A method for the non-destructive determination of the knotty core sizes of standing *Pinus patula* trees, based on ring width assessments at breast height and the pruning history

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Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the authorship owner thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Francis Munalula

Date: 23 February 2010

Abstract

The objective of this study was to develop and assess a methodology of using pruning information (age and height) and ring width measurements on increment core samples taken at breast height from standing pruned *Pinus patula* trees for modeling the knotty core sizes in the pruned section of a tree. A total of 170 trees from 17 compartments, representing a wide variety of growth sites from the Mpumalanga escarpment, were selected and destructively sampled. Sample trees were selected to represent the productive timber volume available from the compartments using stratified sampling. Sample discs were removed at breast height (1.3m) and at six meter height. After drying and sanding, the cross-sectional surfaces of one surface of each of the discs were scanned on a document scanner and the ring widths measured, using an image analysis program. A preliminary study, using 30 discs, was undertaken to ascertain the appropriate number of radii per disc to measure. A comparison between results of two opposite radii, as opposed to four radii, showed that the difference in mean ring width resulting from the two approaches was statistically not significant. In practice this means that for ring width assessment, sampling of increment cores opposite to one another at breast height would be sufficiently accurate to study average ring width variation across the radius of a tree. A study was also conducted to determine to what accuracy ring widths at six metre height could be predicted from breast height measurements. It was shown that cumulative growth at six metre height can be predicted from cumulative growth at breast height, site index and cambial age at breast height as independent variables (R^2 = 0.96). Ring width measurements at breast height can, therefore, be used to predict incremental growth throughout the pruned section. Combined with available information on the pruning history of a stand (pruning heights and pruning age), this study proved that quantitative knowledge on incremental growth can be used as a basis for estimating changes in knotty core sizes along the entire pruned section of the stem.

Analysis of variation for the entire data set from ring width measurements showed that there was far greater variation in knotty core percentages (the percentage of diameter occupied by knotty core) between different compartments than within compartments. Within a tree, the knotty core percentages between three stem sections, 0-2.4m, 2.4–4.8m, and 4.8-7m, were found to increase significantly from the bottom section (49.1%) to the top section (65.4%).

A single 2.4m log from the pruned section of each tree was removed and processed into sawn timber at a sawmill. After drying of the boards, a sub-sample of sawn boards from 17 logs, one log from each compartment, was selected and reconstructed into log form. From the reconstructed log (reconstructed to represent their original position in the log) the actual knotty core size was estimated by measuring the distance from the pith to the end of the branch stub. A comparison of the actual knotty core sizes and the modelled knotty core sizes of a sub-sample of trees showed only a modest relationship (R^2 = 0.62). Reasons for this might be variability in pruning quality, inaccurate pruning records, nodal swellings and the methodology used to measure the actual knotty core sizes.

Knowledge of knotty core sizes of standing trees can be used for many different purposes. Two applications that were assessed and found to be useful include decision support for cross cutting logs and for sawmill production planning purposes. Sawmill simulation software was used to evaluate value -and grade recoveries under different scenarios. Results showed that cross-cutting the pruned sections of logs from a compartment with large within-tree knotty core size variation into shorter logs, as opposed to keeping the pruned sections as single logs, result in increases in grade and value recovery. It was also shown that sawing of pruned logs from compartments with relatively small knotty cores, results in much better grade recoveries than logs from compartments with relatively large knotty cores (this information will be useful for production planning purposes). It can be concluded that the methodology proposed to reconstruct knotty cores from tree ring measurements has the potential to be used as a decision aid in the forest and forest products industry.

Opsomming

Die doel van hierdie studie was die ontwikkeling en evaluasie van 'n metode wat snoei-informasie (ouderdom en hoogte) en jaarringwydte-metings gebruik om die kwaskerne van staande, gesnoeide *Pinus patula* bome te modelleer. 'n Totaal van 170 bome van 17 kompartemente vanaf 'n wye verskeidenheid groeiplekke van die Mpumalanga platorand is in 'n destruktiewe steekproef ingesluit. Bome is gekies met behulp van gestratifiseerde steekproefneming sodat dit die produktiewe houtvolume beskikbaar vanaf 'n kompartement verteenwoordig. Skywe is verwyder op borshoogte (1.3m) en op ses meter hoogte. Nadat die skywe gedroog en geskuur is, is 'n dwarssnit van een oppervlak per skyf geskandeer op 'n normale dokumentskandeerder en jaarringwydtes is gemeet met behulp van beeldverwerkingssagteware. 'n Voorlopige studie waar 30 skywe gebruik was, is gedoen om uit te vind hoeveel radii gemeet moet word op elke skyf. Daar is gevind dat daar nie 'n statisties beduidