soda process to a constant Kappa number and basic density was also measured. The results were used to construct diagrams to depict zones of equal yield, soda charge and basic density within the trees. These presumably hand drawn diagrams are precursors of the tree maps that researchers today produce using modern software packages. Their general conclusion with respect to basic density was that this property increases with age of the tree and for wood of a particular age basic density increases with height in the tree with a more pronounced increase in the lower part of the tree. Pulp yield was found to decrease from the sapwood (44%) towards heartwood (38%) and then peak at 46% near the pith and then decrease again at the pith.

Schimleck and Michell (1998) showed that pulp yield varies radially and from the base of the tree to the top in 15 *E. nitens* trees, aged 18 years. In general the pulp yield increased from the pith to the bark. Pulp yield increased in all the trees from the base to between 10 and 20% height and then either stayed constant for most of the rest of the tree or declined slightly towards the top of the tree. In one tree the pulp yield then increased from 70% height to 90% height.

Kube and Raymond (2002) sampled 55 trees from three sites while assessing the variation in basic density and other properties within 12 year old *E. nitens* and evaluating the ability to predict whole tree values from core samples. They found that basic density differed significantly ($P<0.001$) at the different sampling heights and that the variation pattern was similar at all of the sites. Basic density decreased from the base of the tree to the 10% height and then increased linearly to the 70% height.

Although a number of authors have studied the within tree variation of properties such as basic density and pulp yield, according to Downes *et al*. (1997) very little work has been done in this field and the use of modern technologies such as NIR methods allow for more extensive studies to be done more easily, cheaply and quicker. The ability to analyze larger sample number per tree will also add resolution to the trends obtained and allow for more accurate assessments of the variation patterns.

3.6 Near infrared spectroscopy (NIR)

NIR forms part of the electromagnetic spectrum in the wavelength range 780 nm to 2 500 nm and NIR spectroscopy is based on the absorption of electromagnetic radiation at wavelengths in this range (Osborne, 2000; So *et al*., 2004). Most of the major absorption peaks are found between 1450 and 2500 nm and consist of broad bandwidths. Spectra that occur in this region consist of overtone and combination bands of the fundamental stretching vibrations of –OH, -NH and –CH functional groups (Wetzel, 1983). The spectra obtained are complex but a major advantage that NIR spectroscopy has over other laboratory methods of pulp yield determination is that the spectra contain simultaneous information about all the chemical constituents of the wood sample, which could influence the pulp yield, so the decision of which constituent is important for pulp yield is avoided (Downes *et al*., 1997). The presence of underlying smaller bandwidths and peaks is resolved by applying a second derivative algorithm to the spectra. The basis for vibrational spectroscopy uses the concept that atom-to-atom bonds within molecules vibrate with frequencies that can be quantified (Ciurczak, 2002). The study of NIR is not new and was first observed by Herschel (1800) as the radiation beyond the red portion of the visible spectrum, which was detectable on a photographic plate (Osborne and Fearn, 1986).

NIR reflectance spectroscopy uses the diffuse reflectance of dried ground samples. Each constituent (e.g. cellulose or protein) of complex organic matter has unique absorption properties in the NIR region of the spectrum. These properties result from the bending and stretching vibrations of strong molecular bonds between light atoms (Wessman *et al*., 1988). The procedure involves capturing reflectance spectra after near-infrared radiation is allowed to penetrate the ground sample of the analyte. The spectral information obtained is then calibrated against results obtained using conventional analytical techniques, using linear regression (Sefara *et al.*, 2000). Today, NIR spectroscopy is used as an analytical technique in many research and industrial applications (Wetzel, 1983), McClure (1994) states that virtually no analytical discipline remains untouched by NIR research.

So *et al.* (2004) published an in-depth appraisal of the use of NIR in the forest products industry and claim that NIR technologies had gone unnoticed by the wood research community, with many research organizations now developing appropriate applications. The use of NIR for the rapid assessment of wood properties is growing fast and has implications for wood quality assessments and ultimately tree improvement. So *et al.* (2004) also go on to say that many manufacturing processes are now using NIR as a means of online monitoring and has encouraged many laboratories to investigate the potential applications in wood composites.

Properties such as wood chemistry, fibre morphology and mechanical and physical properties have not been extensively assessed in tree improvement programs due to the inability to rapidly measure these characteristics. There are, however, tree breeding programs in South Africa that have focussed on wood properties such as splitting in some of the *Eucalyptus* species (Malan, 1979; [2]Swain, 2007 *pers. comm.*). These characteristics have been found to be under different levels of genetic control. The development and advancements in NIR spectroscopy has provided tree breeders with a tool to rapidly assess the wood quality of standing trees (So *et al.*, 2004).

The use of x-ray diffraction, x-ray densitometry and image analysis to measure wood properties, such as density, stiffness, microfibril angle, tracheid diameter, coarseness and wall thickness (directly and indirectly) from a single increment core is the basis of the SilviScan system developed at CSIRO in Australia (Downes *et al.*, 1997; So *et al.*, 2004). SilviScan data have been used to calibrate a NIR spectrometer to predict many of these properties (So *et al.*, 2004). Clearwood mechanical properties are a function of wood density and chemistry and microfibril angle and therefore NIR spectroscopy can be used to measure the stiffness of increment cores (So *et al.*, 2004). The potential of NIR spectroscopy to predict pulp yield from small ground wood samples has been demonstrated for a number of eucalypt species by authors such as Michell (1995), Birkett *et al.* (1988) and Wright *et al.* (1990).

NIR analysis is very simple with little room for operator error. It does not necessarily require technically skilled personnel and may even allow for the system to be automated.

---

[2] Ms T-L Swain, Institute for Commercial Forestry Research, P O Box 100281, Scottsville 3209

Technological advancements in recent times, especially in computers have made NIR assessments more accurate and quicker (Osborne and Fearn, 1986; Burns and Ciurczak, 2001; So *et al.*, 2004). Recent trends in the manufacture and design of NIR instruments have been to make them more portable and robust enough to take in-field. These instruments are being used in areas of research such as inspection and security, forensics, safety and quality, pharmaceuticals, food, beverages, and agriculture; environmental analysis, authentication, and medicine (Workman, 2009).

Obvious advantages of NIR spectroscopy over other analytical techniques, such as NMR (nuclear magnetic resonance), X-ray diffraction and GC (gas chromatography) for example, are the speed at which analyses can be done, the non-destructiveness of the technique, simple sample preparation and the versatility of the technique (Osborne and Fearn, 1986; Swamy *et al.*, 2000; Burns and Ciurczak, 2001; Bokobza, 2002). Several constituents of a sample can also be measured concurrently (Osborne, 2000). The application of multivariate analysis (MVA) to NIR spectra has also increased the interest in this analytical technique, as it reduced the problems associated with overlapping signals. This was successfully demonstrated by Norris and Hart (1965, cited by So *et al.*, 2004) when they collected reflectance spectra from wheat and other foodstuffs, to measure moisture content (So *et al.*, 2004). The degree of overlap and the complexity of bands made NIR spectra very difficult to interpret until the advent of computers, which could more easily handle the absorbance data from many spectra, as well as the multivariate statistical methods (Downes *et al.*, 1997). By the late 1980s this technology was being used by the pulp and paper industry (Birkett and Gambino, 1988, 1989; Wright *et al.*, 1990; Garbutt *et al.*, 1992). Today the potential of NIR spectroscopy has been recognised and embraced by the forest products industry (So *et al.*, 2004).

The major disadvantage of NIR spectroscopy is that it is empirical, and there is no mathematical law that describes the interaction of radiation with a sample consisting of heterogeneous absorbing species. This necessitates calibration of the instrument with samples of known composition (Osborne and Fearn, 1986). This preliminary work may be time consuming but is easy to perform (Osborne and Fearn, 1986; Burns and Ciurczak, 2001). Sophisticated software available today offers the user many options of data treatment such as multiple linear regression (MLR), partial least squares (PLS), principal components regression (PCR), factor analysis (FA), neural networks (NN) and Fourier transformation (FT). The time spent calibrating the instrument, is overshadowed by the many advantages of NIR analysis (Burns and Ciurczak, 2001).

NIR spectroscopy has been successfully used to predict pulp yield in other hardwood species as already discussed. Therefore it is likely that it can be used with black wattle. A major benefit is the ability to non-destructively sample from standing trees, preserving these for further research applications, if necessary. The fact that this technique is much quicker and cheaper that conventional methods of pulp yield analysis also facilitates the analysis of large numbers of samples (Schimleck and Michell, 1998). This is of particular importance in a tree breeding scenario where large numbers of trees from whole trials or populations need to be assessed.

The NIR spectrophotometers are calibrated before use in quantitative measurements (Osborne and Fearn, 1986). Calibration, and more specifically spectroscopic calibration is defined as “the process of constructing a model that is used to predict characteristics or properties of unknown samples” (Beebe *et al.*, 1998). Calibration for one or two component matrices can be elementary, but the situation becomes more complex when dealing with biological samples where minute changes in absorbance can indicate large concentration changes, and interfering bands overlap with the bands of interest (Workman, 2001). There are a number of methods of calibrating NIR instruments (Osborne, 2000; Mark, 2000). No matter which mathematical approach is used, the first step is to carry out a calibration experiment. The theory behind this process is based on finding useful variations in two sets of data and establishing regression relationships between these (Michell, 1994).

3.7 Uses of NIR analysis in wood and pulping property

Wood can be classified in various ways according to its chemistry and morphology, and suitability for different purposes and processes can be based on these classifications (Schimleck *et al.*, 1996). In this study, the main interest lies in the suitability of black wattle for chemical pulping, and therefore an indication of the chemical differences of wood samples is important. Chemical differences in wood can be expressed as atomic formulae, functional groups, or in terms of larger chemical entities, such as the content of extractives or lignin (Schimleck *et al.*, 1996). These analyses are time consuming, expensive and inappropriate for screening large numbers of samples in a tree improvement programme.

The ability to measure wood quality at various heights up the tree, and the variation from pith to bark, has led to the production of wood quality maps, which are used to identify the effect of growing conditions on the characteristics under study (So *et al.*, 2004).

As discussed previously, vibrations of chemical bonds give rise to bands in vibrational spectra. Changes in the spectra reflect changes in the underlying chemistry of the substance (Schimleck *et al.*, 1996). These spectra can be measured cheaply and quickly and, in principle, differences in chemical content could be used to classify wood. Prior to 1996, spectroscopy was used to predict differences in chemical components of wood such as lignin, acetyl and carboxyl content, but a means to classify wood in a more systematic manner was not available (Schimleck *et al.*, 1996). This was mostly due to the difficulties in handling the very large numbers of data points which arise from these spectra.

NIR spectroscopy has been used to measure pulp yield in both eucalypts and pines with acceptable levels of accuracy (Birkett and Gambino, 1988; Wright *et al.*, 1990), and this study is possibly the first to use NIR spectroscopy to measure within-tree variation of pulp yield in black wattle. Other characteristics that have been measured using NIR spectroscopy include lignin and cellulose contents, brightness, viscosity and degree of polymerisation (Birkett and Gambino, 1988; Wright *et al.*, 1990; Schultz and Burns, 1990).

3.8 Modelling within-tree variation

Downes *et al*. (1997) describe and discuss four possible conceptual patterns of variation within trees, which generally retain a growth ring structure, although this is not always the case. These are:

- Cylindrical symmetry which does not include a ring structure but conforms to a pattern of cylindrical symmetry,
- Conical symmetry where properties do not differ with height but rather within each ring or growth layer i.e. radially,
- General linear in which the property varies with height and radius, and
- General non-linear where the property of interest may vary non-linearly with height and radius.

These patterns of variation allow the development of general mathematical models to quantify the distribution of wood properties within the trees. For the purpose of this study the cylindrical symmetry pattern of variation was followed and in Chapter 5 the variation found by analysing the predicted screened pulp yield assessed at various heights and distances from the pith is discussed.

Sardinha (1974) followed a sampling strategy that he termed sheath and core sequences. The sheath sequence measures variations within each single ring followed from the base of the tree to the crown. Therefore in each sheath, there is wood that is formed in the same year but from cambium of a younger age as one proceeds up the tree. This wood development is also referred to as oblique. Another sequence of wood development is termed horizontal where the variation in wood properties are shown by their change from the pith to the bark at chosen intervals of height. The wood under study in this regime is formed by cambia of different ages in a series of years. The third sequence of interest is vertical where wood properties are tracked for successive internodes up the tree, but at constant ring number from the pith, i.e. wood formed by cambia of approximately the same physiological age but formed in successive years, referred to as the core sequence.

The within tree sampling strategy employed in this study was not as refined as that of Sardinha (1974) but the samples taken and data obtained can be roughly equated to the three sequences described above. The method used to divide the individual discs in this study, did not use annual rings but rather a mathematical proportion. This does not allow exact ages of wood to be compared but does allow the change with age to be investigated across the discs (horizontal) and in similar regions within the stem from pith to bark as in the vertical sequence and from bark to pith as in the sheath sequence. Sardinha's (1974) approach and disc divisions using growth rings suited the use of x-ray densitometry to measure the change in density from pith to bark or *vice versa* depending on which sequence, either core or sheath, was being evaluated. However, in this study the amount of sample needed for the NIR analysis required larger segments of wood to be milled that what would have been obtained from single growth rings if they could have been determined.

The general model that Downes *et al.* (1997) describe (Equation 3.1) predicts a whole-tree value for each property under investigation, based upon the value of a single growth ring (in this study a single radius) determined from a single sampling point. The model assumes the presence of annual rings, which may not always be present, and contains terms which allow for variation with height, distance from the pith and an interaction term. This equation needs to be summed or integrated over the whole tree to calculate whole-tree values.

Work carried out by Evans *et al.* (1995) shows variation in wood properties within a softwood species, but little information has been reported for eucalypts, and the available reports are, according to Downes *et al.* (1997), contradictory. Equation 3.1 was developed by Downes *et al.* (1997) to estimate average properties of a growth ring at any point within a stem. Hardwoods from tropical or sub-tropical environments, do not have growth rings, however, eucalypts conform to this type of variation (Downes *et al.*, 1997). Although black wattle does not have growth rings, the cross-sectional discs used in this study were sub-sampled in a manor that mimics growth rings or periods (described in more detail in Chapter 4), and it was envisaged that an equation similar to Equation 3.1 would be able to accommodate the radial and vertical variations in pulp yield.

$^{*}P_{ij} = \square + \square_i H^{k} + \square_j R_{N}^{l}$ ....[Equation 3.1]

where

P_{ij} = average value for the wood property in any ring at any point in the tree;
$\square$ = value at zero height in first ring under the bark;
$\square_i$ = coefficient describing rate of change with height within ring number i;
H = height in tree;
k = power term for height;
$\square_j$ = coefficient describing rate of change from bark to pith at height j;
R_N = ring number from bark; and
l = power term for radial variation

[*] For clarity, subscripts omitted by Downes *et al.* (1997) are included in the equation.

An equation similar to [Equation 3.1] was fitted to the data collected in this study and the results are presented in Chapter 6. The data were also subjected to a linear regression analysis, and an equation was derived in this manner to predict point sample pulp yields for black wattle. This equation is also given in Chapter 6.

There are a number of possible sampling techniques for assessing forest plantations for wood and pulp properties, they include using billets (part of the stem), whole stem chip samples, disc samples and pilodyn sampling. These techniques are summarised in Table 3.1, indicating their advantages and disadvantages. The merits of billet and disc sampling of black wattle trees are discussed later in this document.

Table 3.1 A list of various sampling techniques and their advantages and disadvantages, that are available for wood and pulp property assessments of trees (after Downes *et al.*, 1997).

Sampling technique	Advantages	Disadvantages
Billets	Quick Portable Suits trees of all sizes	Tree representation is poor or unknown Bias Destructive
Whole-stem chips	Good tree representation Simple	Slow and expensive Problems related to subsampling chips Can be difficult to transport Destructive
Discs	Potentially good representation if taken at regular intervals Chips may be very uniform	Chipping of discs can be slow and expensive Difficult with small or very large trees Destructive Chipped samples are not true representations of the industrial process. Liquor penetration is different due to the lack of fissures and cracks caused by industrial chippers
Increment cores	Suitable for large sample numbers Quick Non-destructive (theoretically) Minimal stem damage	Poor tree representation Difficult with small or very large trees Over-representation of inner rings Stem decay after coring damage Core alignment is important Chipped samples are not true representations of the industrial process. Liquor penetration is different due to the lack of fissures and cracks caused by industrial chippers
Pilodyn sample	Suitable for large sample numbers Quick Non-destructive Improve accuracy by taking multiple readings Minimal tree damage	Poor tree representation Difficult for small trees Only measures outer ring(s) Sensitive to reaction wood May vary with season

Chapter 4

Materials and Methods

The methodology followed during this study allowed the author to investigate firstly, the variation in tree growth and pulp yield of *Acacia mearnsii* (black wattle) at a macro level by sampling ten trees from each of three age classes (7, 9 and 11 year old) from three sites in the KwaZulu-Natal midlands. Only at one site (Bloemendal), was it possible to sample the three age classes from compartments that were adjacent to each other, at the other two sites the different age classes were sampled from compartments that were some distance from each other. Therefore age effect is treated cautiously as the overall site effect could mask the effect of age. Tree growth data were collected in the field and pulp yield data were obtained using laboratory scale kraft pulp digesters. Basic density was calculated using cross sectional discs cut from the trees during sampling. The laboratory-obtained, pulp yield data were then used to calibrate a NIR spectrophotometer to predict pulp yield values from small wood meal samples taken from the same black wattle trees. This calibration model was then applied to a set of 30 trees sampled from one age class (11 year old), at one site (Bloemendal) in order to measure the within-tree variation in pulp yield. In order to construct a tree map depicting changes in pulp yield from the base of the tree to the top of the tree (longitudinal variation) and from the bark to the pith (radial variation), each of these 30 trees were extensively sampled. Cross-sectional discs were collected at 10 heights from 10 trees, the remaining 20 trees were sampled at four heights. The cross-sectional discs where also cut in circles to represent different percentages of the disc from bark to pith. These circles were intended to mimic growth rings for periods in the tree's development. Ground wood meal samples from these disc segments were then analyzed using the NIR spectrophotometer to predict screened pulp yield from that position in the tree, these data were then used to assess the within-tree variation in pulp yield, the information obtained from these disc samples were used to simulate a sample taken across the radius of the stem and inferences can then be made with respect to the growth of the trees. These results were then used to derive an equation that predicts whole tree pulp yield from a single sampling point at a fixed height up the tree.

This site selection and sampling regime could have been used to much more benefit if more funding was available. The author had to ignore the possibilities of carrying out other analytical techniques such as □-ray densitometry, as described by Grzeskowiak *et al.* (2000) and Zboňák (2002), to measure the within tree variation in density or florescence microscopy combined with image analysis to evaluate a number of other wood anatomical characteristics such as fibre diameter, fibre lumen diameter, fibre wall thickness, vessel diameter or vessel frequency as described by Grzeskowiak *et al.* (2000) for six different

Eucalyptus genotypes. This noted gap in the current knowledge of black wattle wood properties hopefully will become the topic of future study. Duplicate disc samples taken from the trees used in this study have been stored at the ICFR.

4.1 Assessing tree growth and pulp yield across site and age

The age classes chosen for this part of the study were seven, nine and eleven years and are in keeping with the rotation lengths practiced on black wattle in South Africa. The three selected age classes represent the latter part of the growth cycle and no consideration is given to the early part of the growth cycle. It is unlikely that the rotation age of the species will be lengthened beyond the current maximum of 12 years. However, if the pulp yield is found to be acceptable at a younger age (seven years), it is feasible that rotation lengths could be shortened on certain sites, depending on whether a maximum mean annual increment is achieved or not. Another important consideration to be taken into account if a reduction in rotation age is suggested is that the bark of black wattle is considered immature before eight years of age (Schönau, 1979). Therefore, the grower would need to weigh up the benefits of felling his plantations earlier for the timber only and being able to replant the next crop sooner against getting the dual income from the timber and bark at a later harvest date.

Three experimental sites were selected to represent a range of production areas in the KwaZulu-Natal province. The information used to select the sites was obtained from the South African Wattle Growers Union (SAWGU) and two main assumptions were made and applied to the data collected. Firstly, the selected sites were assumed to have been drawn from a wide population of sites with similar environmental conditions. Under this assumption, the sites (three different plantations) were treated as random effects. The plantation-by-age interaction was subsequently a random component used as an error term in testing the differences between the ages with respect to the characteristics assessed. The second assumption made was that the sites were specifically chosen to identify differences in tree growth and pulp yield across these three sites. Under this assumption the site (plantations) were treated as fixed effects. These two assumptions were investigated separately and ultimately the first assumption was adopted and defended in Chapter 5, and the results obtained under these conditions were used in drawing various conclusions and making recommendations. The approach of testing these two scenarios was done in order to assess if the results obtained could be extrapolated to form a general rule for black wattle in the KwaZulu-Natal province or if the results should be restricted to being indicative of the three sites sampled. The information on the three sites is given in Table 4.1. A detailed soils analysis was conducted at each sampling site and the soils information is given in Appendix 1. Basic density has been shown to be influenced by latitude (described in

Chapter 2) but this factor could not be considered when choosing the sampling locations for this study due to funding and other practical constraints for the sampling exercise.

Table 4.1 Detailed information on the three selected sites.

Site	Compartment	Age of trees (years)	Longitude (E)	Latitude (S)	Altitude (m.a.s.l.)	MAT (°C)	MAP* (mm/year)
Bloemendal	12a	7	30°27.875'	29°32.404'	840	17.6	897
Bloemendal	11c	9	30°27.872'	29°32.400'	840	17.9	862
Bloemendal	13	11	30°27.826'	29°32.447'	870	17.9	800
Glen Echo	W010	7	30°26.261'	29°58.645'	690	18.6	848
Glen Echo	2a	9	30°27.191'	29°56.150'	960	18.3	813
Glen Echo	W007	11	30°26.464'	29°57.511'	720	18.0	752
Phoenix	W83	7	30°27.281'	29°55.740'	960	18.3	1098
Phoenix	W92	9	30°26.150'	29°56.181'	840	17.7	1061
Phoenix	W93	11	30°27.388'	29°56.190'	840	18.3	973

*MAP – Mean average precipitation, calculated for the lifetime of the sample trees.

4.1.1 Selecting random sample of trees

Stage one of the study dealt with assessing the variation in growth characteristics and pulp yield in black wattle. Ten trees were randomly selected for each site-by-age combination. The sample trees were selected by drawing a single diagonal through the compartments, this diagonal was measured and divided by ten, a tree was then selected as close as possible to each calculated interval on the diagonal. Collectively, across the age classes and sites, a total of 90 trees were randomly sampled. The samples taken from these trees were then used to calibrate the NIR spectrophotometer, and later used to predict screened pulp yield of samples taken at various positions in selected trees to analyse within-tree variation in pulp yield.

The site, age and tree selection methods described above along with the more detailed sub-sampling methods described later in this chapter resulted in a multi-stage sampling procedure. The sampling exercises were intended to start at a macro level of dividing the wattle growing area into three sites, the ages of wattle trees grown commercially in South Africa into three ages, then move to a micro level by using 10 sample trees to represent each of these areas and age classes, this gave a total of 90 sample trees. Later in the study 30 trees (10 of which were used in the first part of the study) were sampled extensively (as described later) to study the within tree variation of predicted pulp yield, *viz.* a single age class (11 years) and a single site (Bloemendal).

4.1.2 In-field measurements and derived parameters

Prior to felling, the following measurements and assessments were taken for each of the selected tree:

- Diameter at breast height (1.3 m) over bark (Dbhob) measured using a specially calibrated diameter tape.
- The neighbouring trees were counted. If all the immediate neighbours were present a total of eight trees would have been counted. This count was used as a covariate in some preliminary analyses.
- The stem form was assessed, and scored on a scale of 1 – 4. The straighter the tree the higher the score.
- Incidence of disease was assessed and scored from 0 – 4. Disease-free trees were given a score of 0.
- Four bark discs of known diameter were removed from the tree at shoulder height and the mass of the wet discs measured.

Diameter at breast height is one of the standard measurements taken when measuring growth in most forestry research programmes. Together with height, it is used to calculate tree volume. The neighbouring trees were counted to assess the average stocking density (sph) of the sample block and to assess the effect that missing trees had on the growth of the sample trees. Stem form is a standard assessment carried out in the black wattle breeding programme at the ICFR, as is the incidence of disease. The bark discs were taken primarily to calculate bark thickness (Dunlop, 2002c), according to the formula published by Nixon (1977). This data is not presented in this dissertation but was information that was easily obtained during the tree sampling for this study and was intended for internal ICFR use.

The trees were then felled, using a chainsaw, and the following measurements and samples were taken:

- Total height (Total_Ht) was measured using a 30 m tape measure.
- Utilisable height (Ut_Ht) was measured as the height of the tree to an under-bark diameter of 5 cm.
- A billet (on average 1.2 m) was taken from the base of the tree, about 30 cm above the felling cut which was on average about 20 cm above the ground.
- A cross-sectional disc (5 cm thick) was taken immediately above the billet for density determination.
- The bark was then removed from the billet and from the piece of the bole below the billet, and under-bark diameter was measured at breast height (Dbhub) and at the bottom of the bole (Gldub).

Total height was used in the calculation of total tree volume, Ut_Ht was used in calculating the volume of timber acceptable to processors, as the very tips of trees are not accepted by pulp mills. The under-bark diameters and ground line under-bark diameters were measured to accurately calculate timber volume. These data were used to calculate individual standing tree volume, up to a tip diameter of 5 cm, using the volume equation developed by Schönau (1972) (Equation 4.1), adapted from the Schumacher and Hall (1933) equation.

$$ln\ (\text{Volume}) = 1.95322 ln\ (\text{Dbhob}) + 1.2315 ln\ (\text{Total\_Ht}) - 4.7406 \quad \text{[Equation 4.1]}$$

4.1.3 Density determination and billet chipping

Density is the ratio of the mass of a given quantity of a substance to the volume of that given substance, and is expressed in terms of mass per unit volume, in this situation kg m^{-3} (Little, 1999). Basic wood density for each tree was measured according to the TAPPI method T 258 om-85 (Tappi, 1988) using the disc taken above the billet, by dividing the oven-dry weight of the disc by its wet volume. Disc volume was measured by water displacement after the discs had been thoroughly saturated with water. This was carried out at the ICFR. The formula used to calculate basic wood density is:

$$D_B = \frac{Oven\ dry\ mass\,(kg)}{Wet\ volume\,(m^3)} \quad \text{[Equation 4.2]}$$

The billets were chipped using a Demuth transportable chipper (Figure 4.1) at Sappi's Shaw Research Centre, near Howick. The chips from each billet were then mixed thoroughly in a rotating concrete mixer, after which over-sized chips and other debris were removed. The chips were then transported to the Forestry and Forest Products (FFP) centre of the CSIR in Durban for laboratory scale kraft pulping.

Figure 4.1. Demuth transportable chipper used to chip the billets.

4.1.4 Kraft pulp yield assessment

At the FFP, a representative sample of chips from the 90 individual billets were pulped under the cooking conditions described in Table 4.2, in a laboratory scale digester (Figure 4.2). The wet chemistry screened pulp yield data obtained from the billet was used as a representative sample of the tree as it contains juvenile and mature wood and being at the base of the tree, where the tree is thickest, per metre of billet a large proportion of the tree is sampled. A single billet sample taken from the tree has been used by other researchers a representative sample of the tree (Hall *et al*., 1973; Turner *et al*., 1983). A detailed description of the laboratory procedure followed is provided in Appendix 2.

Table 4.2 Cooking conditions for laboratory pulping of chips from individual *Acacia mearnsii* trees.

Wood charge	800 g oven-dry
Active alkalinity	18%
Sulphidity	25%
Cooking liquor to wood ratio	4.5:1
Maximum temperature	170 ºC
Cooking time (Kappa 20)	Varied

Figure 4.2 The laboratory scale digester used for pulping the samples of the *Acacia mearnsii* samples.

4.2 Near Infrared Spectrophotometer Calibration

4.2.1 Sample sites, ages and trees

The 90 trees used to assess the variation in pulp yield in black wattle were used to calibrate the NIR spectrophotometer. At the same time that a chip sample was taken from each billet for pulp yield analysis, a second chip sample was taken for calibration of the NIR spectrophotometer. The second chip samples were Wiley-milled into fine wood meal and screened sequentially through a 40 – 60 mesh (Figure 4.3). Approximately 10 g of sample was prepared for scanning by the NIR spectrophotometer.

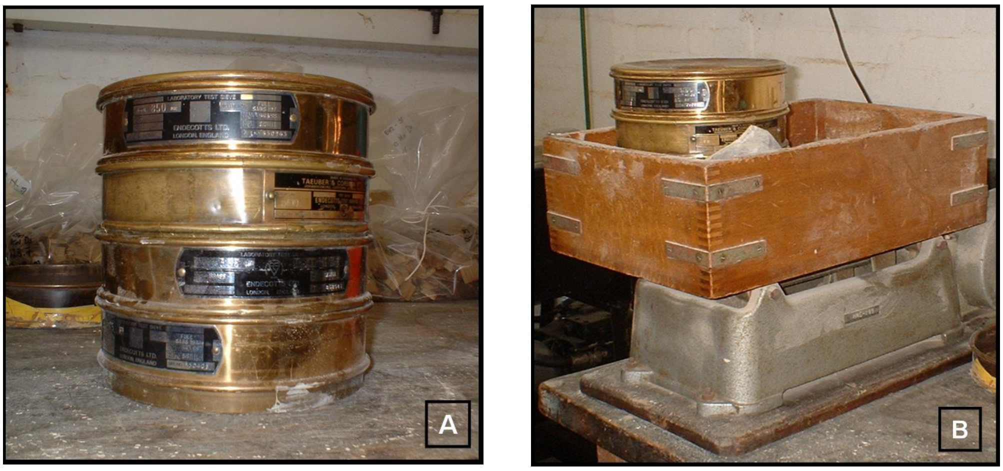

Figure 4.3 The tower of sieves (A) used to screen the *Acacia mearnsii* samples, placed in the tray of a vibrator to assist the screening process (B).

4.2.2 Calibration

The 90 wood meal samples were scanned and diffuse reflectance spectra for each sample were obtained using the NIRSystems Model 6500 scanning spectrophotometer. The procedure described by Sefara *et al.* (2000) was followed, and all spectra were collected at 2 nm intervals over the 400 to 2500 nm range. Each spectrum was based on an average of 32 co-added scans. Reflectance spectra belonging to each sample were saved into a file with the corresponding laboratory acquired pulp yield data. The data were divided into calibration (77%) and validation (23%) sub-sets, the calibration set being used to develop the model and the validation set to test the prediction ability of the model. A multivariate partial least squares (PLS) regression, which analyses the spectra relative to the measured pulp yield, was carried out using the ISI software supplied by NIRSystems. The cross-validation method was used to determine the optimum number of factors (latent variables) required to adequately describe the variation in the data. Major peaks found between 1450 nm and 2500 nm consisting of broad bandwidths suggested the presence of overlapping minor peaks. These small bands were resolved by applying a second derivative algorithm to the spectra. The second derivative technique was combined with various spectral ranges to optimise the model.

4.3 Within-tree variation

Each of thirty trees selected from a single site (Bloemendal) and age class (11) were extensively sampled. The samples were analyzed for density and pulp yield, to assess the extent of variation of these two characteristics within each tree. The eleven-year-old block at Bloemendal was chosen for a number of reasons. It is assumed to be a representative site for growing black wattle trees in South Africa. The site climatic and geographical characteristics equate this site to 26.9% of the wattle growing areas in South Africa ([3]Kunz, *pers. comm*, 2002) and the bark (13 tons/ha) and timber yields (80 tons/ha) are average for South Africa ([4]Feely, *pers. comm,* 2003). This age class represents a large proportion of the age at which trees are felled in South Africa every year. The sampling procedure is detailed below and basically followed the procedure used by Schimleck and Michell (1998) to determine the within-tree variation in kraft pulp yield using near-infrared spectroscopy in fifteen *E. nitens* trees aged 18 years. Wright *et al.* (1990) and Kube and Raymond (2002) used similar sampling systems in their respective studies.

4.3.1 Sample tree selection and sampling

The sample trees were taken from the eleven-year-old block at Bloemendal. The selection procedure described in 4.1.3 was applied, except that in this case two diagonals were used in order to select 30 trees. The 10 trees selected for the pulp yield across site and age study, were used in addition to 20 extra trees. Prior to, and after felling, all the measurements and assessments described previously were carried out on all 30 trees. Ten of the 30 trees were sampled at ten heights (2, 10, 15, 20, 30, 40, 50, 60, 70 and 80% of the Ut_Ht of each tree) by removing two adjacent 5 cm wide cross sectional discs (Figure 4.4). The other 20 trees were sampled at four heights (2, 20, 50 and 80% of the utilisable height of each tree). The extra 20 trees were only sampled at four heights mainly to reduce the laboratory costs of the project. It was also intended that a comparison would be made between the results obtained from the extensive, ten height, sampling strategy and the four height sampling strategy to determine the difference, if any, in the ability and accuracy to predict a single sampling point to represent whole tree pulp yield. The diameter of one of the discs sampled at each height was measured, and this disc was also used to calculate the basic density. The second disc was used for NIR pulp yield assessments. The discs labelled A, B and C (see Figure 4.4) were sub-divided into five circular bands (Figure 4.5), the discs labelled D, E and F were sub-divided into four circular bands, due to smaller diameters, the discs labelled G and H were divided into three circular bands and discs I and J were sub-divided into two circular bands. Once the relevant discs were cut into their

---

[3] Mr R. P. Kunz, Institute for Commercial Forestry Research, P O Box 100281, Scottsville, 3209.
[4] Mr J. E. Feely, South African Wattle Growers Union, P O Box 633, Pietermaritzburg, 3200.

respective circular bands, the ten extensively sampled trees yielded 37 samples per tree and the other 20 trees yielded 14 samples per tree.

As mentioned previously this sampling strategy although not based on divisions delineated by growth rings within each disc, it does allow for an analysis of the changes in pulp yield from pith to bark and from the base of the tree to the top of the tree. The pith to bark divisions of the discs do allow for some comparisons of pulp yield from wood of varying age produced by cambium of differing or similar age. Sardinha (1974) used growth rings as the sampling points and measured changes in density from pith to bark and used the concepts of sheath and core sequences.

The volume of each disc segment was then calculated and a weighting factor was calculated for each segment in order to calculate the proportional contribution that each made to the whole disc. Accordingly the predicted pulp yield results from each segment, obtained using NIR was weighted according to the contribution it made to the whole disc volume. The simplest way to explain this is by using an example. If a disc has a radius of 10 cm and it is cut up into five circular samples each having a cross-section (once cut) of two centimetres, the five samples then have different volumes. Assuming a constant thickness of 5 cm the volume of the entire disc is approximately 1571 cm^3. The volume of the inner sample with radius 2 cm is approximately 63 cm^3, the volume of the next sample is approximately 188.5 cm^3, the volume of the next sample is 314 cm^3, the volume of the next sample is approximately 440 cm^3 and the volume of the outer sample is approximately 565.5 cm^3. Therefore each sample was weighted according to its relative volume in the disc it originated from. The basic density of each disc segment was not determined.

Discs labelled "F, G, H, I and J" taken at 40, 50, 60, 70 and 80% of Ut_Ht with Ut_Ht being at 5 cm diameter

Discs labelled "E" taken At 30% Ut_Ht

Discs labelled "D", taken at 20% Ut Ht

Discs labelled "C", taken at 15% of UT_Ht

Discs labelled "B", taken at 10% of UT_Ht

Discs labelled "A", taken at 2% of UT_Ht

Figure 4.4 Sampling strategy used to remove cross-sectional discs from the trees. Discs A through J were sampled from ten trees and discs A, D, G and J were sampled from the other 20 trees, at Bloemendal.

Figure 4.5 An example of a cross-sectional disc divided into five sections, according to its diameter.

4.3.2 Sample preparation and scanning

Each air-dried disc was cut along the two diagonal lines shown in Figure 4.5**,** and then along the arcs drawn on the discs. Each disc depending on its position in the tree was cut into the appropriate number of arcs as already explained, the distance between the arcs differed for each disc as it was dependent on the disc diameter. This sampling allowed for the assessment of the variation in screened pulp yield across the radius of the disc. For the purposes of this study the interest lies in the positional change in pulp yield but it is recognized that the change in position radially from pith to bark also represents a change in age of the wood sample, with the wood nearer the pith being older than the wood nearer to the bark. The samples originating from the same circle were bulked, milled in a Wiley-mill into fine wood meal particles and screened sequentially through a 40 – 60 mesh using a vibrating tower of sieves (Figure 4.3). These samples were stored in honey jars ready for analysis. Approximately 10 g of sample was used for scanning with the NIR spectrophotometer.

This sampling strategy theoretically would have given 37 wood meal samples from each of the first 10 trees and 14 wood meal samples from the other 20 trees. However, some of the radial segments did not yield enough wood meal of the correct fineness to fill the sample holder, resulting in some missing values, in the NIR analyses. All of the samples were scanned according to the procedure described by Sefara *et al.* (2000) and diffuse reflectance spectra for each sample were obtained using the NIRSystems.

4.3.3 Within-tree pulp yield data manipulation

The pulp yield data obtained from the NIR analysis resulted in either 14 or 37 data points from each of the 20 trees sampled at four heights and each of the 10 trees sampled at ten heights, respectively. The pulp yield estimates for each disc segment were weighted according to their proportional contribution to the whole disc as described in section 4.3.1. Subsequently the average screened pulp yield for each disc was weighted according to the relative volume it represented in the stem. Finally a weighted mean tree screened pulp yield was calculated for each tree. The data manipulation and calculations used in this weighting exercise are summarised in Appendix 3a and 3b. The weighted mean pulp yields for each disc are represented in Figures 5.15 and 5.16 along with the predicted mean pulp yields.

This concept was then extended to calculate the proportional contribution that each sample made to the whole tree, by assigning the appropriate pulp yield per disc segment to the volume it represented up the tree. Volume was calculated using Equation 4.3, which calculates the volume of a truncated cone (Cailliez, 1980).

$$V_{sec} = \frac{\pi}{12}\left(d_1^2 + d_1 d_2 + d_2^2\right) \times l \qquad \text{[Equation 4.3]}$$

Where d_1 and d_2 are the under bark diameters of the lower and upper ends of each section being evaluated and l is the length of the section.

The length of each section was different in each case, and was calculated according to the distance between the discs, such that the disc was at the midpoint of the section Figure 4.6. The diameters associated with the heights at the ends of each section were calculated using a regression equation built for each tree using the ten heights and diameters measured up the stem of each tree. Ultimately a weighted mean pulp yield was calculated for each disc, each section and then whole tree, examples of this data manipulation are given in Appendix 3a and 3b. Ten of the trees used in this part of the study were also assessed for pulp yield using chips obtained from the billet taken from the base of the tree. The pulp yield data obtained from these two approaches were also compared. The mean tree pulp yields obtained using either the ten or the four sample points were also compared to assess the feasibility of reducing the number of sampling heights in future studies.

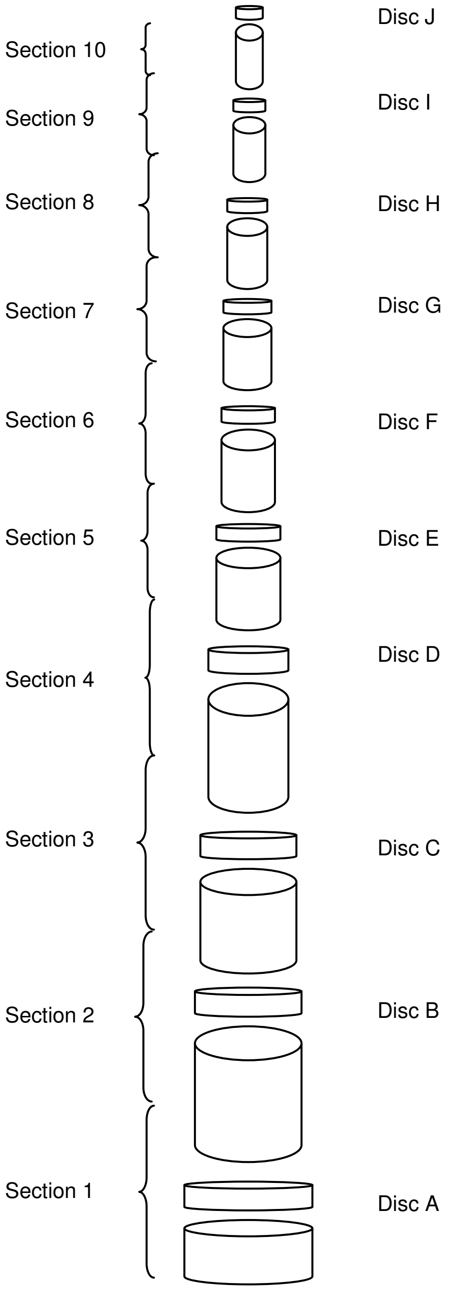

Figure 4.6 Schematic representation of the tree divided by the disc sampling and the sections evaluated for pulp yield by extrapolating the pulp yield values obtained from the NIR analysis of the discs segments.

The NIR pulp yield estimates obtained from each disc (representing different trees and different heights) were then used to build a regression model to predict the pulp yield of the whole tree from a single sampling point. The wet chemistry pulp yield from each billet (representing the whole tree) was used as the response variate in the first model, and the calculated whole tree pulp yield using the NIR data was the response variate in the second case.

4.4 Statistical analyses

All the data collected were analysed using Genstat® for Windows^{TM}, Version 7 (Lane and Payne, 1996). In designing the sampling regime a number of assumptions were made in conjunction with some prior knowledge of the sampling sites.

The prior knowledge of the sampling sites included:
The three sites (Bloemendal, Glen Echo and Phoenix) are different with regards to location, MAT, MAP, soils and altitude. (Table 3.1).
The annual yields, per hectare, of both black wattle timber and bark from these sites are different ([5]Feely, *pers. comm,* 2003).

The assumptions included:
The continuous variables measured on each tree were assumed to be normally distributed.
The ninety trees sampled were considered sufficient to capture the variation in the target population.

As described in more detail in Chapter 5, the data collected allowed for various manipulations and different approaches in attempting to describe and explain the variation of pulp yield across site, site index, age and within-trees. In many of these manipulations regression played a major part of the analyses, especially in the calibration of the NIR instrument and modelling trends within-trees using a limited number of data points.

The decision to declare plantations either fixed or random effects mainly depends on the type of inference to be drawn from the results. If one wishes to have narrow inference space that addresses only the specific plantations used in the study then one declares plantation fixed. If one wishes to have broad inference space then one would declare plantation random. The following two sections demonstrate these differences.

4.4.1 Statistical Analysis (Assuming Plantation to be Fixed Effects)

This model assumed the plantations to be fixed effects and the outline of the analysis of variance under this consideration is shown in Table 4.3. Another approach could have been to nest the ages within plantations but this would have required the assumption that age is dependent on the specific plantation under consideration. In this study this assumption could not be made as the study is designed rather to investigate the age and plantation effects independently and any interactions that exist between the two factors. Based on this assumption the differences in results from either plantations or age classes could then be

---

[5] Mr J. E. Feely, South African Wattle Growers Union, P O Box 633, Pietermaritzburg, 3200

used to make specific recommendations to the plantations and/or age classes used in this study. The interaction component could also be used to explain trends that may exist.

Table 4.3 Outline of the analysis of variance used to analyse the data assuming plantations to be fixed effects.

Source of variation	Degrees of freedom
Plantation	2
Age	2
Plantation.Age	4
Residual	81
Total	89

In this case the statistical model is of the form

$Y_{ijk} = \mu + P_i + A_j + PA_{ij} + e_{ijk}$

Where Y_{ijk} is the response from the k^{th} tree, in the j^{th} age class and in the i^{th} plantation effects, μ is overall mean P_i is the i^{th} plantation effect, A_j is the j^{th} age effect, PA_{ij} is ijth plantation by age interaction effect and e_{ijk} is the random error. The main effects of plantation and age as well as the interaction, in this scenario, are tested against the residual error only.

4.4.2 Statistical Analysis (Assuming Plantation to be Random Effects)

In this analysis plantations were assumed to be random effects and treated as blocking factors. Based on this assumption, the plantation-by-age interaction provided the experimental error and the variation between trees within plantation-by-age unit is the sampling error. The three selected plantations were considered as a representative sample of the wattle growing area in South Africa. The results obtained can therefore be treated as general and applied broadly to other sites within the wattle growing areas. The analysis of variance under this consideration was of the form shown in Table 4.4. (assuming no missing values).

Table 4.4 Outline of the analysis of variance used to analyse the data assuming plantations to be random effects.

Source of variation	Degrees of freedom
Plantation	2
Age	2
Experimental Error Sampling Error	4 81
Total	89

The statistical model is of the form

$Y_{ijk} = \mu + p_i + A_j + pa_{ij} + e_{ijk}$

Where Y_{ijk} is the response from the k^{th} tree, in the j^{th} age class and in the i^{th} plantation, μ is overall mean, p_i is ~*iid* $N(0,\sigma_p^2)$, A_j is the j^{th} age effect , pa_{ij} is ~*iid* $N(0,\sigma_{pa}^2)$ and e_{ijk} is the random environmental and genetic deviation due to the individual trees effect (sampling error) e_{ijk} ~*iid* $N(0,\sigma^2)$. The main effect of plantation and age are tested using the experimental error and the experimental error (which is the plantation by age interaction) is tested using the sampling error. This gives rise to different P-values (as shown in Table 5.2 and Table 5.8) when compared to the same data analyzed with plantations assumed to be fixed effects. Therefore the same data set can give rise to differing scenarios of significance when analyzed with these two different models.

In the results chapter (Chapter 5) of this dissertation both of these statistical approaches, with plantations treated as fixed and random effects, are discussed with relevant results presented. For this study, the scenario with plantations treated as random effects was considered ideal, to allow for some general statements to be made with respect to the greater wattle growing area of South Africa. Under this consideration the results obtained for the different characteristics and properties measured and analysed in this study have many implications for further studies and for the farmers and processors of wattle timber, associated with them. These are discussed in the Chapter 6.

Chapter 5

Results and Discussions

5.1 Variation in tree growth and pulp yield across site and age

As described in Chapter 4, two scenarios were evaluated when analysing the data collected in the initial sampling exercise across the three sites and age classes. Firstly, the plantations were treated as fixed effects and secondly, they were treated as random effects. The two ANOVA tables under these considerations were also explained. In the following sections the results obtained are presented separately, with their appropriate discussions. Finally the implications of the various results are explained and the reasons for accepting the scenario with plantations being treated as random effects are defended. The reference to age when discussing the results obtained should be seen as limited to the three ages actually sampled in this study.

5.1.1 General tree growth data (Assuming plantation as fixed effect)

Considering plantation as a fixed effect allows the differences observed between different plantations to be attributed to actual plantation differences if the differences are significant. It also allows conclusions or inferences to be drawn with regard to the specific plantations used in this study. Ultimately the results could be used to rank the specific plantations for the characteristics under consideration.

The measurements and assessments carried out, in the field, on the 90 sample trees are summarised in Appendix 4. Appendix 5 contains the tree data derived from the field and laboratory measurements. Table 5.1 contains summary data pertaining to the growth variables that have been associated with pulp yield in similar studies, including Volume (calculated using Dbhob and Total_Ht) and disc basic density for the trees sampled (Kube and Raymond, 2002; Borralho *et al.*, 1993; Tibbits and Hodge, 1998). Tree volume is affected by plant population, if a tree has any missing neighbours, it is likely to have "biased" growth due to less demand on localised soil moisture storage, less competition for localised nutrient supplies and increased photosynthetic rates as more sunlight can penetrate the forest canopy (Kunz, 1997). To account for this “bias” a covariate generally non-significant (based on the number of trees surrounding the sample tree) was run when analysing Volume. The preliminary analysis showed the effect of the covariate to be non-significant and was subsequently not used again for any of the growth characteristics. Conventional wisdom suggests that stocking could also affect wood or pulp properties. This analysis was carried out and again it was found to be non-significant. In addition the loss of another degree of freedom, from the few that were available when plantation was considered as random, supports the result of non-significance when using the covariate. The mean squares from the analysis of variance of these variables are provided in Table 5.2.

Table 5.1 Summary of the measured and calculated growth variables associated with pulp yield. (Gldub = ground line diameter under bark, Dbhob = diameter at breast height over bark, Dbhub = diameter at breast height under bark, Ut_Ht = utilisable height).

		Means					
Plantation	Age	Gldub (cm)	Dbhob (cm)	Dbhub (cm)	Ut_Ht (m)	Disc density (kg m^{-3})	Tree Volume (m^3)
Bloemendal	7	14.23	12.53	11.75	13.29	583.6	0.088
	9	14.77	13.17	12.34	14.28	595.6	0.102
	11	16.52	14.43	13.42	14.27	634.2	0.133
Glen Echo	7	16.33	14.26	13.44	12.93	580.4	0.121
	9	15.58	14.01	13.10	13.50	553.3	0.119
	11	21.56	18.77	17.73	15.74	572.3	0.251
Phoenix	7	16.94	14.83	13.93	16.28	536.0	0.148
	9	18.06	16.04	15.00	16.74	533.8	0.188
	11	17.94	15.70	14.63	17.06	569.5	0.180
Overall mean		16.88	14.68	13.93	14.90	573.2	0.148
l.s.d.(0.05)[a]		3.460	2.778	2.633	1.961	32.94	0.0682
s.e.d[b]		1.739	1.396	1.324	0.986	16.55	0.0343

[a] The least significant difference computed at the 5% significance level

[b] The standard error of the difference

The mean values for the growth characteristics from each plantation and age indicated that tree volume which is calculated using tree height and diameter generally increases with age and that on average the trees were biggest at Phoenix, followed by Glen Echo, with the smallest trees coming from Bloemendal.

Table 5.2 Summary of analyses of variance for the growth properties of the trees sampled under the assumption that plantations are fixed effect. (df = degrees of freedom, Gldub = ground line diameter under bark, Dbhob = diameter at breast height over bark, Dbhub = diameter at breast height under bark, Ut_Ht = utilisable height).

		Mean squares (P-Values)					
Source of variation	df	Gldub	Dbhob	Dbhub	Ut_Ht	Disc density	Tree Volume
Plantation	2	65.86 (0.016)	49.624 (0.008)	46.002 (0.007)	72.541 (<0.001)	0.025719 (<0.001)	0.036811 (0.003)
Age	2	72.96 (0.010)	48.888 (0.009)	41.452 (0.011)	17.482 (0.032)	0.008211 (0.004)	0.03860 (0.002)
Plantation.Age	4	25.64 (0.159)	18.094 (0.126)	17.634 (0.100)	4.677 (0.433)	0.002358 (0.153)	0.014207 (0.055)
Residual	81	15.12	9.745	8.759	4.858	0.001370	0.005875
Total	89						

P<0.05 is considered significantly different

The results in Table 5.2 show that the plantations differed significantly with respect to Gldub **(P<0.05)** and highly significantly for Dbhob, Dbhub, Ut_Ht, Disc density and Tree Volume **(P<0.01).** Similarly, significant age effects were found in Ut_Ht **(P<0.05)** and highly significant effects in Gldub, Dbhob, Dbhub, Disc density and Tree Volume **(P<0.01).** However, there were no significant plantation x age interactions effects for these characteristics. The Bloemendal data shows a constant trend with values increasing with tree age. This is not the case for Glen Echo or Phoenix. At Glen Echo the seven-year-old trees were bigger with higher basic density than the nine-year-old trees, except for Ut_Ht where the increase with age trend existed. At Phoenix the nine-year-old trees were the biggest with the lowest basic density. The three compartments sampled at Bloemendal were much closer together than those sampled at Glen Echo and at Phoenix, suggesting that the associated differences in the sites may have influenced the results from Phoenix and Glen Echo.

5.1.2 Pulp yield variation

From the literature it is evident that black wattle, in general, has a high kraft pulp yield when compared to some of the well known *Eucalyptus* species grown commercially around the world for the kraft pulp process (Hannah *et al.*, 1977; Muneri, 1997; Clark *et al.*, 1992). Many of these studies have been carried out with samples taken from either a single site, single age class or from trees of unknown age. In this study, by sampling from three age classes and three sites, and acknowledging that the age classes were possibly influenced by the site effects of the compartments, it was envisaged that the variation in pulp yield would manifest itself. Figure 5.1 represents the frequency distribution of pulp yield from the 90 trees sampled for this study. The distribution is very close to being normal with a skewness value of –0.013. The mean value is 56.29%, minimum is 52.61% and maximum is 59.91%, standard deviation of 1.57, standard error of 0.17, and coefficient of variation of 2.78. The mean value of 56.29% is regarded as a high mean kraft pulp yield and the minimum of 52.61% compares favourably with the mean kraft pulp yield published for other species used in this industry (Hannah *et al.*, 1977; Muneri, 1997; Clark *et al.*, 1992). This would indicate that as a species grown for kraft pulp yield black wattle is one of the more efficient species.

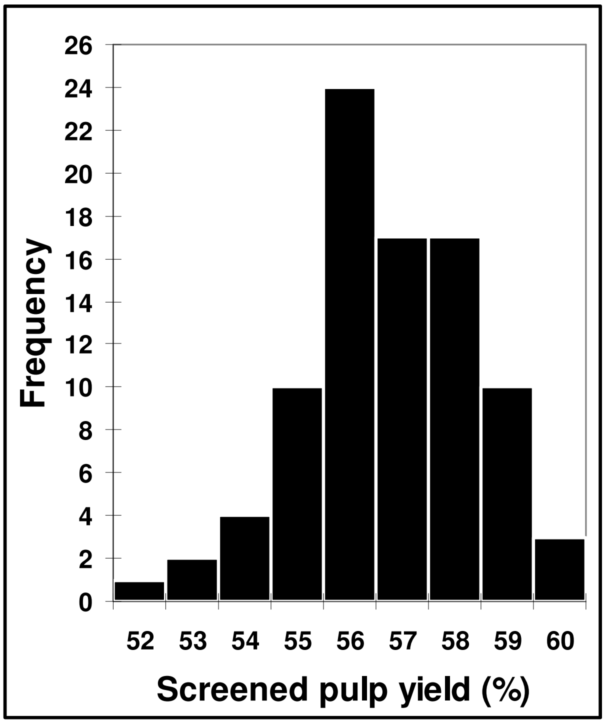

Figure 5.1. Frequency distribution of laboratory tested kraft pulp yield from the individual *Acacia mearnsii* trees sampled in this study.

Table 5.3 presents the ANOVA table for screened pulp yield when analysed with plantations as fixed effects.

Table 5.3 Analysis of variance for screened pulp yield from the trees sampled. (df = degrees of freedom, SS = sum of squares, MS = mean squares, VR = variance ratio, F pr = p-value).

Source of Variation	df	SS	MS	VR	F pr
Plantation	2	42.198	21.099	9.55	<0.001
Age	2	3.000	1.500	0.68	0.510
Plantation.Age	4	17.989	4.497	2.04	0.097
Residual	79(2)	174.506	2.209		
Total	87(2)	235.854			

From Table 5.3 it is clear that pulp yield is highly significantly affected by plantation (P<0.001) but the age of the tree does not affect pulp yield significantly. The plantations with trees exhibiting better growth, (from Table 5.1), having higher pulp yields. Beadle *et al.*, (1996) found similar results for *E. globulus* and *E. nitens*. Locally, in South Africa, Megown *et al.* (2000) and Turner (2001) all found that eucalypt trees grown on better sites produced higher pulp yield. These results suggest that there is an opportunity to alter the felling age of black wattle to an earlier age as long as the trees have reached an acceptable volume and that certain plantations will yield higher pulp yields than others. The results presented in the ANOVA table in Table 5.3 are represented graphically in Figure 5.2 where the mean pulp yield values from the three plantations (including all ages) are shown and the mean pulp yield for the three different age classes (across sites) are shown in Figure 5.3.

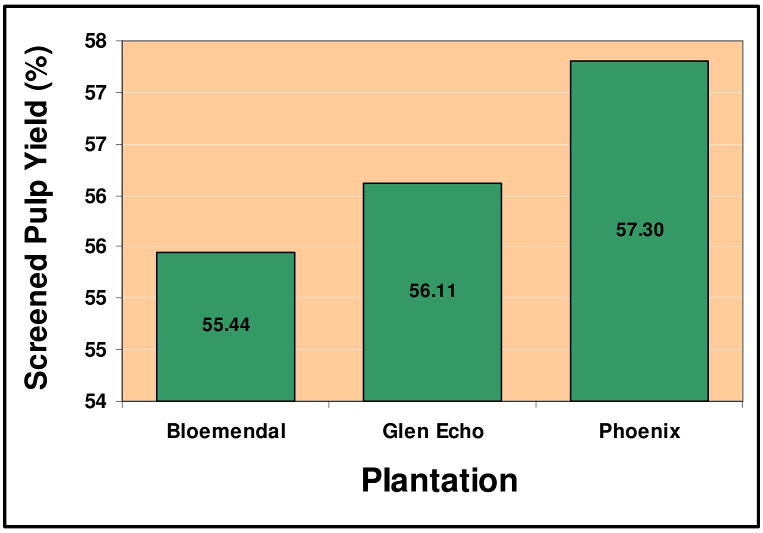

Figure 5.2 Mean pulp yield values obtained for the three plantations, disregarding the age of the sample tress ($P < 0.001$).

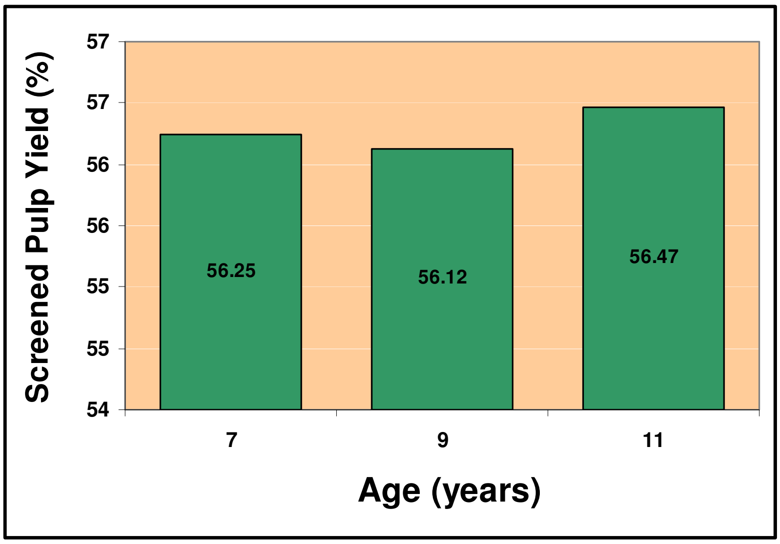

Figure 5.3 Mean pulp yield values obtained for the three age classes sampled across the three plantations ($P = 0.510$).

The plantations sampled significantly affect screened pulp yield, but the ages sampled do not, suggesting that, if pulp yields were acceptable and used as a major selection criteria, black wattle trees could be harvested at seven years old. Megown *et al.*, (2000) found that age had little effect on the screened pulp yield of a eucalyptus clone but that site index or site quality significantly affected pulp yield and concluded that the site index was more important than age when characterising a species for variation in screened pulp yield.

The relationships between the growth characteristics and screened pulp yield are important and are discussed in detail in this chapter. In the world market, when differentiating pulp yields from different species, the perception that bigger trees necessarily yield more pulp, has been dispelled. Within a species this is a truer statement. Smaller tree species, such as black wattle, that consistently give higher pulp yields need to be actively promoted in order to retain their position in the world pulp market. Culturally farmers and timber growers prefer to see big trees in their plantations as apposed to smaller trees even though the pulp yield from the smaller trees may be equal or higher. An initial investigation into the relatedness of the variables was done by scrutinising their correlation coefficients. These associations are shown in Table 5.4.

Table 5.4 Correlation coefficients (r) for associations between growth characteristics and screened pulp yield (n=90). (Gldub = ground line diameter under bark, Dbhob = diameter at breast height over bark, Dbhub = diameter at breast height under bark, Ut_Ht = utilisable height).

Variable	Gldub	Dbhob	Dbhub	Ut_Ht	Basic_density	Tree Volume
Dbhob	0.982***					
Dbhub	0.980***	0.998***				
Ut_Ht	0.694***	0.719***	0.718***			
Basic_density	0.093ns	0.078ns	0.063ns	-0.002ns		
Volume	0.960***	0.968***	0.978***	0.764***	0.062ns	
SPY	0.102ns	0.109ns	0.117ns	0.320**	-0.312**	0.153ns

***= P<0.001; **= P<0.01; ns = not significant

Screened pulp yield is significantly correlated with basic density, and Ut_Ht but not with the other variables. This reinforces the fact that bigger trees (expressed as tree volume) do not necessarily yield more pulp. As Ut_Ht increases, screened pulp yield increases but decreases as disc density increase. The association between basic density and screened pulp yield is a complex one due to the fact that disc density is predominantly a physical measure but is affected by the amount of extractives present and screened pulp yield is a chemical measure and their association is determined by the growth of the trees. Zobel and Jett (1995) explain the effects of internal and external factors on tree physiology, the major determinant of the kind of wood formed and anything that changes the physiology and growth of a tree affects the wood properties. From this study it is evident that under more favourable conditions of rainfall, temperature, altitude and possibly soil type, trees not only grow faster but also have a higher pulp yield, with lower basic density. These results are presented in Figures 5.4 and 5.5.

From Figures 5.4 and 5.5, it is evident that the samples, generally, cluster together according to the plantation from which they were sampled, when looking at screened pulp yield plotted against disc density and Ut_Ht. Density is an important economic factor in the shipping of black wattle chips, as growers are paid on mass and not quality, it would seem that although the trees from Phoenix have the highest pulp yield these trees also have lower density. This decrease in density is significant but compared to other species that are also exported the mean density at Phoenix of 546.4 kg/m^3 is still relatively high. The pulp yield results from Phoenix again re-enforce the relationship between pulp yield and growing conditions of the trees and suggest that these bigger faster growing trees have lower density. Undoubtedly Phoenix had better growing conditions when compared to Glen Echo and Bloemendal for the life spans of the trees sampled. In a study investigating the effect of drought and salinity on the wood and kraft pulps of young plantation eucalypts Clark *et al.*, (1999) found that lower than normal growth rates due to unfavourable growing conditions resulted in trees with higher wood densities and lower pulp yields. However, the statement that density is related to growth rate was treated with caution as Kromhout (1990) again reiterated statements that Turnbull (1937) made, with respect to pine trees, in that density is not related to rate of growth, rather that it is a function of summer wood percent and that summer wood is formed only during the dormancy of height growth. However, black wattle wood is not similar to pine wood but this may not be the case. For black wattle basic density may be related to the rate of growth. Stubbings and Schönau (1972) studied the density and air-drying rates of black wattle throughout the wattle growing areas in South Africa. They found differences in densities but did not equate them to growth rate as they only measured the diameters of the trees and did not have the ages of most of the logs sampled. A broader study to clarify the effect of black wattle tree growth rate on its density is possibly a topic for a future study.

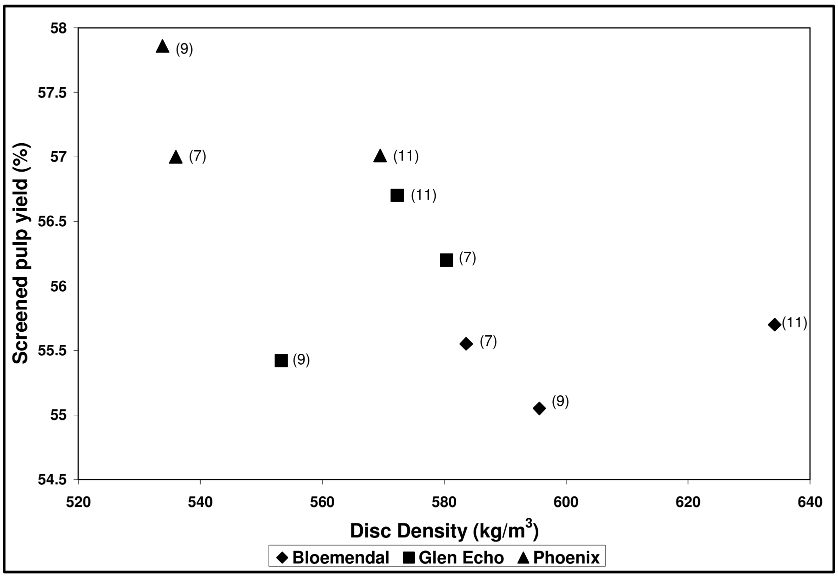

Figure 5.4 Relationship between mean screened pulp yield (%) and mean disc density (kg m^{-3}) from the three plantations sampled. The figures in brackets are the ages of the trees.

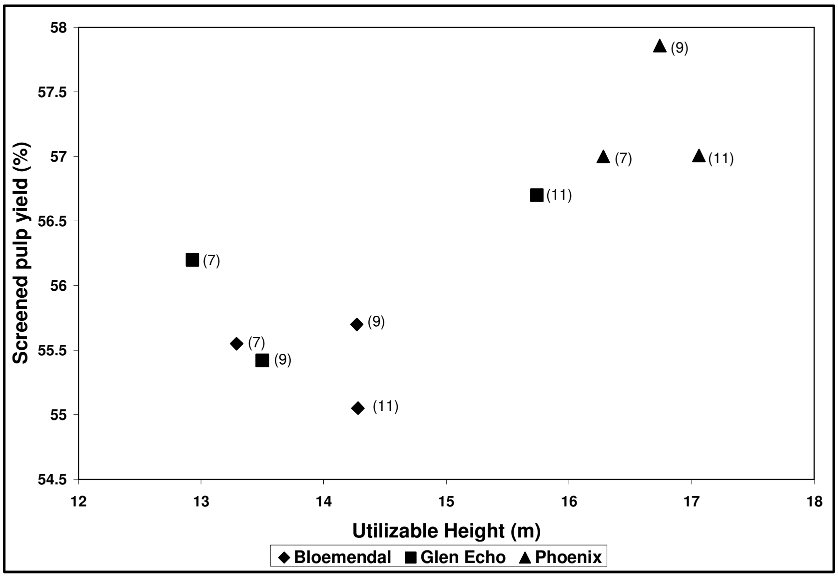

Figure 5.5 Relationship between mean screened pulp yield (%) and mean utilisable height (m) from the three plantations sampled. The figures in brackets are the ages of the trees.

5.1.3 Pulp yield variation across site index

A common measure of site quality in forestry is site index (SI). Site index is calculated as the mean tree height attained at a reference age of five or 10 years (Schönau, 1969), for the area being evaluated. Schönau (1974) maintained that stand density had little bearing on mean tree height and developed the following equation to predict site index (Equation 5.1) (Smith, 2002). For the purposes of this study a reference age of 10 years was used when calculating SI and is indicated in the text as SI_{10}.

$$\log_{10}(SI_{10}) = \log_{10}(Hm) + 1.2524\left(\frac{1}{A} - 0.1\right) \text{ .... [Equation 5.1]}$$

where *Hm* is average stand height and *A* is tree age in years

Site index was calculated for the nine compartments using Equation 5.1 and these indices are presented in Table 5.5.

Table 5.5 Site indices for the nine compartments sampled.

Plantation	Age	SI_{10}
Bloemendal	7	22.30
	9	21.08
	11	23.24
Glen Echo	7	19.38
	9	19.17
	11	21.87
Phoenix	7	25.80
	9	22.50
	11	24.22

Figure 5.6 shows the relationship between site index and screened pulp yield. Studies with eucalypt spp. have shown that screened pulp yield generally increases with higher site index (Megown *et al.*, 2000; Turner, 2001) which again relates to trees, for hardwoods at least, having higher pulp yields under better growing conditions. Figure 5.6 demonstrates that pulp yield from black wattle does not necessarily follow the general trend found in eucalypt species. At Glen Echo, pulp yield increased with SI_{10}, at Bloemendal the seven-year-old trees were growing on a site with a slightly higher SI_{10} but in fact had a slightly lower pulp yield. At Phoenix the trend was the opposite to that found in eucalypts with the trees grown on the site with the lowest SI_{10} having the highest pulp yield and the trees growing on the site with the highest SI_{10} had the lowest pulp yield, however, it must be stressed that the pulp yield percentages obtained at Phoenix were all relatively high.

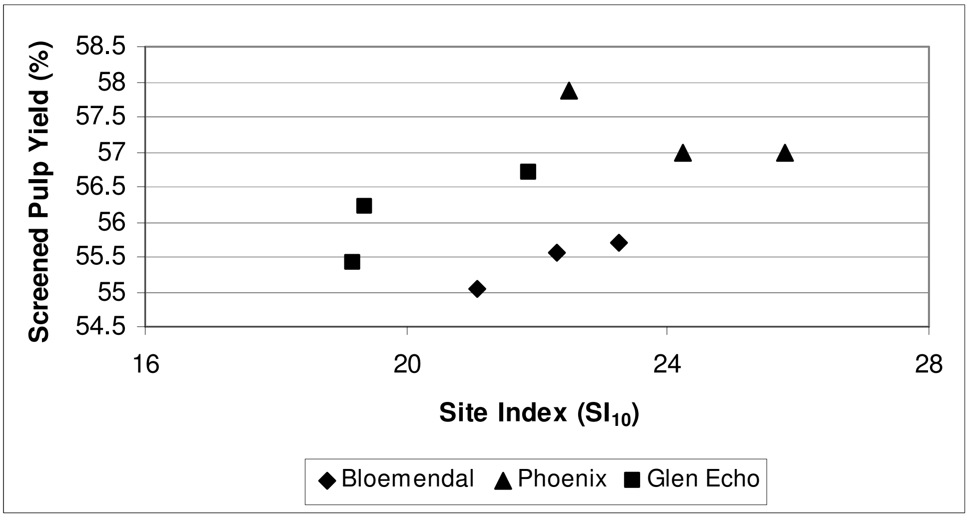

Figure 5.6 Site Index (SI_{10}) plotted against Screened Pulp Yield (%) for the three sites.

5.1.4 Pulp yield variation in relation to mean annual rainfall, mean annual temperature and altitude

The relationships between screened pulp yield, mean annual temperature (MAT), mean annual rainfall (MAP) and altitude were also investigated. The correlation coefficients of these variables are provided in Table 5.6.

Table 5.6 Correlation coefficients for associations between Screened pulp yield, MAT, MAP and Altitude (n=90).

	Screened pulp yield	MAT	MAP
MAT	0.250*		
MAP	0.381***	0.568***	
Altitude	0.158ns	0.060ns	0.803***

***= P<0.001; *= P<0.05; ns = not significant

Screened pulp yield is significantly correlated with MAT and very highly significantly correlated with MAP. Both correlations are positive suggesting that higher rainfall and temperatures improve pulp yield. This again reinforces the notion that better growth conditions improve the pulp yield of black wattle.

5.1.5 General tree growth data (Assuming plantation as random effect)

Under the consideration that plantations are random effects the main area of interest is the amount of the total variation accounted for by the plantations. The assessment of any significant effects of the ages of the trees, with respect to variables of interest such as pulp yield, is key. Table 5.7 presents some of the growth characteristics measured in the field prior to felling along with disc density measures in a laboratory and tree volume which was calculated using diameter and height measurements. These variables are considered to be associated with pulp yield.

Table 5.7 Summary of the measured and calculated growth variables associated with pulp yield. (Gldub = ground line diameter under bark, Dbhob = diameter at breast height over bark, Dbhub = diameter at breast height under bark, Ut_Ht = utilisable height).

Age	Gldub (cm)	Dbhob (cm)	Dbhub (cm)	Ut_Ht (m)	Disc density (kg m^{-3})	Tree Volume (m^3)
7	15.83	13.87	13.04	14.17	566.7	0.1192
9	16.14	14.41	13.48	14.84	560.9	0.1364
11	18.67	16.30	15.26	15.69	592.0	0.1881
Overall Mean	16.88	14.86	13.93	14.9	573.2	0.1479
l.s.d (0.05)	3.630	3.049	3.010	1.550	34.81	0.08544
m.s.e df	4	4	4	4	4	4
s.e.d	1.307	1.098	1.084	0.558	0.01254	0.03078

m.s.e.df - mean square error degrees of freedom

From Table 5.7 it is evident that, in general, trees get bigger with age, across the wattle growing areas sampled. Disc density does not follow the same pattern with nine-year-old trees having the lowest densities. Table 5.8 presents the ANOVA table for the characteristics presented in Table 5.7.

Table 5.8 Summary of analyses of variance for the growth properties of the trees sampled. (Gldub = ground line diameter under bark, Dbhob = diameter at breast height over bark, Dbhub = diameter at breast height under bark, Ut_Ht = utilisable height).

		Mean squares (P-values)					
Source of variation	df	Gldub	Dbhob	Dbhub	Ut_Ht	Disc density	Tree Volume
Plantation	2	65.86	49.624	46.002	72.541	0.025719	0.036811
Age	2	72.96 (0.170)	48.888 (0.181)	41.452 (0.211)	17.482 (0.121)	0.008211 (0.133)	0.03860 (0.180)
Experimental error	4	25.64	18.094	17.634	4.677	0.002358	0.014207
Sampling error	81	15.12	9.745	8.759	4.858	0.001370	0.005875
Total	89						

From Table 5.8 it is clear that age does not have a significant ($P<0.05$) effect on any of these growth characteristics, when the plantations are analyzed as random effects. This suggests that as soon as the growth curve of the trees reaches a plateau the trees can be harvested. This is a simplistic view, which is expanded on, in more detail below. Table 5.9 presents the ANOVA table for pulp yield with plantations treated as random effects.

Table 5.9 Analysis of variance for screened pulp yield from the trees sampled. (df = degrees of freedom, SS = sum of squares, MS = mean squares, VR = variance ratio, F pr = p-value).

Source of Variation	df	SS	MS	VR	F pr
Plantation	2	42.198	21.099	4.69	
Age	2	3.000	1.500	0.33	0.735
Experimental Error	4	17.989	4.497	2.04	
Sampling Error	79(2)	174.506	2.209		
Total	87(2)	235.854			

From Table 5.9 it is clear that age does not significantly affect screened pulp yield. This result along with those presented in Table 5.8, suggest that the importance of tree age when assessing the screened pulp yield of black wattle trees is minimal. With the plantations in this scenario being random effects the results obtained in this part of the study can be applied to wattle plantations across the wattle growing area in South Africa. With tree age not being significant it can be concluded that observed differences are independent of age and are caused by another or other factors, most likely related to the environment such as rooting depth, soil fertility, disease pressure and drought. Assessing trees younger or older than those assessed in this study may also give different results. The practical implication is that, within reason, the felling age across sites could be lowered. As stated earlier the normal felling age for black wattle is between 8 and 12 years. A more critical look at the growth curves of black wattle would then be necessary to decide when growth rate has levelled off and it makes sense from a volume point of view to fell the trees. Figure 5.7 depicts the Mean Annual Increment (MAI) curves of three different site qualities versus age (Smith, 2002). From these curves it is clear that MAI drops off after nine to ten years, therefore if age has no significant effect on pulp yield, then allowing a plantation to grow beyond nine to ten years does not have any advantage from a yield point of view. However, the relative performance of black wattle needs to be compared to other plantation species. If under the conditions in question black wattle yields better than any other species then it is advisable to plant black wattle. This is obviously a generalisation as it is well known that on certain cold, high altitude sites black wattle does not grow very well at all and in particular when small, black wattle is susceptible to frost damage and when older is highly susceptible to snow damage, so sites where the chance of frost or snow exist, should be avoided (Beck and Goodricke, 2002). Table 5.10 presents the estimated variance components for the growth properties and screened pulp yield of the sample trees under the assumption of plantations being random effects.

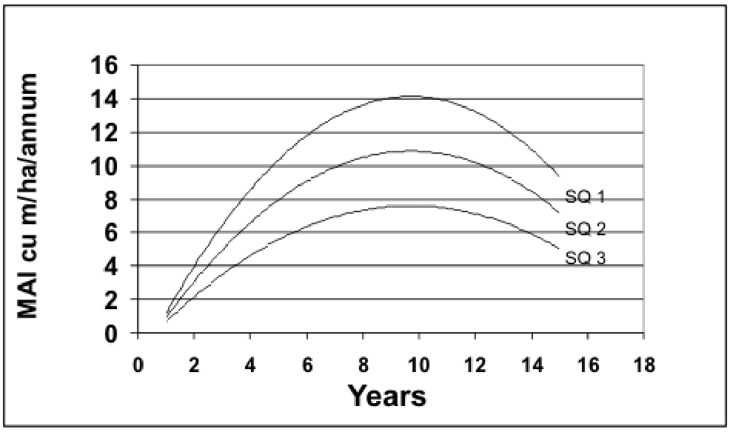

Figure 5.7 Growth of black wattle on three different site qualities with time. Site qualities (SQ) 1, 2 and 3 refer to site indices of 10, 13, and 16 respectively (adapted from Kassier and Kotze, 2000).

Table 5.10 Estimates of variance components for the growth properties and screened pulp yield of the sample trees. (Gldub = ground line diameter under bark, Dbhob = diameter at breast height over bark, Dbhub = diameter at breast height under bark, Ut_Ht = utilisable height).

Variable	Component	Plantation	Plantation.Age	Plantation.Age.Tree
Gldub	Estimate	1.341	1.052	15.116
	%	7.7	6.0	86.3
Dbhob	Estimate	1.051	0.835	9.745
	%	9.0	7.2	83.8
Dbhub	Estimate	0.946	0.888	8.759
	%	8.9	8.4	82.7
Ut_Ht	Estimate	2.264	0.018	4.858
	%	31.7	0.3	68.0
Disc density	Estimate	0.00078	0.00010	0.00137
	%	34.7	4.4	60.9
Tree volume	Estimate	0.00075	0.00083	0.00587
	%	10.1	11.1	78.8
Screened pulp yield	Estimate	0.553	0.229	2.209
	%	18.5	7.7	73.9

From Table 5.10 it is evident that the main source of variation (among the three components namely: Plantation, Plantation.Age and Plantation.Age.Tree) in all of the characteristics assessed in this initial part of the study is from the individual trees, shown by the differences between trees within the age classes and plantations. For the purposes of this study, the assumption that the 90 trees sampled is sufficient, needs to be held. In the ideal situation many more trees need to be sampled to capture more of the variation in the black wattle plantations of South Africa. However, the fact that most of the variation is accounted for by the differences between trees, allows the author to more confidently present the results in the rest of this chapter as being a true reflection of the situation within black wattle trees in South Africa.

Assuming that a proportion of the variation accounted for by the individual trees is genetically controlled, there is therefore good reason to assume that there is a large opportunity for genetic improvement of the characteristics under consideration.

Considering plantations as random effects and with the evidence that age does not significantly affect either growth characteristics or screened pulp yield the following assumption is made. Despite sample numbers in some of the later sections of this chapter being fewer than 90, and taken at one site and age class, the author is confident that they at least capture some of the variation of an infinite population due to the high portion of variation accounted for by the individual trees.

5.2 Near Infrared Spectrophotometer Calibration

5.2.1 Reflectance spectra from the ninety sample trees

To calibrate the NIRSystems Model 6500 scanning spectrophotometer, 90 wood meal samples obtained from each of the trees assessed in the first part of this study for kraft pulp yield, were scanned and diffuse reflectance spectra for each sample were obtained. The spectra and corresponding pulp yield determined in the laboratory were put together into a file and a multivariate partial least squares (PLS) regression analysis was carried out using the ISI software which is supplied by NIRSystems. The optimum number of factors (latent variables) required to describe the variation in the data was determined using a cross validation technique. An example of the spectrum obtained from one of the samples is shown in Figure 5.8.

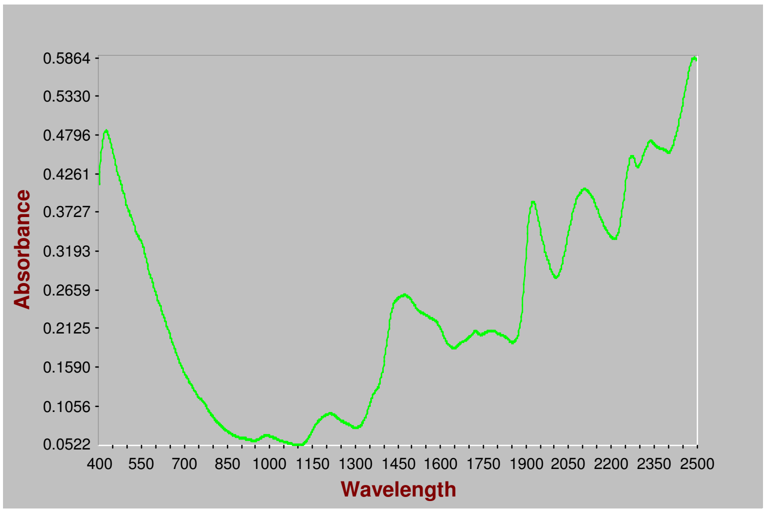

Figure 5.8 Example of the spectrum obtained from one of the samples scanned for the purpose of this study.

Most of the major peaks are found between 1450 and 2500 nm wavelengths and consist of broad bandwidths. Spectra that occur in this region consist of overtone and combination bands of the fundamental stretching vibrations of –OH,-NH and –CH functional groups (Wetzel, 1983). The spectra obtained are complex but a major advantage that NIR spectroscopy has over other methods of pulp yield determination, such as a laboratory scale kraft (sulphate) process, is that each spectrum provides information on all the chemical constituents in the wood important in paper-making, so the decision of which constituent is important for pulp yield is avoided (Downes *et al.*, 1997). The presence of underlying smaller bandwidths and peaks was resolved by applying a second derivative algorithm to the spectra. Figure 5.9 shows an example of a second derivative spectrum of one of the samples examined.

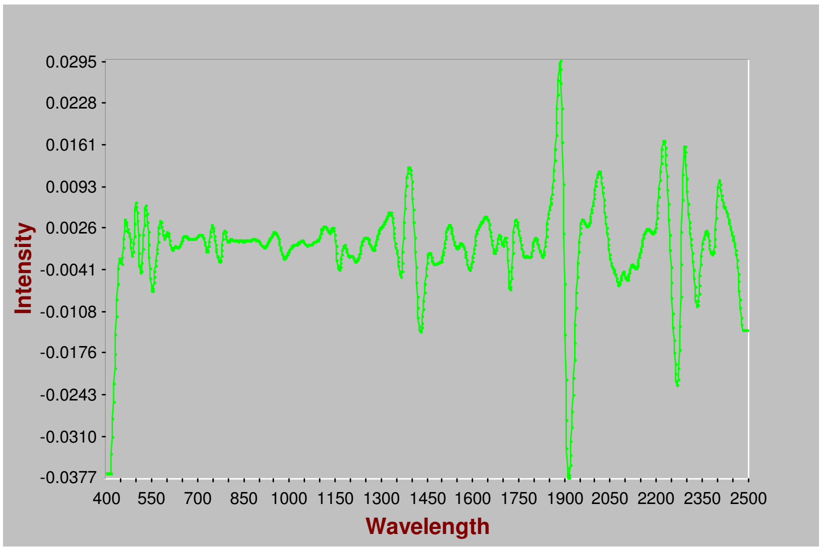

Figure 5.9 Example of a second derivative spectrum of one of the samples.

The summary of the calibration results relating the laboratory pulp yield to the second derivative spectra is presented in Table 5.11.

Table 5.11 Equation constraints used in developing a model to predict screened pulp yield from NIR analyses. (R^2 = coefficient of determination, SEC = standard error of calibration, Press = prediction sum of squares).

	R^2	SEC	Press
Factor 1	0.2801	1.4172	131.407
Factor 2	0.6849	0.9458	94.0304
Factor 3	0.7288	0.8853	64.8907
Factor 4 *	0.7894	0.7871	62.2965
Factor 5	0.8015	0.7713	54.4448
Factor 6	0.8444	0.6893	53.317
Factor 7	0.8709	0.6339	53.311
Factor 8	0.8794	0.6185	47.8765

The optimum Partial Least Squares (PLS) factors was found to be equal to four, with R^2 = 0.7894 and standard error of calibration (SEC) = 0.7871 and PRESS (Prediction Sum of Squares) = 62.2965, which is used to determine the optimum number of PLS-factors so that one does not overfit the model. The log (Press) is plotted against the PLS factors in Figure 5.10 and four factors were chosen based on the graph plateau and acceptable R^2.

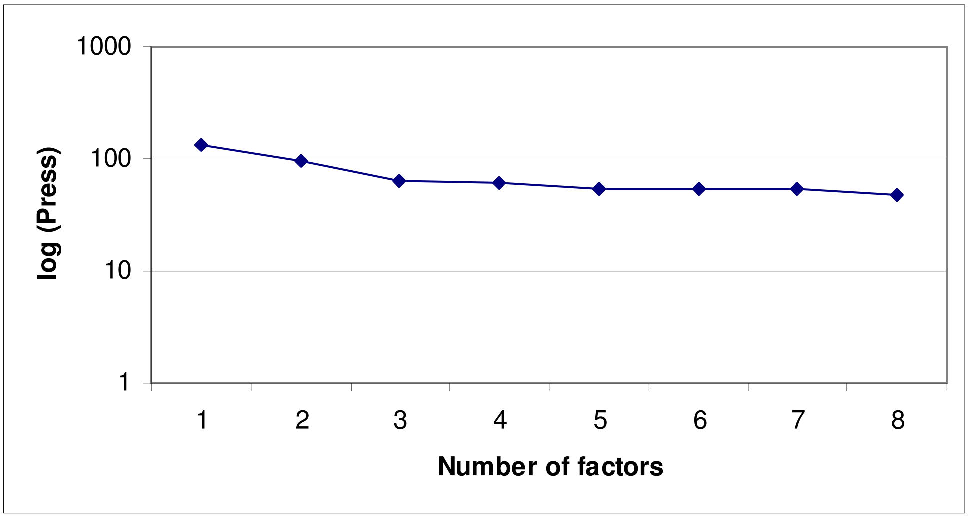

Figure 5.10 Representation of the graph used to assist in deciding how many factors to use. Factor 4 was chosen as the beginning of the plateau.

The calibration was then tested for its ability to predict pulp yield. This was achieved by randomly separating the 87 (3 values were not included as they were considered to be outliers given that they were far outside of the observed sample range) original spectra into a calibration and validation set. The calibration set consisted of 77% (60 samples) of the samples and the validation set of the remaining 23% (18 samples), with nine samples being removed from the sets as outliers, because of their residuals being outside of the observed range for the samples. This partitioning of 77% as calibration set and 23% as validation set is consistent with other studies, Shimleck and French (2002) used a 75:25 split in their study of pulp yield in *Eucalyptus globulus*, while Michell (1995), in his study of pulpwood quality estimations of eucalypt woods, used a ratio of 20% validation and 80% calibration. The validation set was used to test the prediction power of the model built using the other 60 samples. The accuracy of the model was evaluated by comparing the predicted pulp yield to the laboratory pulp yield. Table 5.12 summarises the details of the calibration model.

Table 5.12 Statistical parameters for the calibration and validation models.

	Calibration Set (77%)			Validation Set (23%)		
Spectra	R^2	SEC	PLS factors	R^2	SEP	Average residual*
2nd derivative	0.7894	0.7871	4	0.5386	0.8745	0.468

*average of the absolute values of the residual.

The validation $R^2 = 0.5386$ with a standard error of prediction (SEP) = 0.8745. Although the R^2 is not high the SEP is acceptable in comparison to a similar study performed on eucalypt clones (Sefara *et al.*, 2000). The unaccounted variation could be due to the small sample size of trees used as the validation set. Table 5.10 presented evidence that 73.9% of the total variation in screened pulp yield is accounted for by differences between trees.

Figure 5.11 presents the correlation plot corresponding to the model developed using the second derivative spectra. The plot shows an even distribution of the points along the diagonal suggesting a linear fit. The calibration model is linear with $R^2 = 0.7891$ with a slope of 0.7892 and a y-intercept of 11.805. These results imply that pulp yield is reasonably modelled by the NIR spectra.

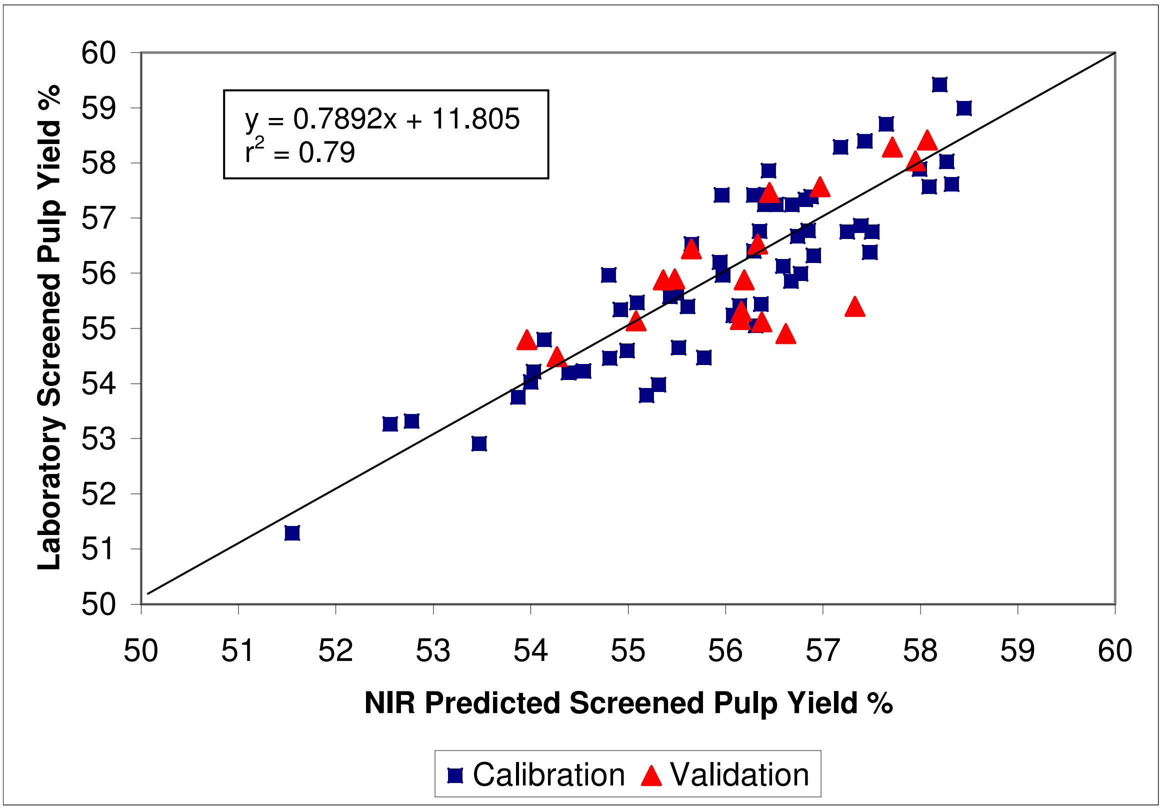

Figure 5.11 Pulp yield correlation plot corresponding to the model developed using second derivative spectra. The blue squares represent the calibration set which was used to generate the regression line for the model and the red triangles represent the data used to validate the model. The diagonal line is shown for comparison purposes and represents the line of equality between predicted and actual pulp yield and is not a regression line.

In Figure 5.11 more than 75% of the samples in the validation set have residuals (laboratory pulp yield minus predicted pulp yield) of less than one, with the average residual = 0.468. The average laboratory pulp yield for the validation set is 56.15% and the average predicted pulp yield for the validation set is 56.3%. These results suggest that NIR can be used to predict pulp yield for *Acacia mearnsii* for a range of age classes and sites.

5.3 Within-tree variation

5.3.1 Within-tree variation in pulp yield

The within-tree variation in pulp yield data collected using the NIR spectrophotometer is presented in Appendix 6. The patterns and trends which became evident after studying this data are presented and discussed below.

As described earlier 30 trees from one site (Bloemendal) and one age class (11 years) were sampled. A cross sectional disc was taken at four heights (2, 20, 50 and 80% of Ut_Ht) from 20 trees and the other ten trees were sampled at ten heights (2, 10, 15, 20, 30, 40, 50, 60, 70 and 80% of Ut_Ht). The sampling heights were selected to provide representative samples within a tree. Each disc taken at the various heights was cut into small segments to facilitate the analyses of pulp yield from the bark to pith. The larger (lower) discs where cut along more radii than the smaller (higher) discs. The average pulp yield (expressed in percentage), predicted using NIRS, from bark to pith and from the discs taken at four heights of the 30 trees sampled are shown in Figure 5.12. The calculated pulp yield for each disc is presented and discussed later in this chapter.

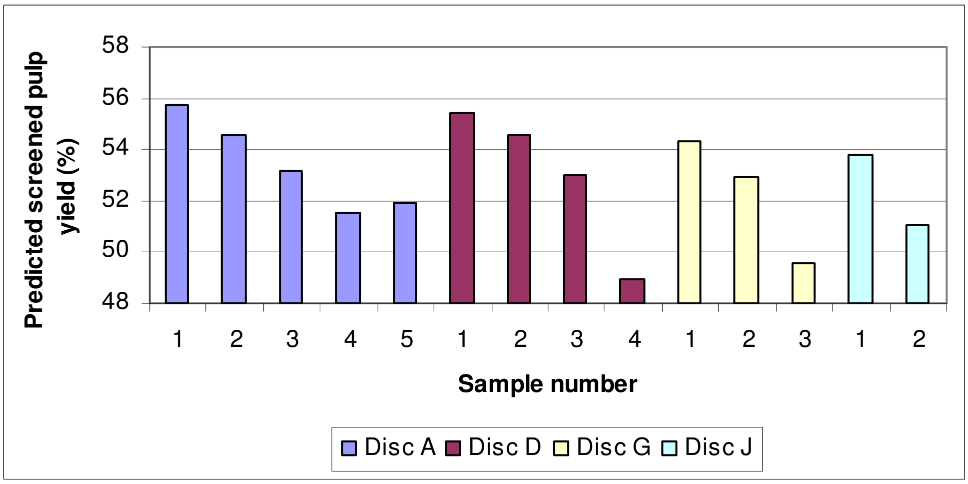

Figure 5.12 Average pulp yield from pith to bark from the four discs taken from all 30 trees. (Disc A = 2% height, Disc D = 20% height, Disc G = 50% height and Disc J = 80% height). The sample numbers ascend from bark to pith for each disc (sampling height).

Figure 5.12 results show that screened pulp yield decreases, on average, from bark to pith at all four heights sampled, except for the increase from position 4 to position 5 (nearest the pith) at the 2% height. These results are consistent with those found by Schimleck and Michell (1998) in their study of within-tree variation in pulp yield of *E. nitens*, where on average pulp yield decreased from bark to pith. The trends observed in screened pulp yield for the 10 trees sampled at ten heights are shown in Figures 5.13 and 5.14.

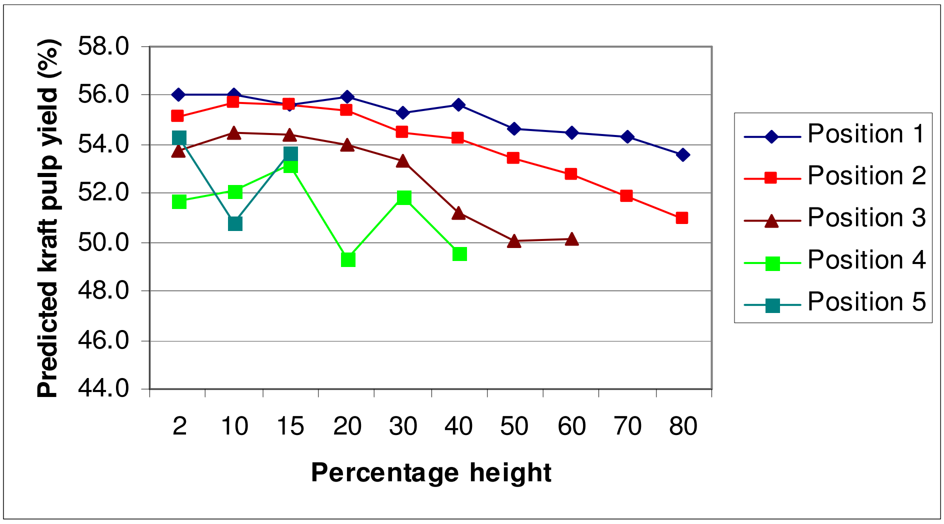

Figure 5.13 Variation in average predicted screened pulp yield with height, from ten black wattle trees. The positions ascend from bark to pith.

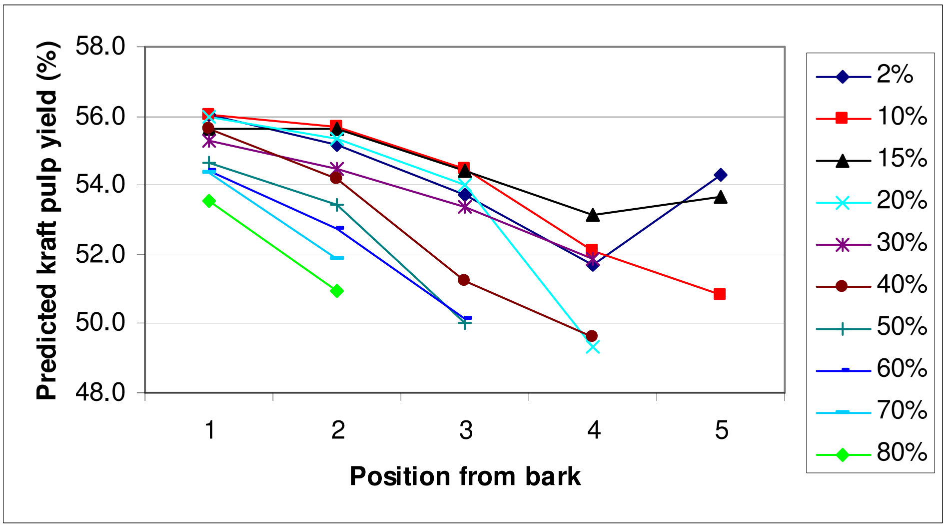

Figure 5.14 Variation in average predicted screened pulp yield from bark to pith, from ten black wattle trees, at the ten heights sampled.

Again the general trend is that from bark to pith at all heights up the tree pulp yield decreases, with the two exceptions being at 2% and 15% heights where the inner most samples had higher screened pulp yields than the adjacent samples as indicated in Figure 5.14. A more in depth look at the slopes and intercepts of the regression lines for each height and position indicated that slopes were different with different intercepts, suggesting that the patterns in pulp yield within the sampled trees is not uniform.

The data presented in Figure 5.12 and in Figure 5.14 were analyzed using a mixed model to check if the differences observed in the predicted pulp yield from the different sampling positions was significantly different. The results of this analysis are presented in Table 5.13, for both the ten tree extensive sampling regime and for all thirty trees using the four sampling heights.

Table 5.13 Results from the mixed model analysis of the predicted pulp yields from the within tree sampling strategy (n.d.f – numerator degrees of freedom, d.d.f – denominator degrees of freedom).

Ten trees sampled at ten heights					
Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Disc	41.92	9	4.66	266	<0.001
Disc Position	163.5	4	40.87	266	<0.001
Disc.Disc Position	45.52	23	1.98	266	0.006
Thirty trees sampled at four heights					
Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Disc	39.54	3	13.18	338	<0.001
Disc Position	240.1	4	60.02	338	<0.001
Disc.Disc Position	28.23	6	4.7	338	<0.001

The mixed model analyses results presented in Table 5.13 show that pulp yield changes significantly between discs and across the different sampling points within each disc. There is also a significant interaction between the discs and the positions of the samples within the discs. These results disprove the null hypothesis stating that pulp yield is independent of the position at which it is measured within the trees.

As a matter of interest the author depicted the mean divisions used to divide the discs taken from the ten trees sampled at ten heights in Figure 5.15 and Figure 5.16 in an attempt to compare the sampling strategy used in this study to that used by Sardinha (1974). These figures indicate that the sampling strategy used could roughly be equated to the sheath strategy used by Sardinha but less easily to the core sequence. The tree maps presented in Figure 5.19 and Figure 5.20 graphically depict the changes in pulp yield predicted from the 30 trees sampled at four heights and the ten trees sampled at ten heights respectively. The resolution is better in Figure 5.20 using the more extensive data and clearly shows a decrease in pulp yield from bark to pith suggesting that the wood produced in the same time period (not years in this case) but from cambium of decreasing age, as one moves up the tree, has similar pulp yield.

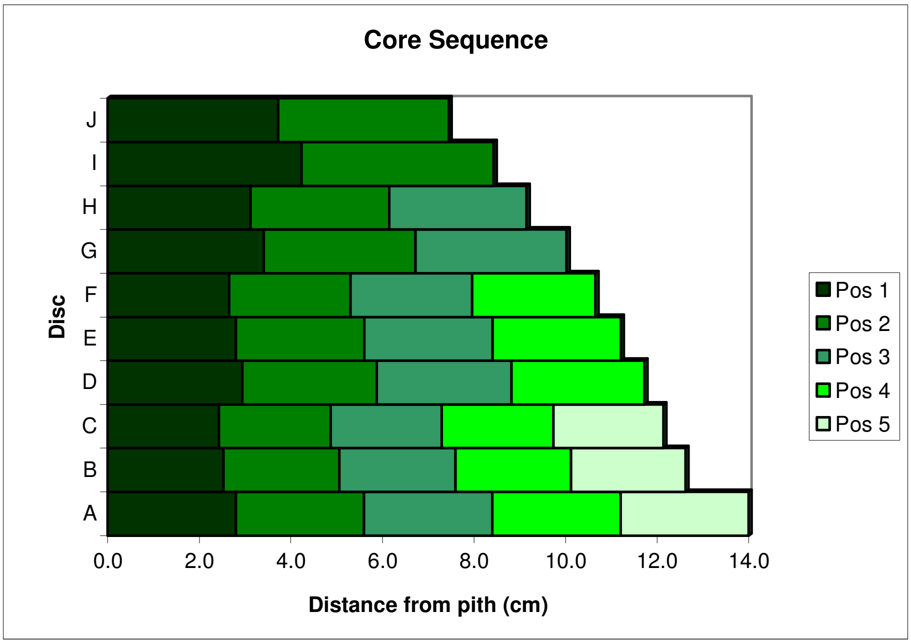

Figure 5.15 A graphical representation of the disc divisions treated as a core sampling technique. Pos 1 is position 1 nearest the pith.

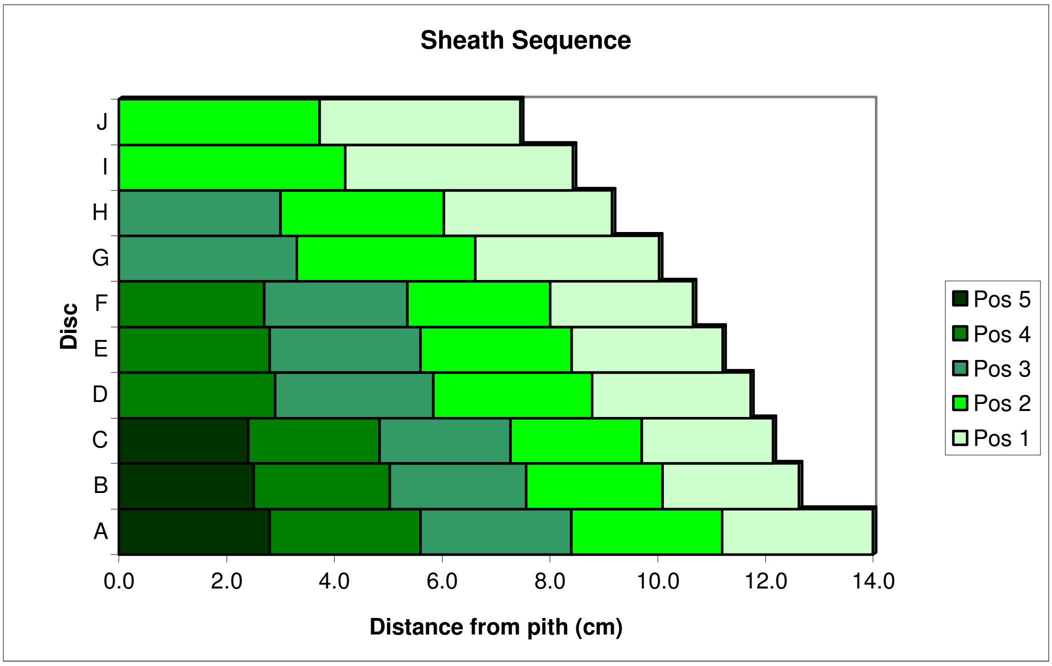

Figure 5.16 A graphical representation of the disc divisions treated as a sheath sampling technique. Pos 1 is position 1 nearest the bark.

From Figure 5.15 depicting a core sequence approach it is clear that the overlap in disc divisions as one moves up the tree are not enough to equate the changes in pulp yield from pith to bark to those found by Sardinha (1974). Figure 5.16 depicts a sheath sequence approach and at least for positions 1 and 2 one could equate the samples as being produced in similar time periods but from cambium of decreasing age as one moves up the tree.

Average screened pulp yield also varies with height up the tree and the trend observed from the data collected from the 30 trees sampled at fours heights are presented in Figure 5.15.

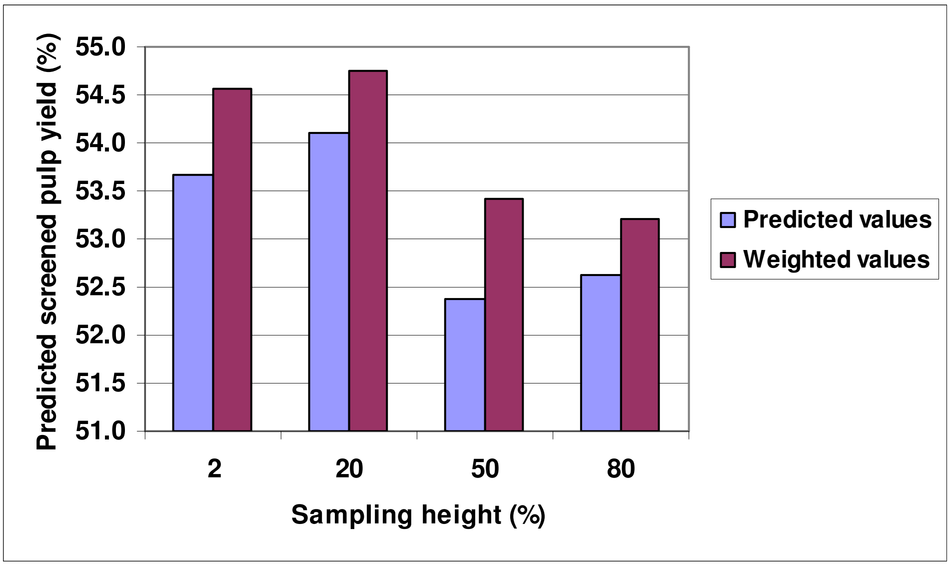

Figure 5.17 Average pulp yield at four different heights up the tree. The blue bars represent predicted values using NIR, the purple bars represent the weighted mean values (Correlation = 95.8%).

Figure 5.17 shows that pulp yield remains relatively stable from the base of the tree up until 20% height and then drops off towards the top of the tree. This trend is more clearly defined by the results presented in Figure 5.18, which shows the change in pulp yield up the tree when sampled at ten heights. Here again the yield is relatively stable from the base of the tree to 20% height, it also decreases from this height to the top of the tree with an unexpected increase in yield at the 70% height. Schimleck and Michell (1998) found similar results in their study of *E. nitens*. As these results have shown wood properties vary greatly within a tree and this variation can be influenced by the amount of juvenile and mature wood present at the sample height. Juvenile wood is formed near the pith of the tree and therefore trees have more mature wood at the base of the tree and juvenile wood near their tops. Juvenile wood is lower in density, has more sapwood and its fibres are shorter and thinner (Zobel and Talbert, 1984; Bamber, 1985). Juvenile and mature wood properties differ greatly and could be the topic for another wood property study in black wattle. In general it can be said that the lower 30% of the utilisable stem yields more pulp than the rest of the stem on a per unit height. As the stem is also thicker at the base of the tree this implies that the lower part of the tree is more valuable from a screened pulp yield perspective than the rest of the tree.

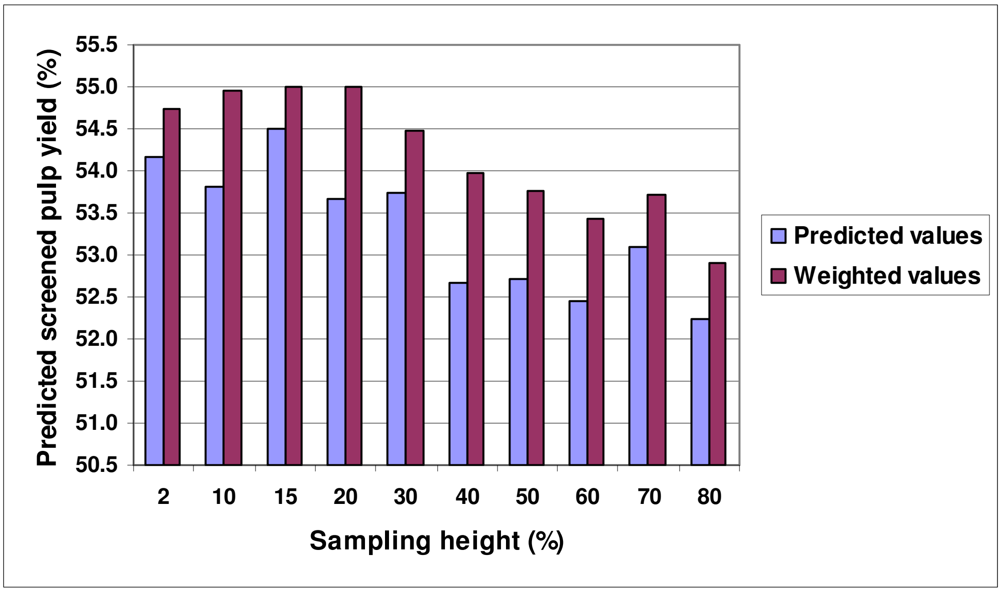

Figure 5.18 Average pulp yield at ten different heights up the tree. The blue bars represent predicted values using NIR, the purple bars represent the weighted mean values (Correlation = 91.8%).

The results presented by the blue bars in Figure 5.17 and 5.18, are averages of the absolute values obtained by the NIR analysis of the individual samples, i.e. the value of each segment within a disc was summed and then divided by the number of segments. However, in the make-up of the entire tree, each sample represents a volume of timber that varies according to its position in the segment and the distance between it and the next sampling point. Therefore, a weighting system was applied to the NIR screened pulp yield results when adding all the measured values together to represent the whole tree as described in Chapter 4, section 4.3.3.

The mean predicted values are consistently lower than the weighted values. This trend is explained by the fact that when calculating the mean predicted values, as explained above, the value of each segment within a disc was summed and then divided by the number of segments, therefore each value had an equal effect on the mean value. This biased the mean in a positive direction because as seen in Figures 5.12 and 5.14, pulp yield decreases from bark to pith. Therefore the results from the centre of the tree should have less effect that the values from the segments closer to the bark, which are also larger proportions of the tree. This is exactly what is being achieved by the weighting so the mean predicted values should be consistently lower. However, from a tree breeding point of view the selection process is essentially based on ranking. The weighted and predicted values are highly correlated with each other 95.8% and 91.8% for the four height sampling and ten height sampling respectively. Therefore it can be concluded that at both levels of sampling it is not necessary to go through the process of weighting the NIR pulp yield data for each disc segment. The mean results obtained will suffice when ranking trees for pulp yield.

5.3.2 Within-tree variation map

Using the data collected using the NIR spectrophotometer and a software package used by the FFP-CSIR, a tree map was produced to graphically represent the average changes in screened pulp yield within the black wattle trees sampled. The map obtained using 30 trees with four sampling heights is presented in Figure 5.19. The few sample points per tree did not allow the software to draw a smooth map. The few data points also resulted in the software package assigning a range in pulp yield (37.3 to 62.5%) that was greater than the actual range predicted by the NIR. The legend in Figure 5.19 therefore implies that the ranges in predicted SPY depicted by the different colours are larger than the real values for the lowest and highest range. The actual range in predicted SPY was 45.5 to 58.5%. From this modelled map an equation was derived to predict screened pulp yield:

SPY = 50.9777 + 0.6777 height + 0.0000657984 exp(height) – 0.100486 height^2
+ 5.15313 log(radius) (R^2 = 94.7%) ....[Equation 5.2]

Although the regression coefficient is very high, the model is very complex with height and diameter still having to be measured to predict the pulp yield.

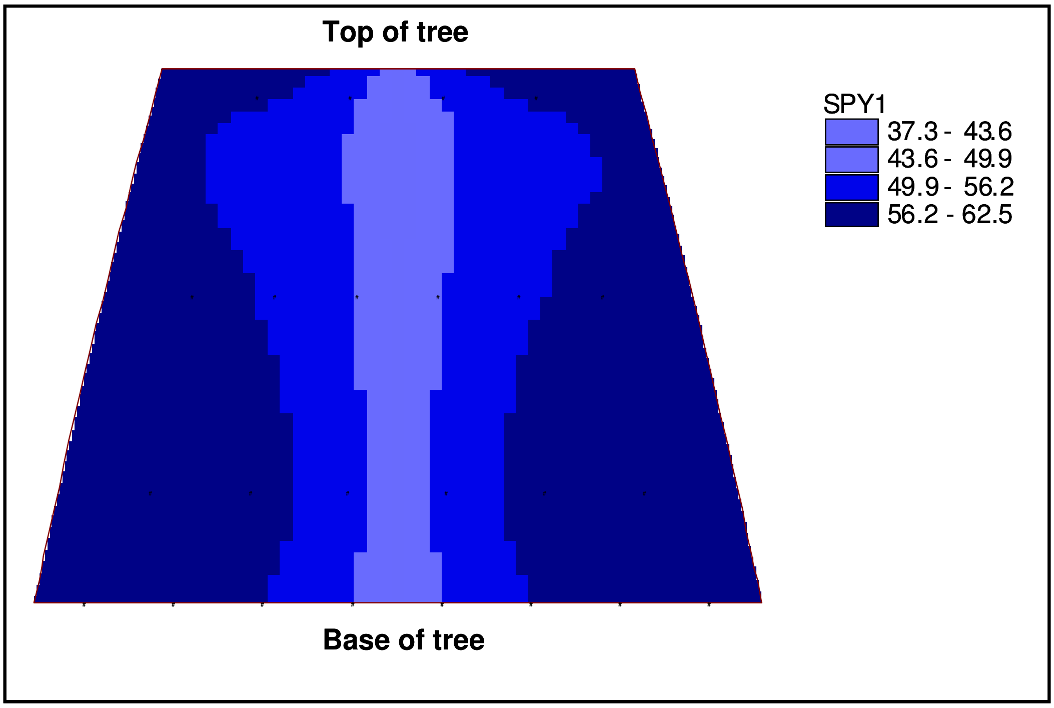

Figure 5.19 Within-tree variation map of screened pulp yield (SPY) obtained from the data collected from 30 trees sampled at four heights.

Figure 5.20 represents the map obtained using ten trees sampled at ten heights. The model derived using these data is:

SPY = 50.6476 + 1.00285 radius ($R^2 = 72.6\ \%$) ....[Equation 5.3]

Although this regression is not as powerful, the model is much simpler and only requires diameter to be measured.

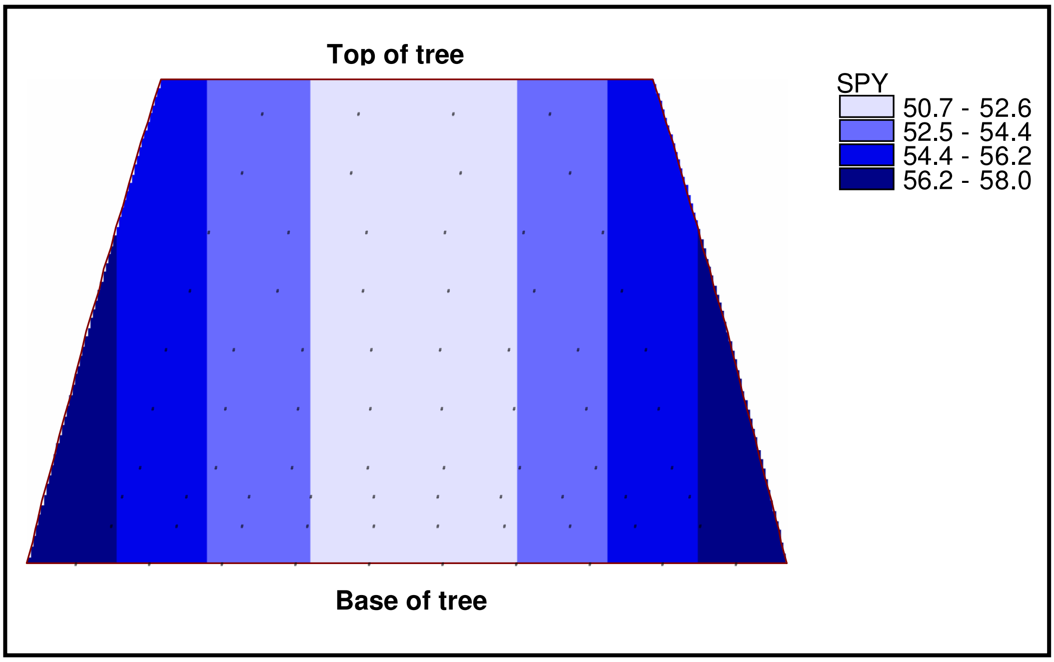

Figure 5.20 Within-tree variation map of screened pulp yield (SPY) obtained from the data collected from 10 trees sampled at 10 heights.

It is evident from Figures 5.19 and 5.20 that the more extensive the sampling regime followed, the better the understanding and picture, of within-tree variation is obtained. Together with the data described by Figures 5.13 and 5.14 it is clear that within-tree patterns of variation of pulp yield in black wattle trees is not uniform. However, from the trends displayed in the two maps presented and from data presented in section 5.3.1 it is clear that pulp yield increases from pith to bark and is highest at the lower part of the tree. The differences in slope and intercept of the regression lines described earlier are evident but the average tree map shown in Figure 5.20 depicts reasonably constant variation at this level of sampling. The variation observed could be due to different growing conditions that occurred during the life span of the trees. As already mentioned it seems that better growing conditions, such as those that occur at the Phoenix plantation, give rise to better pulp yields. Using the same argument for within-tree variation of pulp yield more favourable growing seasons could possibly lead to better pulp yield from the wood put down during that period.

Clark *et al.* (1999) found that irrigated trees had significantly higher pulp yields than rain fed trees. The main issue for this work is the ability to use this information to predict a single sampling point to assess whole tree pulp yield. This is discussed later and at this point it is evident from the models presented above that we can predict pulp yield with the within-tree predicted SPY data collected.

5.3.3 Within-tree variation in basic density

The basic density of all 10 discs taken from the 30 trees was determined. The variation in density of the discs from the base to the top of the tree is shown in Figure 5.21. The general trend is that density decreases from the base of the tree to the top of the tree.

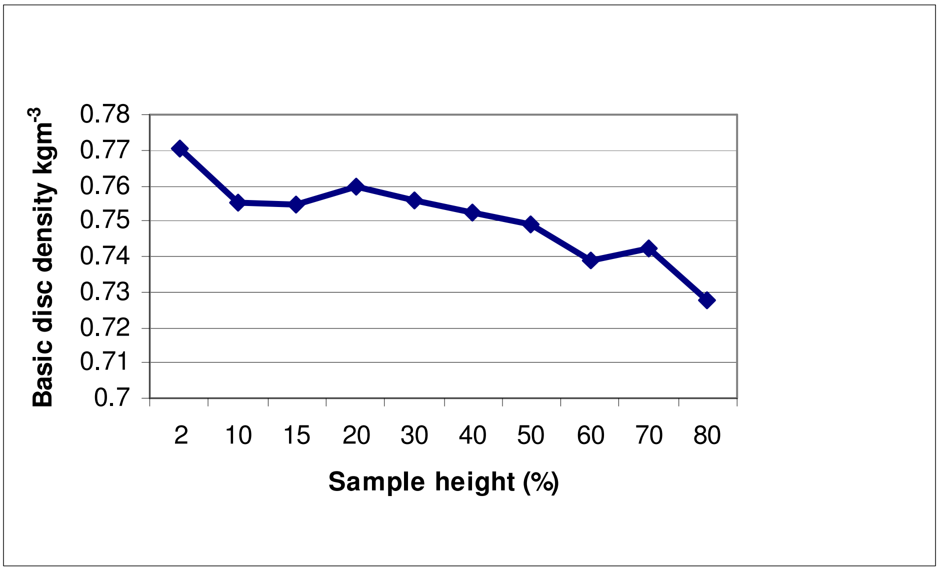

Figure 5.21 Average disc basic density at the ten sample heights up the tree.

5.4 Single sample point correlation with whole tree pulp yield

The data obtained from the 10 extensively sampled trees were used to determine a suitable future sampling scheme that would correlate to the whole tree screened pulp yield. The NIR average pulp yield for each sampling height were correlated to the screened pulp yield obtained for the 10 trees firstly, by wet chemistry in the laboratory digesters, using the billet sample and secondly to the calculated whole tree pulp yield from the NIR predicted pulp yield. The results of these correlations are presented in Table 5.14.

Table 5.14 Mean sample height correlations to the whole tree pulp yield assessed by wet chemistry and calculated from the NIR data.

		Correlation with whole-tree	
Sampling Height (%)	Mean Tree Height (m)	Billet	Calculated
2	0.28	0.728	0.872
10	1.4	0.824	0.935
15	2.1	0.388	0.827
20	2.81	0.873	0.87
30	4.21	0.842	0.936
40	5.61	0.539	0.927
50	7.02	0.558	0.891
60	8.42	0.672	0.944
70	9.82	0.366	0.804
80	11.22	0.406	0.807

The results given in Table 5.14 show high correlations with the calculated whole tree pulp yield. This is most probably due to the high level of auto-correlation with the different height values as a result of individual height values used to calculate the whole tree pulp yield. Therefore the correlations with the billet sample pulp yield is far more important in this study, because the base line pulp yield for the trees in this study were determined using the billet samples. The highest correlation being with the 20% height sample. The average 20% height for the trees sampled was 2.81 m, which is an impractical height for sampling. Therefore the 10% height sample with a correlation coefficient of 0.824 was chosen as the most practical height at which to sample in future. The average 10% height was 1.40 m which is a practical height at which to sample.

A regression model was then built to predict the whole tree pulp yield from the 10% sample height values.

The model built using the billet pulp yield data, as the response variate is as follows:
Let $X_{1.4}$ be the predicted SPY from sample at 1.4 m. Thus, for the whole tree:

$SPY = 26.67 + 0.538X_{1.4}$ ....[Equation 5.4]
(0.131)
( ) denotes standard error

This equation accounts for 63.9% of the variation in screened pulp yield. The regression is significant (p=0.003).

The model built using the calculated whole tree pulp yield data, as the response variate is as follows:

$SPY = 17.74 + 0.679\ X_{1.4}$ ....[Equation 5.5]
(0.0912)
( ) denotes standard error

This equation accounts for 85.8% of the variation in screened pulp yield. However, this model is heavily biased by auto-correlation and is included for completeness, but is not recommended for use.

These models verify the hypothesis posed that whole tree pulp yield can be calculated or predicted using the predicted pulp yield from a small sample of wood taken at the correct height up the tree.

5.5 Comparisons between wet chemistry screened pulp yield and whole tree predicted screened pulp yield

Ten of the 90 trees assessed for screened pulp yield came from the 11-year-old Bloemendal trees that were also used in the extensive within-tree variation study. The weighted whole tree predicted SPY from these ten trees were compared to the laboratory screened pulp yield data from the same ten trees. As a validation of Equation 5.4, the author included the 10% height weighted calculated SPY. These comparisons are shown in Table 5.15 and the correlations between the values are given in Table 5.16.

Table 5.15 Comparisons between the wet chemistry, whole tree predicted and 10% height predicted values obtained for screened pulp yield from ten 11-year-old trees sampled at Bloemendal.

Tree	Wet chemistry SPY (%) from the billets. The % of the tree represented by the billet is presented in brackets.	Mean weighted total tree SPY (%) calculated from the ten trees sampled at ten heights (MWTTSPY-10)	Mean weighted total tree SPY (%) calculated from the ten trees sampled at four heights (MWTTSPY-4)	10% height predicted SPY (%)
1	56.8 (14.0)	53.7	53.2	55.2
2	56.9 (13.8)	55.1	54.7	56.3
3	56.5 (13.6)	55.7	55.9	57.4
4	55.9 (12.8)	55.8	55.8	56.7
5	52.9 (14.3)	52.0	51.9	52.1
6	55.4 (13.1)	54.9	55.3	55.0
7	55.2 (11.8)	54.0	53.5	53.8
8	55.9 (12.7)	52.5	52.1	53.3
9	55.4 (13.8)	53.7	53.5	54.4
10	56.1 (13.2)	54.91	54.3	55.19

Table 5.16 Correlations between the wet chemistry, whole tree predicted and 10% height predicted values obtained for screened pulp yield from ten 11-year-old trees sampled at Bloemendal.

	Wet chemistry	(MWTTSPY-10)	(MWTTSPY-4)
(MWTTSPY-10)	0.626		
(MWTTSPY-4)	0.517	0.975	
10% height SPY (%)	0.769	0.931	0.902

The results presented in Figure 5.15 and Figure 5.16 indicate that values obtained via laboratory analysis, by weighting all of the predicted values obtained from the samples taken throughout the tree and from the weighted predicted SPY from the disc taken at 10% of utilisable height are all of a similar order. The correlation between the wet chemistry results and the 10% height weighted SPY of 0.769 substantiates the results presented in section 5.4 where it was shown that a regression model could be used to predict whole tree SPY using the value predicted from sampling at the 10% height. The low correlation between the mean weighted total tree SPY obtained from sampling only four heights (MWTTSPY-4) and the wet chemistry results is totally expected as the billet did not share any wood with any of the four samples. The billet was taken between the 2% height and the 20% height which were the two lower heights sampled using only four heights. The very high correlation between the MWTTSPY-4 values and the mean weighted total tree SPY obtained from sampling ten heights (MWTTSPY-10) is rather meaningless because of the low correlation between the MWTTSPY-4 and the wet chemistry results. Therefore if future studies are carried out to refine the calibration model, it is suggested that the more extensive sampling regime is used

Chapter 6

Overall Conclusions

The use of NIR spectroscopy in the non destructive prediction of pulp yield of forestry species is becoming more widespread (Birkett and Gambino, 1989; Wallbäcks *et al.*, 1991; Garbutt *et al.*, 1992; Michell, 1994; Schimleck *et al.*, 1996; Sefara *et al.*, 2000, Raymond and Schimleck, 2002; So *et al.*, 2004). This study was embarked upon to determine if this technology could be applied to *Acacia mearnsii* (black wattle). The experiment encompassed sampling ten trees from each of three age classes (7, 9 and 11 years old) from three plantations (Bloemendal, Glen Echo and Phoenix) in KwaZulu Natal. Growth characteristic measurements were made on the 90 trees and they were sampled for laboratory pulp yield assessments, in order to examine the variation in growth characteristics and pulp yield across these age classes and plantations. The 90 samples used for the pulp yield analysis where also used to calibrate a NIR spectrophotometer to predict pulp yield from small samples of milled wood. Thirty 11-year-old trees were then extensively sampled from the Bloemendal plantation in order to determine the within-tree patterns of variation in pulp yield, using the NIR model developed in the first part of the study. The within-tree variation data were used to identify a non-destructive sampling height for pulp yield prediction in future.

Results obtained from the tree growth data measured prior to felling and calculated after felling, across the three sites and age classes, as well as the pulp yield results were analyzed. First, the plantations were considered fixed effects, and then as random effects. The fixed effects scenario was used to look at differences in tree growth and pulp yield characteristics across the three sites sampled, in order to be able to draw specific conclusions relating to the three sites.

When plantations were considered as random effects the aim was to be able to draw general conclusions about the population of trees sampled. This model was chosen as the one of most benefit. Tree age did not have a significant effect on any of the growth characteristics analysed. Age does not affect pulp yield significantly either, therefore when assessing the value of a plantation from a growth or pulp yield point of view, age is not a significant factor. The main driver in deciding whether to fell the trees or not depends on what point on the relevant growth curve the trees are lying. If the mean annual increment has reached a maximum there is very little evidence supporting a decision to allow the trees to grow for longer, at least for the ages used in this study. The data that is currently available allows only the associated conclusions to be drawn. Future experiments designed with different objectives in mind such as to determine what the pulp yield from black wattle trees would be when sampled at ages outside of the range used in this study, would provide additional information in this area of wood research.

Using the 90 samples from the three ages and plantations a NIR spectrophotometer was successfully calibrated to measure pulp yield from small samples of milled wood. The second derivative spectra obtained from the samples along with multivariate analyses using partial least squares was able to build a model with R^2 = 78.9% and SEC = 0.79, using four factors. These results suggest that with the samples available for the calibration and validation steps, the model built can reasonably predict pulp yield from small samples of wood.

The within-tree variation study gave an insight into the variation of pulp yield from the base of the tree to the top of the tree and from the bark to the pith. The two sampling intensities suggest that the more a tree is sampled the better the understanding gained of the variation. In general pulp yield decreases as one samples from the outside of the tree to the inside of the tree and is relatively stable from the base of the tree to about 15 – 20% of the height and then declines towards the top of the tree. A closer look at the slopes and intercepts of regression lines that describe the change in pulp yield within the tree showed that the variation patterns are not uniform within the tree, but for the purposes of this study the variation was not a major factor.

The final part of this study was to use the data collected using the NIR model, from the extensive sampling within the 30 trees at Bloemendal to identify a single sampling height, whose pulp yield correlates best to whole tree pulp yield. This point was found to be at 1.4 m above the ground and the model built for whole tree pulp yield using this sample accounts for 63.9% of the variation found in the sample population.

This study is the first of its kind undertaken in South Africa, and possibly globally, for *A. mearnsii* (black wattle). It has given an account of the variation in growth characteristics and more importantly from a uniqueness point of view, into the variation in pulp yield across three sample sites and three age classes. The calibration of the NIR spectrophotometer has broken ground for future such work, preferably with more samples to refine the model built. The within-tree variation study has modelled the changes in pulp yield both vertically and horizontally within the trees and allowed the production of a tree map depicting the changes in pulp yield. Ultimately the identification of a non-destructive sampling height that can be used to predict whole tree pulp yield was found, giving tree breeders a tool, with which to predict pulp yield without sacrificing the genotype. Individual trees can thus now be ranked according to pulp yield and superior individuals or families could be targeted as parents for future generations of higher pulp yielding black wattle trees. As previously described, black wattle is not the most important forestry species in South Africa, nor are the trees the biggest, if compared to eucalypts or pines, but the combination of their relatively high basic wood density and high pulp yield makes them a sought after raw product in niche international wood markets. The ability to select and breed for pulp yield will assist in retaining these important markets in future. An important aspect of work that should be carried out in black wattle is an inheritance study of pulp yield. This should be done prior to embarking on an exercise of evaluating the existing breeding population using the relatively expensive technique of NIR. There is no point in using this technique to select for pulp yield if there is little to no genetic variation.

This study, however, has not concluded this work. With more samples being used to improve the NIR calibration more accurate predictions could be obtained in future. This study has focused mainly on the effects of the position in the tree on pulp yield, but there are other factors that influence the pulp yield from individual trees. Characteristics such as the physiological age of the wood sampled, fibre length, lignin content, cellulose content and vessel dimensions also play a role in pulp yield and quality. The investigation into the variation of these within a tree along with the results presented in this dissertation could lead to the development of models that account for more of the variation observed. It is now up to the industry to decide if more of this work should be undertaken.

References

Artuz-Siegel, E. A., Wangaard, F. F. And Tamalong, F. N. 1968. Relationships between fiber characteristics and pulp-sheet properties in Phillipine hardwoods. *Tappi*. **51**(6): 261 – 267.

Bamber, R. K. 1985. The wood anatomy of eucalypts and papermaking. *Appita*. **38**:210 - 216.

Bamber, R. K., Horne, R. and Graham-Higgs, A. 1982. Effect of fast growth on the wood properties of *Eucalyptus grandis*. *Australian Forestry Research*. **12**:163 – 167.

Banks, C. H. 1954. The mechanical properties of timber with particular refernce to those grown in the Republic of South Africa. (Fully revised in 1973 and metricated in 1976). Bulletin 48, Department of Forestry, RSA (December 1977).

Barefoot, A. C., Hitchings, R. G. and Ellwood, E. L. 1966. Wood characteristics and kraft paper properties of four selected Loblolly Pines. III. Effect of fiber morphology in pulps examined at a constant permanganate number. *Tappi*. **49**(4): 137 – 147.

Batchelor, B. K., Crawford, I. A. and Turner, C. H. 1970. The assessment of a forest for pulping. *Appita*. **24**:27 - 44.

Batchelor, B. K., Prentice, F. J. and Turner, C. H. 1971. The assessment of a forest for pulping Pt II. *Appita*. **24**:253 - 260.

Beadle, C. L., Turnbull, C. R. A. and Dean, G. H. 1996. Environmental effects on growth and kraft pulp yield of *Eucalyptus globulus* and *E. nitens*. *Appita*. **49**:239 - 242.

Beck, S. L. 2000. Micropropagation of *Acacia mearnsii* (de Willd). PhD Thesis. Department of Botany, Faculty of Science, University of Natal, Pietermaritzburg. 128p.

Beck, S. L. and Goodricke, T. G. 2002. Threats to wattle plantations I: Abiotic and mammalian. *In* Black Wattle: The South African Research Experience Eds. R. W. Dunlop and L. A. MacLennan. Institute for Commercial Forestry Research, Pietermaritzburg, pp. 101 – 104.

Beebe, K. R., Pell, R. J. and Seascholtz, M. B. 1998. Chemometrics: A practical guide. John Wiley & Sons Ltd, New York.

Bhat, R. V. and Virmani, K. C. 1953. Indigenous cellulosic raw materials for the production of pulp, paper and board. *The Indian Forester*. **79**:526 - 538.

Birkett, M. D. and Gambino, M. J. T. 1988. Potential application for near infrared spectroscopy in the pulping industry. *Paper Southern Africa*:34 - 38.

Birkett, M. D. and Gambino, M. J. T. 1989. Estimation of pulp kappa number with near infrared spectroscopy. *TAPPI Journal*. **72**:193 - 197.

Boden, D. I. 1982. The relationship between timber density of the three major pine species in the Natal midlands and various site and tree factors. Wattle Research Institute Report, 120 – 126.

Bokobza, L. 2002. Origin of near-infrared absorption bands. *In* Near-Infrared Spectroscopy. Ed. Y.O. H. W. Siesler, S. Kawata, H. M. Heise. WILEY-VCH, Weinheim, pp. 11 - 41.

Borralho, N. M. G., Cotteril, P. P. and Kanowski, P. L. 1993. Breeding objectives for pulp production of *Eucalyptus globulus* under different industrial cost structures. *Canadian Journal of Forest Research*. **23**:648 - 656.

Britt, K. W. 1965. Handbook of pulp and paper technology. Ed. K. W. Britt. Reinhold, New York.

Burns, D. A. and Ciurczak, E. W. 2001. Handbook of Near-Infrared Analysis. Marcel Dekker, Inc., New York.

Cailliez, F. 1980. *Forest volume estimation and yield prediction. Volume 1- Volume Estimation*. Pp. 31 – 38. Food and Agriculture Organization of the United Nations, Rome.

Ciurczak, E. W. 2002. Principles of Near-infrared spectroscopy. *In* Handbook of Near-Infrared Analysis. Eds. D.A. Burns and E. W. Ciurczak. Marcel Dekker, Inc., New York, p. 9.

Clark, N. B. 2001. Longitudinal density variation in irrigated hardwoods. *Appita*. **54 (1)**: 49 – 60.

Clark, N. B. and Hicks, C. C. 2003. Evaluation of the pulpwood quality of 13 lesser-known eucalypt species. *Appita*. **56 (6)**: 53 – 60.

Clark, N. B., Balodis, V., Fang, G. and Wang. J. 1992. Pulpwood potential of Acacias. *In* Australian tree species research in China. Ed. A.G. Brown. Australian Centre for International Agricultural Research, Zhangzhou, Fujian Province, PRC, pp. 196 - 202.

Clark, N. B., Read, S. M. and Vinden, P. 1999. Effects of drought and salinity on wood and kraft pulp from young plantation eucalypts. *Appita*. **52 (2)**. 93 – 98.

Clarke, C. R. E. 1995. Variation in growth, wood, pulp and paper properties of nine eucalypt species with commercial potential in South Africa. *In* School of

Agricultural and Forest Sciences. University College of North Wales, Bangor, p. 155.

Clarke, C. R.E . and Wessels, A. M. 1995. Variation and measurement of pulp properties in eucalypts. *In* "Eucalypt plantations: Improving fibre yield and quality" (Eds B. M. Potts, N. M. G. Borralho, J. B. Reid, R. N. Cromer, W. N. Tibbits, and C. A. Raymond). pp 93 - 100. Proc CRCTHF – IUFRO Conference, Hobart, 19 – 24 February. (CRC for Temperate Hardwood Forestry: Hobart).

Clarke, C. R. E., Shaw, M. J. P., Wessels, A. M. and Jones, W. R. 1999. Effect of differences in climate on growth, wood, and pulp properties of nine eucalypt species at two sites. *TAPPI Journal*. **82**:89 - 99.

Corson, S. R. 1999. Tree and fibre selection for optimal TMP quality. Appita. **52(5)**: 351 – 357.

Crawford, I. A., Prentice, F. J. and Turner, C. H. 1972. Variation in pulping quality within two trees of *E. delegatensis*. *Appita*. **25(5)**: 353 – 358.

Dadswell, H. E. and Wardrop, A. B. 1959. Growing trees with wood properties desirable for paper manufacture. Appita. **12(4)**: 129 – 136

Downes, G. M., Hudson, I. L., Raymond, C. A., Dean, G. H., Michell, A. J., Schimleck, L. R., Evans, R. and Muneri, A. 1997. Sampling Plantation Eucalypts for wood and fibre properties. CSIRO publishing, Australia.132p.

Dunlop, R. W. 2002a. *Acacia mearnsii* (De Wild). *In* Plant Resources of Tropical Africa: Precursor. Eds. L. P. A. Oyen and R. H. M. Lemmens. J. Veenman drukkers, Ede, Wageningen, pp. 30 - 35.

Dunlop, R. W. 2002b. Introduction. *In* Black Wattle: The South African Research Experience. Eds. R. W. Dunlop and L. A. MacLennan. Institute for Commercial Forestry Research, Pietermaritzburg, pp. 1 - 2.

Dunlop, R. W. 2002c. Tree improvement. *In* Black Wattle: The South African Research Experience. Eds. R. W. Dunlop and L. A. MacLennan. Institute for Commercial Forestry Research, Pietermaritzburg, pp. 11 – 32.

Dunlop, R. and Hagedorn., S. 1998. Final report on two Australian *Acacia mearnsii* (Black Wattle) provenance trials established in KwaZulu-Natal and south eastern Mpumalanga. Institute for Commercial Forestry Research, Pietermaritzburg.

Dunlop, R. W., Goodricke, T. G. and Clarke, C. R. E. 2000. Open-pollinated family variation in growth, wood and dissolving pulp properties of *Acacia mearnsii*. *In*

Forest genetics for the next millennium: IUFRO Working Party 2.08.01 Tropical Species Breeding and Genetic Resources. Pietermaritzburg, Institute for Commercial Forestry Research, International Conference Centre: Durban, South Africa, pp. 103 - 106.

Edlund, U. 2003. Rapid classification of wood using near-infrared spectroscopy (NIR) and modern multivariate data analysis techniques. http://www.bfafh.de/aktuell/pdf/g8edlund.pdf, accessed 6 June 2003.

Evans, R., Downes, G. M., Menz, D. and Stringer, S. 1995. Rapid measurement of variation in tracheid transverse dimensions in a radiate pine tree. *Appita*. **48**:134 - 138.

Fang, G., Wang, J. and Liu, G. 1994. Kraft pulping properties of plantation-grown *Acacia mearnsii* from Zhangzhou. *In* Australian tree species research in China Ed. A.G. Brown. Australian Centre for International Agricultural Research, Zhangzhou, Fujian Province, PRC, pp. 214 - 217.

Farrington, A. and Hickey, B. 1989. Wood sources for the Port Huon Mil: NSSC pulping of some young eucalypt species. *Appita* **42**(6). 419 – 423.

FSA. 2002a. Forestry and Forest Products Industry Facts and Figures - 1979/80 to 2000/2001. South Africa.

FSA. 2002b. Abstract of South African forestry facts for the year 1999/2000

Garbutt, D. C. F., Donkin, M. J and Meyer, J. H. 1992. Near infra-red reflectance analysis of cellulose and lignin in wood. *Paper Southern Africa*. **3**:45 - 48.

Goldstein, I, S. 1980. New technology for new uses of wood. *Tappi*. **63(2)**: 105 – 108.

Greaves, B. L., Borralho, N. M. G. and Raymond, C. A. 1997. Breeding objective for plantation eucalypts grown for production of kraft pulp. *Forest Science*. **43**:465 - 472.

Grzeskowiak, V., Turner, P. and Megown, R. A. 2000. The use of densitometry and image analysis techniques to predict pulp strength properties in *Eucalyptus* plantations. TAPPSA Conference “African Paper Week ‘2000 and beyond’”. Durban, South Africa. 17 – 20 October, 2000.

Hall, M. J., Hansen, N. W. and Rudra, A. B. 1973. The effect of species, age and wood characteristics on Eucalypt kraft pulp quality. *Appita*. **26**:348 - 354.

Hannah, B. C., Fergus, B. J. and Jones, R. N. 1977. Kraft pulping and bleaching studies on young exotic hardwood species. *Appita*. **30**:483-487.

Haygreen, J. G. and Bowyer, J. L. 1996. Forest products and wood science: an introduction. Third edition, Iowa State University Press. Ames Iowa. 484p.

Henry, C. M. 1999. Near-IR gets the job done. *Analytical Chemistry News and Features*. 625A – 628A.

Herbert, M. A. 1993. Site requirements of exotic hardwood species. Institute for Commercial Forestry Research, Pietermaritzburg, p. 17.

Herbert, M. A. 2000. Site requirements and species matching: Eucalypts and Wattles. *In* Southern African Forestry Handbook Ed. D.L. Owen. South African Institute of Forestry, Pretoria, pp. 85 - 94.

Herschel, W. 1800. Investigation of the power of prismatic colours to heat and illuminate objects; with remarks, that prove the different refrangibility of radiant heat. To which is added, an inquiry into the method of viewing the sun advantageously with telescopes of large apertures and high magnifying powers. *Philosophical Transactions of the Royal Society*. **90**:255 - 283.

Higgins, H. G. 1970. Technical assessment of eucalypt pulps in the papermaking economy. *Appita*. **26**:417 - 426.

Hill, J. 1770. The construction of timber, London.

Hillis, W. E. 1997. Wood properties and uses. *In* Black wattle and its utilisation - Abridged English edition. Eds. A.G.Brown and H.C. Ko. Rural Industries Research and Development Corporation, Kingston, pp. 89 - 93.

Hinterstoisser, B., Schwanninger, N., Gierlinger, N. and Grabner, M. 2001. Infrared spectroscopy: A tool for rapid wood assessment. G8 meeting of experts, 27 November, Hamburg, Germany.

ICFR. 1989. Genetic improvement of *Acacias*. Institute for Commercial Forestry Research, Pietermaritzburg.

Jones, T. G. and Richardson, J. D. 1999. Relationships between wood and chimimechanical pulping properties of New Zealand grow *Eucalyptus nitens* trees. *Appita*. **52**: 51 - 61

Kassier, H. W. and Kotze, H. 2000. Growth modelling and yield tables. *In*: South African Forestry Handbook 2000. Vol 1. Southern African Institute of Forestry. V&R printers, Pretoria

Kelley, S. S., Rials, T. G., Groom, L. R. and So, C. 2004a. Use of near infrared spectroscopy to predict mechanical properties of six softwoods. *Holzforschung*. **58**: 252 – 260.

Kelley, S. S., Rials, T. G., Snell, R., Groom, L. H. And Sluiter, A. 2004b. Use of near infrared spectroscopy to measure the chemical and mechanical properties of solid wood. *Wood Sci Technol.* **38**: 257 – 276.

Kibblewhite, R. P. 1999. Designer fibres for improved papers through exploiting genetic variation in wood microstructre. *Appita*. **52**:429 - 440.

Kromhout, C. P. 1990. A review of research on wood properties in South Africa. *Suid-Afrikaanse Bosboutydskrif*. Nr 152. 67 – 71.

Kube, P. D. and Raymond, C. A. 2002. Prediction of whole-tree basic density and pulp yield using wood core samples in *Eucalyptus nitens*. *Appita*. **55**:43 - 48.

Kunz, R. 1997. Neighbourhood analysis of tree growth data. ICFR Bulletin Series 5/97.

Lane, P. W. and Payne, R. W. 1996. Genstat® for Windows^{TM}, an introductory course. Lawes Agricultural Trust, Rothamsted Experimental Station.

Ledeboer, M. S. J. 1944. Vegetative propagation of tan wattles. *Journal of South African Forestry Association*. **12**: 29 – 32.

Little, K. M. 1999. The influence of vegetation control on the growth and pulping properties of a *Eucalyptus Grandis x Camaldulensis* hybrid clone. PhD Thesis. Department of Botany, Faculty of Science, University of Natal, Pietermaritzburg. 136p

Logan, A. F. 1986. Australian acacias for pulpwood. *In* Australian acacias in developing countries. Ed. J.W. Turnbull. ACIAR, Forestry Training Centre, Gympie, Queensland, Australia., pp. 89 - 94.

Malan, F. S. 1979. The control of end splitting in sawlogs: A short literature review. *Suid-Afrikaanse Bosboutydskrif*. Nr 107. 14 – 18.

Malan, F. S., Male, J. R. and Venter, J. S. M. 1994. Relationships between the properties of eucalypt wood and some chemical, pulp and paper properties. *Paper Southern Africa* 1.2/94. 6 – 16.

Mark, H. 2000. Quantitative spectroscopic calibration. *In* Encyclopedia of Analytical Chemistry Ed. R.A. Meyers. John Wiley & Sons Ltd., Chichester.

Martin, P. 1994. A laymans guide to the pulp and papermaking industry in South Africa. Mondi Ltd, Richards Bay.

McClure, W. F. 1994. Near-Infrared Spectroscopy - The giant is running strong. *Analytical Chemistry*. **66**:43 - 53.

Megown, K. A., Turner, P., Male, J. R. and Retief, R. J. 2000. The impact of site index and age on the wood, pulp and pulping properties of a *Eucalyptus grandis* clone (Tag 5). *In* Forest genetics for the next millennium: IUFRO Working Party 2.08.01 Tropical Species Breeding and Genetic Resources.

Pietermaritzburg, Institute for Commercial Forestry Research, International Conference Centre: Durban, South Africa, pp. 169 - 173.

Michell, A. J. 1994. Vibrational spectroscopy - a rapid means of estimating plantation pulpwood quality? *Appita*. **47**:29 - 37.

Michell, A. J. 1995. Pulpwood quality estimation by near-infrared spectroscopic measurements on eucalypt woods. *Appita*. **48**:425-428.

Michell, A. J. and Schimleck, L. R. 1996. NIR spectroscopy of woods from *Eucalyptus globulus*. *Appita*. **49**:23-26.

Miranda, I., Almeida, M. H. and Pereira, H. 2001. Provenance and site variation of wood density in *Eucalyptus globulus* Labill. at harvest age and its relation to a non-destructive early assessment. *Forest Ecology and Management*. **149**:235 - 240.

Muneri, A. 1997. Kraft pulping properties of *Acacia mearnsii* and *Eucalyptus grandis* grown in Zimbabwe. *South African Forestry Journal*. **179**:13-19.

National Water Act. 1998. Act No 36 of 1998, South Africa.

Nicholson, C. L. R. 1991. The pulping and mechanical properties of black wattle timber. ICFR Annual Research Report for 1991: 147, Pietermaritzburg

Nixon, K. M. 1977. Breeding black wattle (*Acacia mearnsii* De Wild) for bark, tannin and timber in South Africa. *In* Third World Consultation on Forest Tree Breeding. CSIRO, Canberra, pp. 629 - 637.

Norris, K. H. and Hart, J. R. 1965. Direct spectrophometric determination of moisture content of grain and seeds. *In*: Principles and methods of Measuring Moisture Content in Liquids and Solids. Vol. 4. A. Waxler, Ed. Reinhold, New York. Pp. 19 – 25.

Osborn, J. B. 1931. Seed selection in black wattle (*Acacia mollissima*). *Empire Forestry Journal*. **10**:190 - 202.

Osborne, B. G. 2000. Near-infrared spectroscopy in food analysis. *In* Encyclopedia of Analytical Chemistry Ed. R.A. Meyers. John Wiley & Sons, Chichester.

Osborne, B. G. and Fearn, T. 1986. Near Infrared spectroscopy in food analysis. Lomgman Scientific and Technical, Avon. 200 p.

Pearson, R. G. and Gilmore, R. C. 1980. Effect of fast growth rate on the mechanical properties of loblolly pine. *Forest Products Journal*. **30**(5): 47 – 54.

Pizzi, A. 1978. Wattle-based adhesives for exterior grade particleboards. *Forest Products Journa*l. **28** (12): 42 – 47

Pizzi, A., Rossouw, D. DU T., Knüffel, W. and Singmin, M. 1980. Fast-setting phenolic and tannin-based 'Honeymoon' adhesive systems for exterior grade finger-joints. CSIR Special Report HOUT 184. Pretoria South Africa. 35 p.

Pulpwatch. 2003. Glossary and terms used in the pulp and paper industry. http://www.pulpwatch.com/glossary.htm, accessed 7 June 2003.

Raymond, C. A., Banham, P. and MacDonald, A. C. 1998. Within tree variation and genetic control of basic density, fibre length and coarseness in *Eucalyptus regnans* in Tasmania. *Appita*. **51**:299 - 305.

Raymond, C. A. and Shimleck, L. R. 2002. Development of near infrared reflectance analysis calibrations for estimating genetic parameters for cellulose contant in *Eucalyptus globulus*. *Canadian Journal of Forest Research*. **32**:170-176.

SAWGU. 2001. S.A. Wattle Growers' Union annual report and accounts. South African Wattle Growers' Union, Pietermaritzburg, p. 6.

Sardinha, R. M. A. 1974. Variation in density and some structural features of wood of Eucalyptus saligna Sm. from Angola. PhD thesis. University of Oxford. p 349.

Schimleck, L. R. and Michell, A. J. 1998. Determination of within-tree variation of kraft pulp yield using near-infrared spectroscopy. *TAPPI Journal*. **81**:229-236.

Schimleck, L. R. and French, J. 2002. Application of NIR spectroscopy to clonal *Eucalyptus globulus* samples covering a narrow range of pulp yield. *Appita*. **55**:149 - 154.

Schimleck, L. R., Michell, A. J. and Vinden, P. 1996. Euclaypt wood classification by NIR spectrscopy and principal component analysis. *Appita*. **49**:319 - 324.

Schönau, A.P.G. 1969. A site evaluation study in black wattle. PhD Thesis, University of Stellenbosch.

Schönau, A. P. G. 1972. Metric timber volume, percentage utilisation and stump and kerf wastage table for black wattle, *Acacia mearnsii*. Wattle Research Institute, Pietermaritzburg, pp. 39 - 47.

Schönau, A. P. G. 1974. Metric site index curves for black wattle. Wattle Research Institute Report for 1973 – 1974, p46.

Schönau, A. P. G. 1979. The variation of bark components and quality with age in young black wattle trees. Wattle Research Institute, Pietermaritzburg, pp. 99 - 105.

Schönau, A. P. G. and Fitzpatrick, R. W 1981. A tentative evaluation of soil types for commercial afforestation in the Transvaal and Natal. *South African Forestry Journal*. **116**:28 - 39.

Schultz, T. P. and Burns, D. A. 1990. Rapid secondary analysis of lignocellulose: comparison of near infrared (NIR) and fourier transformed infrared (FTIR). *TAPPI Journal*. **73**:209 - 212.

Schumacher, F. X. and Hall, F. S. 1933. Logarithmic expressions of timber-tree volume. *Journal of Agriculture Research*. **47** (9), pp 719 – 734.

Sefara, N. L., Conradie, D. and Turner, P. 2000. Progress in the use of near-infrared absorption spectroscopy as a tool for rapid determination of pulp yield in plantation eucalypts. *TAPPSA.* November:15 - 17.

Shaw, M. J., Clarke, C. R., Pallet, R. N. and Morris A. R. 1998. Differentiationg timber to optimize the pulping process. *Appita*. **51**:456 - 460.

Sherry, S. P. 1958. Report on a tour of Black Wattle areas in Australia. Wattle Research Institute, Pietermaritzburg, pp. 28 - 33.

Sherry, S. P. 1971. The Black Wattle (*Acacia mearnsii* de Wild). University of Natal, Press, Pietermaritzburg.

Smith, C. W. 2002. Growth and yield prediction. *In* Black wattle: The South African research experience. Ed. R.W.Dunlop and L.A. MacLennan. Institute for Commercial Forestry Research, Pietermaritzburg, pp. 93 - 99.

So, C., Via, B. K., Groom, L. H., Schimleck, L. R., Shupe, T. F., Kelley, S. S. and Rials, T. G. 2004. Near infrared spectroscopy in the forest products industry. *Forest*

Products Journal. **54** (3), pp 7 – 16.

Stubbings. J. A. and Schönau, A.P.G. 1972. Density and air-dry rate of the timber of black wattle (*Acacia mearnsii*). Wattle Research Institute, Pietermaritzburg, pp. 36 - 38.

Swamy, A. R., Mason, J. C., Lee, H., Meadows, F., Baars, M., Strekowski, L. and Patonay, G. 2000. Near infrared absorption/luminescence measurements. *Encyclopedia of Analytical Chemistry.* **12:**10526 - 10559

Tappi. 1988. Basic density and moisture content of pulpwood. *Tappi Test Methods.* **1**. 1 – 6p.

Taylor, F. W. 1973. Variations in the anatomical properties of South African grown *Eucalyptus grandis*. *Appita*. **27**:171-178.

Tibbits, W. and Hodge, G. 1998. Genetic parameters and breeding values for *Eucalyptus nitens* wood fiber production traits. *Forest Science*. **44**:587 - 598.

Turnbull, J. M. 1937. Variations in strength of pine timbers. *South African Journal of Science*. **33**: 653-682.

Turner, C. H., Balodis, V. and Dean, G. H. 1983. Variability in pulping quality of E. globules from Tasmanian provenances. *Appita*. **36(5)**: 371 – 376.

Turner, P. 2001. Strategic and tactical options for managing the quality and value of eucalypt plantation resources. Presented at IUFRO Conference “Desarrollando el Eucalipto del futuro/Developing the Eucalypt of the future”. Valdivia, Chile. 10-15 September 2001.

Unkalkar, V. G., Kulkarni, A. G., Tripathi, R. S. and Jauhari, M. B. 1975. In-tree variation of wood and kraft pulp quality of *Eucalyptus* hybrids. *IPPTA*. **XII**:38 - 46.

van Buijtenen, J. P. 1982. Fibre for the future. *Tappi*. **65**(8): 10 – 12.

van Wyk, W. J., and Gerischer, G. F. R. 1999. The pulping properties of *Acacia, Eucalyptus* and *Pinus* species grown in KwaZulu-Natal. Unpublished.

Wallbäcks, L., Edlund, U., Norden, B. and Berglund, I. 1991. Multivariate characterization of pulp using solid-state 13C NMR, FTIR, and NIR. *Tappi*. **74:** 201 – 206.

Webster, N. and McKechnie, J. L. 1980. Websters new twentieth century dictionary of the English language unabridged. William Collins, 2129 pp.

Wessman, C. A., Aber, J. D., Peterson, D. L. and Melillo, J. M. 1988. Foliar analysis using near infrared reflectance spectroscopy. *Canadian Journal of Forest Research*. **18**:6 - 11.

Wetzel, D. L. 1983. Near-infrared reflectance analysis: Sleeper among spectroscopic techniques. *Analytical Chemistry*. **55**:1165A - 1176A.

Workman, Jr, J. J. 2001. NIR spectroscopy calibration basics. *In* Handbook of near-infrared analysis. Eds. D.A. Burns and E. W. Ciurczak. Marcel Dekker, Inc., New York, pp. 91 - 128.

Workman, J. 2009. Process and field applications using portable instruments. http://www.industrymatter.com/processandfieldapplicationsusingportableinstruments.aspx, accessed 21 January 2009.

WRI. 1951. Bark analysis. Wattle Research Institute Report, Pietermaritzburg, p. 25.

WRI. 1952. Vegetative propagation. Wattle Research Institute Report, Pietermaritzburg, p. 23.

WRI. 1957. Vegetative propagation. Wattle Research Institute Report, Pietermaritzburg, p. 18.

WRI. 1980. Analytical services. Wattle Research Institute Report, Pietermaritzburg, pp. 13 – 14.

Wright, J. A. 1987. Results of micropulping wood samples of seven pine hybrid families in Zululand. *In*: Proceedings of the Southern Forest Tree Improvement Conference. 1987. p. 399 – 406.

Wright, J. A., Birkett, M. D. and Gambino, M. J. T. 1990. Prediction of pulp yield and cellulose content from wood samples using near infrared reflectance spectroscopy. *TAPPI Journal*. **73**:164 - 166.

Zboňák, A. 2002. A comparison of methods to measure wood density. Paper presented at TAPPSA conference – "Adding Value in Global Industry", Durban, South Africa, 8-11 October 2002.

Zobel, B. J. and Talbert, J. T. 1984. Applied Forest Tree Improvement. John Wiley & Sons, Inc, USA. 505p.

Zobel, B. J. and van Buijtenen, J. P. 1989. Wood Variation Its Causes and Control. Springer–Verlag, Berlin. 337p.

Zobel, B. J. and Jett, J. B. 1995. Genetics of wood production. Springer –Verlag, New York. 337p.

Index of Appendices

Appendix 1 Detailed soils information for the nine sampling areas.

Plantation	Age	Soil depth(cm)	Silt %	Clay %	Sand %	Description	Soil form	ph (KCL)	Ca (meq/100g)	Mg (meq/100g)	K (meq/100g)	Na (meq/100g)	Sum of cations	Organic Carbon (WB)	Ex.acid meq/100g	P ppm
Bloemendal	7	0-20	34	63	3	C	Hutton/Inanda	3.68	0.25	0.16	0.07	0.09	0.57	5.19	5.02	2.82
		20-50	29	66	5	C		3.97	1.17	0.95	0.05	0.07	2.24	3.15	2.19	0.74
		50-80	23	75	2	C		4.29	0.66	1.15	0.04	0.08	1.93	1.85	0.66	0.43
		80-120	21	75	4	C		4.49	0.37	1.56	0.03	0.10	2.07	1.37	0.21	0.32
	9	0-20	31	62	8	C	Inanda	3.81	0.42	0.30	0.11	0.06	0.88	4.69	3.15	2.29
		20-50	25	69	6	C		4.19	1.22	1.16	0.07	0.09	2.52	2.84	3.36	0.21
		50-80	23	73	4	C		4.49	0.64	1.45	0.04	0.10	2.22	1.73	0.50	0.37
		80-120	26	67	7	C		4.55	0.24	1.60	0.04	0.10	1.97	1.08	0.63	0.58
	11	0-20	33	62	5	C	Magwa/Shale	3.74	0.27	0.23	0.11	0.10	0.72	4.50	4.57	1.48
		20-50	26	66	7	C		3.96	0.52	0.60	0.07	0.09	1.27	3.05	2.62	0.42
		50-80	29	61	10	C		4.07	0.32	0.84	0.06	0.10	1.31	2.21	2.12	0.53
Glen Echo	7	0-20	18	10	71	SL	Clovelly	3.99	0.63	0.57	0.08	0.05	1.32	0.60	0.63	0.45
		20-50	19	9	72	SL		4.11	0.36	0.72	0.04	0.08	1.19	0.38	0.35	0.30
		50-80	21	8	72	SL		4.39	0.17	0.49	0.03	0.08	0.76	0.16	0.15	0.20
		80-120	15	12	73	SL		4.38	0.36	0.91	0.08	0.20	1.55	0.22	0.15	0.10
	9	0-20	12	11	77	SL	Inanda	3.98	0.09	0.07	0.04	0.03	0.23	0.86	1.43	2.07
		20-50	13	13	74	SL		4.12	0.12	0.09	0.04	0.05	0.28	0.72	1.64	1.67
		50-80	11	13	76	SL		4.02	0.13	0.19	0.02	0.03	0.37	0.36	1.36	1.12
		80-120	13	20	67	SCL		4.03	0.15	0.28	0.02	0.03	0.48	0.45	1.52	2.54
	11	0-20	11	7	82	LS	Oakleaf/Tukulu	4.13	1.00	0.35	0.04	0.03	1.43	0.61	0.43	0.96
		20-50	15	8	76	LS		3.94	0.68	0.27	0.04	0.03	1.02	0.54	0.85	0.91
		50-80	16	8	76	LS		4.16	0.73	0.27	0.03	0.03	1.06	0.36	0.98	0.91
		80-120	13	6	80	LS		4.28	0.65	0.40	0.03	0.03	1.10	0.34	0.20	0.65
Phoenix	7	0-20	23	34	43	CL	Kranskop	4.00	0.09	0.09	0.08	0.09	0.34	5.50	2.26	1.93
		20-50	20	40	40	C		4.13	0.07	0.10	0.05	0.06	0.27	4.06	1.95	0.31
		50-80	19	43	37	C		4.31	0.09	0.20	0.03	0.05	0.36	2.76	1.04	0.10
		80-120	15	49	36	C		4.67	0.06	1.03	0.03	0.07	1.19	1.04	0.52	0.16
	9	0-20	21	34	45	CL	Kranskop/Magwa	4.05	0.81	0.40	0.07	0.06	1.35	4.87	2.65	0.32
		20-50	21	36	43	CL		4.11	0.60	0.61	0.05	0.09	1.34	4.86	2.42	0.27
		50-80	17	35	48	SC		4.21	0.30	0.70	0.03	0.09	1.11	2.61	1.75	0.37
		80-120	20	54	26	C		4.06	0.48	1.50	0.03	0.12	2.12	1.57	2.17	0.96
	11	0-20	36	38	26	CL	Kranskop/Magwa	4.10	0.61	0.41	0.11	0.07	1.20	7.03	2.68	0.11
		20-50	26	38	36	CL		4.09	0.30	0.52	0.06	0.09	0.96	5.10	2.66	0.10
		50-80	22	35	44	CL		4.18	0.16	0.58	0.04	0.08	0.85	4.14	1.85	0.67
		80-120	22	31	47	SCL		4.26	0.13	0.72	0.03	0.07	0.95	1.56	1.39	0.10

Appendix 2a The laboratory kraft pulp yield analysis procedure.

Step 1 The pulping cycle used:

- Ambient to170 ^{0}C = 90 minutes
- Permeating at 170 ^{0}C = depends on the cooking time to achieve a desired kappa no.
- Blow-down = 20 minutes

Degassing carried out at 120 and 140^{0}C to remove gases not condensable in water

Step 2 Chip screening

The chips were screened to remove knots and bark, and any over and under-sized chips. They were then allowed to air-dry on custom built chip drying racks. The drying period was approximately three weeks which proved to be sufficient for the chips to reach equilibrium moisture with the atmosphere.

Step 3 Chip moisture content evaluation

Once the chips have been screened, determine the moisture content of the chips by drying a representative sample of the wet chips to a constant mass at 105 ± 3 ºC. This usually takes between 24 and 48 hours. The moisture content is calculated as follows:

$$Moisture\ content\ (\%) = \frac{Mass\ of\ wet\ chips - Mass\ of\ OD\ chips}{Mass\ of\ OD\ chips} \times 100\%$$

Step 4 Mass of chips needed

Take a representative sample of the chips and weigh out a mass equivalent to 800 g of oven-dried chips. Use the following equation to determine the mass of chips to weigh out based on its moisture content:

$$Mass\ of\ Chips\ to\ be\ weighed\ out(g) = \frac{800 \times 100}{(100 - moisture\ content\ )}$$

Step 5 Amount of cooking liquor needed

The amount of cooking liquor to measure out depends on the %AA charge. For an 18% AA charge, the volume of liquor needed for the cook is calculated as follows:

$$A.A\,/\,O.D\ wood\ = \frac{18\,\% \times\ 800g}{100\,\%} = 144\ \ g$$

Therefore the volume of liquor is:

$$Volume\ of\ liquor\ (ml) = \frac{144\,(g)\ \times 1000\,(ml\,/\,L)}{Active\ alkalinity\,(g\,/\,L)}$$

The value for the active alkalinity (AA) is obtained from the standardisation of the cooking liquor. (Appendix 2b)

Step 6 Total volume of liquor

The next step is to calculate the total volume of liquid to be used. This value depends on the liquid to solid ratio. Therefore for a 4.5:1 (liquid: solid), the total liquid volume will be 4.5 x 800 =3600mL. From this, the amount of water to add to the digester is calculated as follows:

$$Vol.\,of\ water = Total\ liquid\ vol. - vol.\,of\ liquor - moisture\ in\ wood$$

Step 7 Loading the digester

Place the wood chips into the digester, fit on the metal sieve and add the appropriate amounts of water and cooking liquor.

After the cook and blow-down to atmospheric pressure has been completed, carefully remove the hot pulp from the digester and thoroughly wash the pulp through the 10mesh and 200mesh screens to separate the fibres from the rejects. The pulp remaining on the 10mesh screen is considered as rejects. Dry the rejects in an oven set at 105 ± 3 ^{0}C and determine the mass of the rejects.

Place the washed pulped into a clean cotton bag with a draw- string. Dewater the pulp by placing in into a spin drier for 10 minutes.

Thereafter transfer the pulp into a strong plastic bag and determine the mass of the wet pulp. Take a representative sample of the pulp and determine the moisture content.

Step 8 Calculating yields

Calculate the moisture content, the screened pulp yield, percent rejects and total yield as follows:

$$Moisture\,(\%) = \frac{Mass\ of\ wet\ pulp - Mass\ of\ dry\ pulp}{Mass\ of\ wet\ pulp} \times 100\%$$

$$Pulp\,(\%) = 100 - \%\ Moisture$$

$$Screened\ Pulp\ Yield\,(\%) = \frac{\%\ Pulp \times Mass\ of\ wet\ pulp}{OD\,mass\ of\ chips}$$

$$\mathrm{Re}\ jects\,(\%) = \frac{OD\ mass\ of\ rejects}{OD\ mass\ of\ chips} \times 100\%$$

$$Total\ Yield\,(\%) = \%\,Screened\ pulp\ yield + \%\,\mathrm{Re}\ jects$$

Appendix 2b Preparation and Standardisation of Kraft cooking liquor.

This method describes the procedure for the preparation and standardisation of Kraft cooking liquor. The concentration and properties of the cooking liquor are expressed in terms of active alkalinity (AA), total alkalinity (TA) and sulphidity.

A. PREPARATION OF COOKING LIQUOR

Sulphidity = 22%
Total Alkalinity = 170 g/L (as Na_2O)

1. REAGENTS

1.1 Sodium hydroxide (NaOH) – commercial grade

1.2 Sodium Sulphide (Na_2S) – commercial grade

2. ANALYTICAL PROCEDURE

2.1 Dissolve 3600 g NaOH in cold water.

2.2 Dissolve 2114 g Na_2S in hot water and allow impurities to settle overnight or preferably for a few days.

2.3 Decant the clear sodium sulphide solution into the sodium hydroxide solution and mix both solutions thoroughly. Make up the mixture to 20 L with water.

B. STANDARDISATION OF COOKING LIQUOR

1. APPARATUS

1.1 Burette – 50mL
1.2 Pipette – 10mL
1.3 Erlenmeyer flask – 250mL
1.4 Measuring cylinder – 50 and 100mL

2. REAGENTS

Sodium Hydroxide (1.0N)

Dissolve 40.0 (±0.01) g of NaOH in 500mL of deionised water. Allow the solution to cool and then transfer to a 1000mL volumetric flask. Make up to the mark with deionised water.

2.2 Hydrochloric acid (1.0N)

Add 100.0 (±0.1) mL of concentrated HCl (32%) to 500mL of deionised water in a 1000mL volumetric flask. Mix the solution well and make up to the mark with deionised water. This solution should be standardised using the 1.0N sodium hydroxide solution prepared above, as follows:
Pipette 25.0 (± 0.1) mL of the 1.0 N NaOH solution. Add a few drops of phenolphthalein indicator and titrate to the end point with the 1.0N HCl solution. Calculate the exact concentration of the HCl as follows:

$$[HCl] = \frac{V_{NaOH} \times [NaOH]}{V_{HCl}}$$

2.3 Barium Chloride (10%)

Dissolve 100g of $BaCl_2.2H_2O$ in 500mL of deionised water contained in a 1000mL volumetric flask. Make up to the mark with deionised water.

2.4 Phenolphthalein Indicator

Add 50mL of ethanol to 50mL of water (1:1). Mix the solution thoroughly. Dissolve 0.05 g of phenolphthalein in this solution.

2.5 Methyl Orange

Dissolve 0.01 g of methyl orange in 100mL of water.

3. ANALYTICAL PROCEDURE

3.1 Total Alkalinity

Pipette 10.0 (± 0.1) mL of the well agitated cooking liquor (prepared above), into a 250mL Erlenmeyer flask. Add 100mL of deionised water and a few drops of phenolphthalein indicator. Titrate the solution with 1.0 N hydrochloric acid solution until colourless (Reading A). Without discarding the solution add a few drops of methyl orange and titrate further until red (Reading B).

Calculate the total alkalinity (as Na_2O, g/L) as follows:

$$Total\ Alkalinity = \mathrm{Re}ading\ B \times 3.1$$

3.2 Active Alkalinity

Pipette 10.0 (± 0.1) mL of the well agitated cooking liquor (prepared above), into a 250 mL Erlenmeyer flask. Add 100mL of deionised water and 50mL of a 10% $BaCl_2$ solution. Mix well and add a few drops of phenolphthalein indicator and titrate with 1.0N hydrochloric acid until colourless (Reading C). Do not discard the solution.

Calculate the active alkalinity (as Na_2O, g/L) as follows:

$$Active\ Alkalinity = \left(B - \left[(A - C) \times 2\right]\right) \times 3.1$$

3.3 Sulphidity

Without discarding the above solution, add to it a few drops of formaldehyde, and titrate to the end point (Reading D).

Calculate the sulphidity (as Na_2O, g/L) as follows:

$$Sulphidity = (D - C) \times 6.2$$

3.4 % Sulphidity

$$\%\ Sulphidity = \frac{Sulphidity}{Total\ Alkalinity} \times 100\%$$

Appendix 3a Raw data manipulation to calculate whole tree weighted mean pulp yield for the 10 trees sampled at 10 heights.

SUMMARY OUTPUT

Tree_No.	**Average**
Total_Ht	18.62
Dbhob	14.23
Dbhub	13.26
2% hgt	0.28
10% hgt	1.40
15% hgt	2.10
20% hgt	2.81
30% hgt	4.21
40% hgt	5.61
50% hgt	7.02
60% hgt	8.42
70% hgt	9.82
80% hgt	11.22
UT_Ht	14.03
2% hgt d	14.21
10% hgt d	12.65
15% hgt d	12.17
20% hgt d	11.76
30% hgt d	11.21
40% hgt d	10.61
50% hgt d	10.04
60% hgt d	9.18
70% hgt d	8.46
80% hgt d	7.45
UT hgt d	5.00

Regression Statistics	
Multiple R	0.988558239
R Square	0.977247391
Adjusted R Square	0.974719324
Standard Error	0.703459881
Observations	11

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	191.290983	191.290983	386.559	1.05561E-08
Residual	9	4.453702233	0.494855804		
Total	10	195.7446852			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	23.24191673	0.898090742	25.8792521	9.26E-10	21.21029278	25.2735407	21.21029278	25.27354068
X Variable 1	-1.674096009	0.085147607	-19.66110468	1.06E-08	-1.866713424	-1.48147859	-1.866713424	-1.481478594

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
1	-0.546987555	0.827987555	1.240689825
2	2.064602219	-0.661602219	-0.991371351
3	2.868168303	-0.763668303	-1.144311273
4	3.554547667	-0.748547667	-1.121653904
5	4.475300472	-0.266300472	-0.399035328
6	5.479758077	0.132241923	0.198156612
7	6.433992802	0.581007198	0.870604533
8	7.873715369	0.544284631	0.815577962
9	9.079064496	0.741935504	1.111745974
10	10.76990146	0.454098535	0.680439493
11	14.87143669	-0.841436686	-1.260842544

PROBABILITY OUTPUT

Percentile	*Y*
4.545454545	0.281
13.63636364	1.403
22.72727273	2.1045
31.81818182	2.806
40.90909091	4.209
50	5.612
59.09090909	7.015
68.18181818	8.418
77.27272727	9.821
86.36363636	11.224
95.45454545	14.03

Appendix 3a cont. Raw data manipulation to calculate whole tree weighted mean pulp yield for the 10 trees sampled at 10 heights.

		Section Volume (m^3)	**Section Volume x SPY**
4% hgt	0.562	0.016	0.879
12.5% hgt	1.754	0.043	2.336
17.5% hgt	2.455	0.021	1.179
25% hgt	3.508	0.028	1.515
35%hgt	4.911	0.029	1.577
45% hgt	6.314	0.021	1.143
55% hgt	7.717	0.015	0.786
65% hgt	9.120	0.009	0.496
75%hgt	10.523	0.005	0.277
UT_HT	14.030	0.008	0.412
GLDUB	15.650		
4% hgt d	22.301		
12.5% hgt d	20.306		
17.5% hgt d	19.132		
25% hgt d	17.370		
35% hgt d	15.021		
45% hgt d	12.673		
55% hgt d	10.324		
65% hgt d	7.975		
75% hgt d	5.626		
UT_HT d	5.000		
Total Vol	0.195		
Total Section Vol.SPY	10.598		
WMTSPY	54.487		

Appendix 3a cont. Raw data manipulation to calculate whole tree weighted mean pulp yield for the 10 trees sampled at 10 heights.

Tree	Disc	Disc diam	Height %	Height (m)	Proportional diam	Position	SPY	Disc Area	Pos. Area	Pos.Area.SPY	Disc.Area.SPY	WMDSPY
All	A	14.21	2	0.28	14.21	1	56.05	158.59	57.09	3199.76		
All	A	14.21	2	0.28	11.37	2	55.14		44.41	2448.47		
All	A	14.21	2	0.28	8.53	3	53.73		31.72	1704.25		
All	A	14.21	2	0.28	5.68	4	51.67		19.03	983.35		
All	A	14.21	2	0.28	2.84	5	54.29		6.34	344.40	8680.24	54.73
All	B	12.65	10	1.40	12.65	6	56.03	125.68	45.25	2535.14		
All	B	12.65	10	1.40	10.12	7	55.69		35.19	1959.85		
All	B	12.65	10	1.40	7.59	8	54.46		25.14	1369.04		
All	B	12.65	10	1.40	5.06	9	52.09		15.08	785.54		
All	B	12.65	10	1.40	2.53	10	50.81		5.03	255.45	6905.02	54.94
All	C	12.17	15	2.10	12.17	11	55.63	116.32	41.88	2329.56		
All	C	12.17	15	2.10	9.74	12	55.63		32.57	1811.85		
All	C	12.17	15	2.10	7.30	13	54.43		23.26	1266.28		
All	C	12.17	15	2.10	4.87	14	53.13		13.96	741.65		
All	C	12.17	15	2.10	2.43	15	53.67		4.65	249.74	6399.09	55.01
All	D	11.76	20	2.81	11.76	16	55.96	108.62	47.52	2659.35		
All	D	11.76	20	2.81	8.82	17	55.35		33.94	1878.73		
All	D	11.76	20	2.81	5.88	18	54.01		20.37	1100.00		
All	D	11.76	20	2.81	2.94	19	49.33		6.79	334.85	5972.93	54.99
All	E	11.21	30	4.21	11.21	20	55.29	98.70	43.18	2387.53		
All	E	11.21	30	4.21	8.41	21	54.50		30.84	1680.83		
All	E	11.21	30	4.21	5.61	22	53.35		18.51	987.31		
All	E	11.21	30	4.21	2.80	23	51.85		6.17	319.83	5375.50	54.47
All	F	10.61	40	5.61	10.61	24	55.62	88.41	38.68	2151.44		
All	F	10.61	40	5.61	7.96	25	54.21		27.63	1497.73		
All	F	10.61	40	5.61	5.31	26	51.23		16.58	849.29		
All	F	10.61	40	5.61	2.65	27	49.60		5.53	274.09	4772.56	53.98
All	G	10.04	50	7.02	10.04	28	54.65	79.17	44.68	2441.80		
All	G	10.04	50	7.02	6.63	29	53.44		25.86	1382.23		
All	G	10.04	50	7.02	3.31	30	50.05		8.62	431.49	4255.53	53.75
All	H	9.18	60	8.42	9.18	31	54.44	66.19	37.36	2033.82		
All	H	9.18	60	8.42	6.06	32	52.77		21.62	1141.02		
All	H	9.18	60	8.42	3.03	33	50.12		7.21	361.23	3536.08	53.43
All	I	8.46	70	9.82	8.46	34	54.35	56.21	42.16	2291.18		
All	I	8.46	70	9.82	4.23	35	51.86		14.05	728.74	3019.92	53.72
All	J	7.45	80	11.22	7.45	36	53.55	43.59	32.69	1750.62		
All	J	7.45	80	11.22	3.73	37	50.93		10.90	555.08	2305.70	52.89

Appendix 3b Raw data manipulation to calculate whole tree weighted mean pulp yield for the 30 trees sampled at 4 heights.

SUMMARY OUTPUT

Tree_No.	**Average**
Total_Ht	18.93
Dbhob	14.49
Dbhub	13.50
2% hgt	0.29
10% hgt	1.43
15% hgt	2.14
20% hgt	2.85
30% hgt	4.28
40% hgt	5.70
50% hgt	7.13
60% hgt	8.55
70% hgt	9.98
80% hgt	11.41
UT_Ht	14.26
2% hgt d	14.42
10% hgt d	12.88
15% hgt d	12.30
20% hgt d	12.01
30% hgt d	11.33
40% hgt d	10.64
50% hgt d	9.99
60% hgt d	9.31
70% hgt d	8.53
80% hgt d	7.49
UT hgt d	5.00

Regression Statistics	
Multiple R	0.989759214
R Square	0.979623302
Adjusted R Square	0.977359224
Standard Error	0.40327548
Observations	11

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	70.36738867	70.36738867	432.681	6.41999E-09
Residual	9	1.463680013	0.162631113		
Total	10	71.83106869			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	14.00010147	0.213391786	65.60749938	2.24E-13	13.51737534	14.48282759	13.51737534	14.48282759
X Variable 1	-0.59002928	0.028365449	-20.800985	6.42E-09	-0.654196432	-0.525862127	-0.654196432	-0.525862127

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
1	13.83194312	0.584723543	1.528366497
2	13.15891639	-0.282249725	-0.737752103
3	12.73832385	-0.441657187	-1.154415716
4	12.31773132	-0.307731315	-0.804356585
5	11.47654624	-0.149879572	-0.391759352
6	10.63536116	0.001305505	0.003412365
7	9.794176085	0.192490582	0.503137182
8	8.952991008	0.353675658	0.924447174
9	8.111805932	0.414860735	1.084374412
10	7.270620855	0.222712478	0.582132008
11	5.588250702	-0.588250702	-1.537585882

PROBABILITY OUTPUT

Percentile	*Y*
4.545454545	5
13.63636364	7.493333333
22.72727273	8.526666667
31.81818182	9.306666667
40.90909091	9.986666667
50	10.63666667
59.09090909	11.32666667
68.18181818	12.01
77.27272727	12.29666667
86.36363636	12.87666667
95.45454545	14.41666667

Appendix 3b cont. Raw data manipulation to calculate whole tree weighted mean pulp yield for the 30 trees sampled at 4 heights.

		Section Volume (m^3)	**Section Volume x SPY**
4% hgt	0.570	0.009	0.515
35% hgt	4.990	0.053	2.914
65% hgt	9.267	0.032	1.730
UT_HT	14.257	0.018	0.916
GLDUB	15.363		
4% hgt d	13.664		
35% hgt d	11.056		
65% hgt d	8.532		
UT_HT d	5.000		
Total Vol	0.113		
Section Vo	6.075		
WMTSPY	53.559		

Appendix 3b cont. Raw data manipulation to calculate whole tree weighted mean pulp yield for the 30 trees sampled at 4 heights.

Disc	Disc diam	Height %	Height (m)	Proportional diam	Position	SPY	Disc Area	Pos. Area	Pos.Area.SPY	Disc.Area.SPY	WMDSPY
A	14.42	2.0	0.3	14.42	1	55.73	163.24	71.42	3979.87		
A	14.42	2.0	0.3	10.81	2	54.44		51.01	2777.25		
A	14.42	2.0	0.3	7.21	3	53.16		30.61	1627.09		
A	14.42	2.0	0.3	3.60	4	51.22		10.20	522.61	8906.81	54.56
D	12.01	20.0	2.9	12.01	5	55.28	113.29	63.94	3534.22		
D	12.01	20.0	2.9	7.93	6	54.59		37.01	2020.44		
D	12.01	20.0	2.9	3.96	7	52.43		12.34	646.86	6201.51	54.74
G	9.99	50.0	7.1	9.99	8	54.34	78.33	44.21	2402.17		
G	9.99	50.0	7.1	6.59	9	53.01		25.59	1356.54		
G	9.99	50.0	7.1	3.30	10	49.54		8.53	422.56	4181.27	53.38
J	7.49	80.0	11.4	7.49	11	53.79	44.10	33.08	1779.19		
J	7.49	80.0	11.4	3.75	12	51.53		11.03	568.10	2201.75	49.93

Appendix 4 Raw data collected prior to felling.

Plantation	Compartment	Age	Tree Number	Disease Score	Stem Form	Neighbours	Total_Ht (m)	UT_Ht (m)	Dbhob (cm)	Dbhub (cm)	Gldub (cm)
Bloemendal	12a	7	1	0	3	5	15.9	11.8	9.5	9.0	12.5
Bloemendal	12a	7	2	0	3	4	16.9	13.5	11.8	10.9	12.3
Bloemendal	12a	7	3	0	3	4	18.5	15.3	15.4	14.5	16.8
Bloemendal	12a	7	4	0	3	4	18.1	14.3	14.0	13.5	15.8
Bloemendal	12a	7	5	0	2	6	18.4	13.7	13.8	12.9	15.9
Bloemendal	12a	7	6	0	2	3	17.8	14.2	14.9	13.9	17.4
Bloemendal	12a	7	7	0	2	4	16.3	11.9	10.5	9.8	12.9
Bloemendal	12a	7	8	0	3	5	18.9	15.2	13.3	12.5	13.9
Bloemendal	12a	7	9	0	3	5	15.0	10.9	10.7	9.7	12.1
Bloemendal	12a	7	10	0	3	6	16.2	12.1	11.4	10.8	12.7
Bloemendal	11c	9	1	0	3	5	17.8	14.6	12.4	11.7	14.2
Bloemendal	11c	9	2	0	4	3	19.6	15.9	14.6	13.8	17
Bloemendal	11c	9	3	0	4	4	17.2	13.8	12.9	12.1	14.5
Bloemendal	11c	9	4	1	3	6	17.9	13.8	12.9	12.2	14.6
Bloemendal	11c	9	5	0	3	4	17.2	12.5	9.8	9.2	10.9
Bloemendal	11c	9	6	0	2	5	18.4	13.7	16.6	15.6	17.5
Bloemendal	11c	9	7	0	4	4	17.6	14.1	13.1	12.2	14.7
Bloemendal	11c	9	8	0	4	4	19.5	15.6	14.5	13.3	16.4
Bloemendal	11c	9	9	0	3	6	17.0	13.9	9.9	9.3	11.4
Bloemendal	11c	9	10	0	2	5	18.4	14.9	15.0	14.0	16.5
Bloemendal	13	11	1	0	3	5	17.6	13.4	11.7	11.0	13.2
Bloemendal	13	11	2	0	2	5	20.9	15.8	13.0	12.3	16
Bloemendal	13	11	3	1	4	4	21.2	17.2	18.7	17.4	21.3
Bloemendal	13	11	4	0	4	4	19.4	15.0	16.7	15.4	17.4
Bloemendal	13	11	5	0	3	5	20.2	16.3	17.3	16.0	18.8
Bloemendal	13	11	6	0	2	5	18.0	13.6	16.3	15.2	18.9
Bloemendal	13	11	7	0	4	5	17.2	12.0	10.0	9.3	10.8
Bloemendal	13	11	8	0	2	6	19.5	14.4	14.3	13.0	15.2
Bloemendal	13	11	9	0	3	3	19.2	14.5	16.2	15.2	21.8
Bloemendal	13	11	10	0	3	6	15.5	10.5	10.1	9.4	11.8

Plantation	Compartment	Age	Tree Number	Disease Score	Stem Form	Neighbours	Total_Ht (m)	UT_Ht (m)	Dbhob (cm)	Dbhub (cm)	Gldub (cm)
Glen Echo	W010	7	1	0	3	3	17.2	12.1	13.2	12.3	15.3
Glen Echo	W010	7	2	0	3	4	16.8	11.4	13.7	12.9	16.3
Glen Echo	W010	7	3	0	2	2	17.3	12.4	15.2	14.2	17.1
Glen Echo	W010	7	4	0	2	3	15.7	11.2	12.2	11.5	13.7
Glen Echo	W010	7	5	0	3	3	19.6	14.4	16.7	15.8	19.8
Glen Echo	W010	7	6	1	4	2	19.1	15	15.8	15	18.3
Glen Echo	W010	7	7	0	3	2	19.9	16.4	21.5	20.4	24.8
Glen Echo	W010	7	8	0	3	4	14.6	8.7	9.9	9.4	10.9
Glen Echo	W010	7	9	0	4	3	17.6	13.4	12.6	11.9	14.6
Glen Echo	W010	7	10	0	4	3	18.1	14.3	11.8	11	12.5
Glen Echo	2a	9	1	0	2	2	15.1	10.5	10.8	10.3	12
Glen Echo	2a	9	2	0	4	2	20.4	17	13.8	12.9	14.5
Glen Echo	2a	9	3	0	3	5	19.1	14.7	17.5	16.6	19.3
Glen Echo	2a	9	4	1	2	4	19.3	15.2	20.3	18.5	25.8
Glen Echo	2a	9	5	1	3	4	20.2	15.8	16	15.2	17.8
Glen Echo	2a	9	6	0	4	5	15.7	11.2	11.9	11	12.5
Glen Echo	2a	9	7	0	3	4	17.7	12.8	15.2	13.8	17.7
Glen Echo	2a	9	8	0	4	4	14.8	10.7	10.9	10.2	11.4
Glen Echo	2a	9	9	0	4	3	18.5	13.8	12.8	12.2	13.2
Glen Echo	2a	9	10	0	4	7	17.5	13.3	10.9	10.3	11.6
Glen Echo	W007	11	1	0	3	5	19.1	13.3	12	11.3	13
Glen Echo	W007	11	2	0	3	4	21	16.2	22	20.6	25
Glen Echo	W007	11	3	0	2	4	22.1	17.7	20.8	19.4	24.2
Glen Echo	W007	11	4	0	4	3	20.1	17.2	19.1	17.7	22.8
Glen Echo	W007	11	5	0	2	1	21.7	16.5	23	22.1	26.2
Glen Echo	W007	11	6	0	4	3	23.5	19.2	24.6	23.7	28.5
Glen Echo	W007	11	7	0	2	4	16.8	12	14.4	13.3	15.4
Glen Echo	W007	11	8	1	4	5	22.7	19.4	22.7	21.6	27.7
Glen Echo	W007	11	9	1	2	4	17	11.1	12.3	11.5	14
Glen Echo	W007	11	10	0	2	3	18.3	14.8	16.8	16.1	18.8

Appendix 4 cont. Raw data collected prior to felling.

Plantation	Compartment	Age	Tree Number	Disease Score	Stem Form	Neighbours	Total_Ht (m)	UT_Ht (m)	Dbhob (cm)	Dbhub (cm)	Gldub (cm)
Phoenix	W83	7	1	0	3	5	21.9	18.6	20.9	20	23.5
Phoenix	W83	7	2	0	4	6	19.6	15.8	12.7	11.8	13.5
Phoenix	W83	7	3	0	2	5	19.2	15.6	12.5	11.8	14.8
Phoenix	W83	7	4	0	3	4	21.7	17.1	16.5	15.7	19.5
Phoenix	W83	7	5	0	4	5	20.7	16.7	13.6	12.8	15.8
Phoenix	W83	7	6	0	2	4	18.6	13.5	12.8	11.8	15
Phoenix	W83	7	7	0	2	5	21.9	18.5	15.6	14.7	17.3
Phoenix	W83	7	8	0	4	6	19.8	16.2	15.3	14.3	17.7
Phoenix	W83	7	9	0	2	7	19	14.8	14.5	13.6	17
Phoenix	W83	7	10	0	2	5	19.3	16	13.8	12.8	15.3
Phoenix	W92	9	1	0	3	4	21.6	18.3	23.4	22	27.5
Phoenix	W92	9	2	0	3	6	22.3	18.8	19.2	17.6	21.7
Phoenix	W92	9	3	0	4	5	20.3	15.7	12.9	12	13.2
Phoenix	W92	9	4	0	2	7	22.3	18.2	14.7	13.9	16.9
Phoenix	W92	9	5	0	1	4	14.1	8.9	10.7	10	12.2
Phoenix	W92	9	6	0	3	4	20.4	16.1	12.9	12	13.8
Phoenix	W92	9	7	0	4	3	22.7	19	18.2	17.2	20.8
Phoenix	W92	9	8	0	3	6	22.9	18.7	18.2	17.3	21.5
Phoenix	W92	9	9	0	3	6	22.7	18.5	15.6	14.7	17.5
Phoenix	W92	9	10	0	4	5	20	15.2	14.6	13.3	15.5
Phoenix	W93	11	1	0	2	7	22.9	18.8	20.9	19.1	24.6
Phoenix	W93	11	2	0	3	8	19.4	14.3	13.8	12.9	15.5
Phoenix	W93	11	3	0	3	6	18.5	13.3	12.3	11.4	14
Phoenix	W93	11	4	0	3	7	22.9	19	15.8	14.6	18.6
Phoenix	W93	11	5	0	4	6	24	19.5	16.2	15.3	17.3
Phoenix	W93	11	6	0	3	6	23	19.4	17.3	16.3	21.1
Phoenix	W93	11	7	0	3	6	22.5	18.7	18	16.7	20
Phoenix	W93	11	8	0	4	6	20	15.9	15.1	14.2	15.9
Phoenix	W93	11	9	0	3	6	19.3	13.8	12.5	11.7	15
Phoenix	W93	11	10	0	3	6	22	17.9	15.1	14.1	17.4

Appendix 5 Data derived from the infield measurements and laboratory analyses.

Plantation	Compartment	Age	Tree_No.	Bark Weight (g)	Bark_Thickness (mm)	Basic density (kgm^{-3})	Screened Pulp yield (%)	Volume (m^3)
Bloemendal	12a	7	1	12.3	3.4	548	*	0.045
Bloemendal	12a	7	2	14.2	3.9	613	57.2	0.073
Bloemendal	12a	7	3	13.7	3.8	591	55.4	0.138
Bloemendal	12a	7	4	12.5	3.4	545	55.6	0.111
Bloemendal	12a	7	5	15.5	4.3	595	55.3	0.111
Bloemendal	12a	7	6	18.8	5.2	606	54.7	0.123
Bloemendal	12a	7	7	12.9	3.5	607	55.2	0.056
Bloemendal	12a	7	8	13.6	3.7	573	55.2	0.106
Bloemendal	12a	7	9	13.8	3.8	636	54.8	0.052
Bloemendal	12a	7	10	12.3	3.4	522	56.4	0.065
Bloemendal	11c	9	1	13.4	3.7	582	*	0.086
Bloemendal	11c	9	2	17.1	4.7	623	55.9	0.133
Bloemendal	11c	9	3	15.4	4.2	594	55.1	0.089
Bloemendal	11c	9	4	13.0	3.6	577	54.2	0.094
Bloemendal	11c	9	5	11.5	3.2	642	56.0	0.052
Bloemendal	11c	9	6	20.3	5.6	552	54.0	0.159
Bloemendal	11c	9	7	15.2	4.2	626	54.5	0.095
Bloemendal	11c	9	8	18.1	5.0	596	53.8	0.131
Bloemendal	11c	9	9	10.8	3.0	581	54.5	0.052
Bloemendal	11c	9	10	15.8	4.3	583	57.5	0.130
Bloemendal	13	11	1	15.3	4.2	642	56.8	0.076
Bloemendal	13	11	2	15.6	4.3	631	56.9	0.115
Bloemendal	13	11	3	26.7	7.3	596	56.5	0.238
Bloemendal	13	11	4	27.7	7.6	625	55.9	0.171
Bloemendal	13	11	5	20.1	5.5	665	52.9	0.193
Bloemendal	13	11	6	23.0	6.3	620	55.4	0.149
Bloemendal	13	11	7	13.3	3.7	649	55.2	0.054
Bloemendal	13	11	8	*	*	659	55.9	0.127
Bloemendal	13	11	9	21.0	5.8	636	55.4	0.159
Bloemendal	13	11	10	13.7	3.8	619	56.1	0.049

Plantation	Compartment	Age	Tree_No.	Bark Weight (g)	Bark_Thickness (mm)	Basic density (kgm^{-3})	Screened Pulp yield (%)	Volume (m^3)
Glen Echo	W010	7	1	17.7	4.9	582	55.1	0.093
Glen Echo	W010	7	2	15.0	4.1	568	59.9	0.097
Glen Echo	W010	7	3	16.3	4.5	621	56.0	0.124
Glen Echo	W010	7	4	14.6	4.0	545	52.6	0.071
Glen Echo	W010	7	5	16.1	4.4	573	55.4	0.173
Glen Echo	W010	7	6	14.1	3.9	543	57.2	0.151
Glen Echo	W010	7	7	19.4	5.3	608	54.6	0.289
Glen Echo	W010	7	8	11.6	3.2	517	54.7	0.043
Glen Echo	W010	7	9	16.1	4.4	546	58.4	0.088
Glen Echo	W010	7	10	16.2	4.4	645	58.0	0.080
Glen Echo	2a	9	1	9.7	2.7	464	54.0	0.054
Glen Echo	2a	9	2	12.4	3.4	593	57.5	0.125
Glen Echo	2a	9	3	21.6	5.9	566	57.8	0.184
Glen Echo	2a	9	4	25.0	6.9	532	53.3	0.249
Glen Echo	2a	9	5	17.9	4.9	552	56.3	0.166
Glen Echo	2a	9	6	18.3	5.0	611	55.2	0.068
Glen Echo	2a	9	7	20.4	5.6	634	53.3	0.127
Glen Echo	2a	9	8	13.0	3.6	514	55.9	0.053
Glen Echo	2a	9	9	14.4	3.9	562	54.2	0.096
Glen Echo	2a	9	10	10.6	2.9	505	56.8	0.066
Glen Echo	W007	11	1	11.9	3.3	541	55.3	0.088
Glen Echo	W007	11	2	21.9	6.0	571	55.1	0.323
Glen Echo	W007	11	3	22.5	6.2	680	56.0	0.309
Glen Echo	W007	11	4	18.5	5.1	514	57.9	0.232
Glen Echo	W007	11	5	23.6	6.5	575	56.4	0.367
Glen Echo	W007	11	6	21.6	5.9	592	56.2	0.462
Glen Echo	W007	11	7	18.0	5.0	554	56.3	0.107
Glen Echo	W007	11	8	22.8	6.3	595	59.0	0.378
Glen Echo	W007	11	9	15.9	4.4	532	58.4	0.080
Glen Echo	W007	11	10	20.4	5.6	569	56.5	0.161

Appendix 5 cont. Data derived from the infield measurements and laboratory analyses.

Plantation	Compartment	Age	Tree_No.	Bark Weight (g)	Bark_Thickness (mm)	Basic density (kgm^{-3})	Screened Pulp yield (%)	Volume (m^3)
Phoenix	W83	7	1	23.1	6.3	526	55.5	0.308
Phoenix	W83	7	2	16.7	4.6	542	56.2	0.102
Phoenix	W83	7	3	14.9	4.1	521	56.0	0.096
Phoenix	W83	7	4	15.4	4.2	545	58.1	0.192
Phoenix	W83	7	5	15.5	4.3	534	57.2	0.124
Phoenix	W83	7	6	18.0	4.9	593	*	0.097
Phoenix	W83	7	7	17.6	4.8	561	57.7	0.174
Phoenix	W83	7	8	16.6	4.6	537	58.3	0.148
Phoenix	W83	7	9	18.9	5.2	500	59.4	0.127
Phoenix	W83	7	10	17.9	4.9	508	54.5	0.117
Phoenix	W92	9	1	24.6	6.7	578	57.3	0.378
Phoenix	W92	9	2	22.6	6.2	557	58.3	0.267
Phoenix	W92	9	3	13.6	3.7	471	59.8	0.109
Phoenix	W92	9	4	14.7	4.0	562	57.7	0.158
Phoenix	W92	9	5	13.5	3.7	476	57.4	0.048
Phoenix	W92	9	6	13.2	3.6	498	57.6	0.110
Phoenix	W92	9	7	17.5	4.8	551	58.1	0.246
Phoenix	W92	9	8	16.7	4.6	510	58.7	0.248
Phoenix	W92	9	9	16.4	4.5	559	55.9	0.182
Phoenix	W92	9	10	16.9	4.6	576	57.9	0.137
Phoenix	W93	11	1	20.9	5.7	583	55.6	0.325
Phoenix	W93	11	2	17.6	4.8	559	57.4	0.118
Phoenix	W93	11	3	15.4	4.2	560	56.8	0.089
Phoenix	W93	11	4	17.7	4.9	557	56.7	0.188
Phoenix	W93	11	5	14.3	3.9	502	57.4	0.210
Phoenix	W93	11	6	16.7	4.6	638	56.8	0.226
Phoenix	W93	11	7	18.3	5.0	584	58.0	0.238
Phoenix	W93	11	8	17.6	4.8	556	57.6	0.146
Phoenix	W93	11	9	13.9	3.8	561	56.4	0.097
Phoenix	W93	11	10	14.5	4.0	595	57.4	0.164

Appendix 6 NIR predicted screened pulp yield for all of the samples analysed (missing values excluded).

Sample identifier	Predicted pulp yield %	Sample identifier	Predicted pulp yield %	Sample identifier	Predicted pulp yield %	Sample identifier	Predicted pulp yield %
01_A01	56.38	02_H02	53.87	04_D02	55.38	06_A01	55.99
01_A02	55.43	02_H03	52.36	04_D03	54.87	06_A02	56.34
01_A03	54.16	02_I01	55.16	04_E01	57.66	06_A03	55.23
01_A04	51.14	02_I02	52.99	04_E02	54.85	06_A04	54.87
01_B01	56.13	02_J01	53.87	04_E03	54.41	06_B01	56.28
01_B02	56.05	02_J02	51.88	04_F01	57.17	06_B02	55.82
01_B03	54.99	03_A01	57.17	04_F02	54.75	06_B03	54.31
01_B04	52.00	03_A02	58.84	04_F03	53.08	06_C01	56.22
01_C01	55.84	03_A03	55.18	04_F04	50.75	06_C02	55.91
01_C02	55.65	03_A04	48.93	04_G01	56.41	06_C03	55.41
01_C03	53.07	03_B01	57.74	04_G02	53.88	06_D01	55.99
01_C04	50.94	03_B02	59.41	04_H01	56.44	06_D02	55.04
01_D01	56.51	03_B03	57.63	04_H02	54.60	06_D03	54.26
01_D02	56.54	03_B04	53.50	04_H03	52.16	06_E01	55.52
01_E01	54.48	03_B05	49.71	04_I01	58.97	06_E02	55.09
01_E02	54.43	03_C01	56.66	04_I02	56.31	06_E03	54.08
01_F01	54.37	03_C02	56.51	04_J01	54.96	06_F01	56.12
01_F02	51.99	03_C03	56.09	05_A01	54.65	06_F02	56.39
01_G01	53.54	03_C04	52.22	05_A02	50.20	06_F03	54.08
01_G02	51.43	03_D01	57.23	05_A03	50.89	06_G01	54.27
01_H01	53.49	03_D02	58.48	05_A04	47.03	06_G02	57.63
01_H02	53.07	03_D03	55.70	05_B01	54.67	06_H01	54.67
01_I01	53.96	03_E01	55.79	05_B02	51.57	06_H02	53.56
01_I02	51.11	03_E02	56.86	05_B03	51.19	06_I01	54.08
01_J01	52.51	03_E03	54.24	05_B04	47.96	06_J01	56.03
02_A01	56.04	03_F01	56.70	05_B05	48.77	06_J02	53.37
02_A02	55.72	03_F02	55.77	05_C01	54.67	07_A01	55.05
02_A03	54.06	03_F03	53.79	05_C02	51.78	07_A02	55.09
02_A04	53.12	03_G01	56.51	05_C03	54.84	07_A03	50.10
02_B01	56.08	03_G02	54.89	05_D01	54.30	07_A03	52.10
02_B02	56.93	03_G02	51.04	05_D02	51.12	07_B01	55.30
02_B03	57.04	03_H01	54.79	05_D03	51.50	07_B02	55.08
02_B04	55.08	03_H02	53.46	05_D04	45.64	07_B04	52.60
02_C01	56.83	03_I01	54.78	05_E01	53.42	07_C01	55.74
02_C02	56.39	03_I02	53.23	05_E02	50.21	07_C02	55.08
02_C03	55.31	03_J01	54.31	05_E03	49.37	07_C03	53.45
02_C04	55.18	03_J02	52.21	05_E04	48.36	07_C04	53.10
02_D01	56.71	04_A01	57.82	05_F01	55.78	07_D01	55.45
02_D02	57.00	04_A02	55.16	05_F02	51.71	07_D02	54.90
02_D03	56.32	04_A03	56.43	05_F03	45.53	07_D03	51.93
02_E01	55.46	04_A04	53.96	05_F04	45.98	07_E01	55.13
02_E02	55.54	04_A05	54.42	05_G01	52.73	07_E02	54.59
02_E03	54.00	04_B01	57.88	05_G02	50.64	07_E03	54.41
02_E04	54.09	04_B02	56.08	05_G03	45.50	07_E04	51.09
02_F01	55.69	04_B03	57.14	05_H01	53.39	07_F01	54.78
02_F02	55.34	04_B04	55.10	05_H02	51.34	07_F02	54.31
02_F03	52.22	04_C01	53.47	05_H03	46.07	07_F03	52.46
02_G01	54.81	04_C02	58.20	05_I01	53.52	07_F04	49.66
02_G02	54.71	04_C02	55.99	05_I02	48.96	07_G01	54.94
02_G03	52.71	04_C04	56.32	05_J01	53.20	07_G02	54.15
02_H01	54.25	04_D01	57.49	05_J02	48.93	07_H01	54.31

Appendix 6 cont. NIR predicted screened pulp yield for all of the samples analysed (missing values excluded).

Sample identifier	Predicted pulp yield %	Sample identifier	Predicted pulp yield %	Sample identifier	Predicted pulp yield %	Sample identifier	Predicted pulp yield %
07_H02	53.23	09_D04	50.44	11_D03	54.50	15_J01	54.87
07_H03	50.12	09_E01	54.87	11_G01	54.31	15_J02	52.50
07_I01	54.05	09_E02	54.01	11_G02	54.18	16_A01	55.70
07_I02	51.97	09_E03	52.99	11_G03	49.72	16_A02	53.41
07_J01	54.56	09_E04	51.33	11_J01	54.20	16_A03	52.18
08_A01	55.86	09_F01	55.74	11_J02	51.24	16_A04	50.49
08_A02	54.77	09_F02	54.21	12_A01	55.67	16_A05	53.16
08_A04	49.82	09_F04	51.13	12_A02	55.82	16_D01	55.44
08_B01	55.91	09_FO3	49.28	12_A03	55.79	16_D02	52.06
08_B02	54.07	09_G01	54.05	12_A04	53.18	16_D03	52.17
08_B03	51.26	09_G02	51.87	12_A05	53.71	16_G01	53.96
08_B04	49.20	09_G03	50.14	12_D02	56.25	16_G02	52.20
08_C01	55.76	09_H02	52.87	12_D03	55.47	16_G03	51.02
08_C02	55.24	09_H03	50.06	12_G01	55.39	16_J01	53.46
08_C03	52.18	09_H04	53.95	12_G02	55.48	16_J02	51.10
08_C04	50.48	09_I01	53.67	12_G03	53.28	17_A01	56.33
08_D01	55.04	09_I02	51.11	12_J01	55.00	17_A02	55.81
08_D02	53.06	09_J01	51.02	12_J02	54.12	17_A04	52.83
08_D03	50.13	09_J02	53.92	13_A01	55.48	17_D01	55.79
08_E01	54.91	10_A01	56.21	13_A02	53.71	17_D02	56.18
08_E02	53.50	10_A02	56.08	13_A03	50.06	17_D03	52.39
08_E03	51.29	10_A03	56.23	13_A04	49.46	17_G01	54.48
08_F01	53.99	10_A04	55.81	13_D01	56.17	17_G02	52.14
08_F02	52.16	10_A05	56.54	13_D02	54.35	17_G03	50.43
08_F03	48.17	10_B01	54.80	13_D03	51.07	17_J01	52.55
08_G01	53.73	10_B02	56.61	13_G01	53.76	17_J02	48.10
08_G02	49.96	10_B04	53.71	13_G02	53.36	18_A01	55.86
08_G03	46.20	10_C01	56.00	13_G03	48.25	18_A02	55.34
08_H01	55.22	10_C02	56.78	13_J01	53.67	18_A03	54.46
08_H02	50.80	10_C03	54.83	13_J02	55.86	18_A04	52.23
08_H03	44.01	10_D01	55.76	14_A01	56.86	18_D01	55.88
08_I01	52.26	10_D02	56.49	14_A02	53.35	18_D02	54.52
08_I02	46.36	10_D03	56.67	14_A03	51.32	18_D03	55.76
08_J01	52.88	10_E01	55.69	14_A04	51.10	18_G01	54.89
08_J01	45.53	10_E02	55.89	14_D01	53.84	18_G02	55.43
09_A01	55.28	10_E03	55.45	14_D02	55.60	18_G03	50.51
09_A02	54.07	10_F01	55.86	14_D03	50.63	18_J01	55.93
09_A03	55.21	10_F02	55.45	14_G01	54.85	18_J02	50.35
09_A04	51.91	10_F03	52.78	14_G02	51.49	19_A01	56.07
09_B01	55.52	10_G01	55.48	14_J01	52.76	19_A02	53.21
09_B02	55.30	10_G02	55.25	14_J02	48.86	19_A03	53.65
09_B03	53.15	10_H01	55.01	15_A01	55.63	19_A04	50.12
09_B04	52.26	10_H02	53.69	15_A02	55.09	19_D01	55.15
09_B05	51.47	10_I01	53.01	15_A03	53.48	19_D02	53.30
09_C01	55.10	10_J01	54.78	15_A04	49.95	19_D03	53.34
09_C02	54.74	10_J02	52.37	15_A05	52.06	19_G01	53.19
09_C03	53.12	11_A01	57.56	15_D01	56.01	19_G02	55.22
09_C04	52.00	11_A02	56.93	15_D02	55.38	19_G03	48.59
09_C05	52.53	11_A03	55.31	15_D03	53.51	19_J01	54.72
09_D01	55.14	11_A04	54.73	15_G01	54.91	19_J02	49.46
09_D02	55.48	11_D01	56.34	15_G02	52.83	20_A01	55.31
09_D03	53.58	11_D02	56.32	15_G03	55.88	20_A02	55.47

Appendix 6 cont. NIR predicted screened pulp yield for all of the samples analysed (missing values excluded).

Sample identifier	Predicted pulp yield %	Sample identifier	Predicted pulp yield %	Sample identifier	Predicted pulp yield %		
20_A03	53.91	24_D02	53.13	28_G02	50.67		
20_A04	53.85	24_D03	50.67	28_G03	48.86		
20_D01	52.25	24_G01	52.82	28_J01	52.15		
20_D02	55.32	24_G02	53.76	28_J02	51.33		
20_D03	54.80	24_G03	48.66	29_A01	56.72		
20_G01	52.02	24_J01	53.48	29_A02	57.93		
20_G02	54.91	24_J02	51.60	29_A03	55.83		
20_J01	55.07	25_A01	55.04	29_A04	52.00		
20_J02	52.13	25_A02	56.00	29_A05	49.42		
21_A01	55.53	25_A03	54.57	29_D01	55.08		
21_A02	54.07	25_A04	50.08	29_D02	54.93		
21_A03	50.89	25_D01	54.89	29_D03	51.31		
21_A04	50.50	25_D02	55.45	29_D04	53.23		
21_D01	54.94	25_D03	51.74	29_G01	53.32		
21_D02	52.81	25_G01	54.27	29_G02	53.25		
21_D03	49.04	25_G02	52.66	29_G03	48.93		
21_D04	52.66	25_J01	53.80	29_J01	53.41		
21_G01	55.13	25_J02	51.18	29_J02	52.69		
21_G02	51.81	26_A01	55.26	30_A01	55.53		
21_G03	50.36	26_A02	53.40	30_A02	56.02		
21_J01	54.13	26_A03	53.30	30_A03	54.34		
21_J02	50.84	26_A04	51.61	30_D01	55.29		
22_A01	56.15	26_D01	55.81	30_D02	55.30		
22_A02	52.10	26_D02	53.87	30_D03	52.82		
22_A03	49.67	26_D03	55.39	30_G01	55.30		
22_A04	46.95	26_G01	53.77	30_G02	52.19		
22_D01	50.03	26_G02	52.32	30_J01	54.73		
22_D02	52.37	26_G03	49.59	30_J02	51.28		
22_D03	47.28	26_J01	53.73				
22_G01	53.80	26_J02	51.73				
22_G02	50.84	27_A01	54.16				
22_G03	46.54	27_A02	51.43				
22_J01	52.39	27_A03	49.48				
22_J02	48.77	27_A04	48.06				
23_A01	53.96	27_D01	54.17				
23_A02	51.22	27_D02	53.22				
23_A03	50.53	27_D03	50.03				
23_A04	45.86	27_D04	49.64				
23_D01	54.86	27_G01	54.15				
23_D02	52.25	27_G02	50.02				
23_D03	48.33	27_G03	48.03				
23_G01	53.53	27_J01	54.60				
23_G02	51.63	27_J02	51.12				
23_G03	46.04	28_A01	53.84				
23_J01	53.67	28_A02	50.79				
23_J02	47.84	28_A03	50.80				
24_A01	54.72	28_A04	48.20				
24_A02	55.21	28_D01	53.57				
24_A03	54.84	28_D02	52.17				
24_A04	54.45	28_D03	49.59				
24_D01	54.78	28_G01	52.53				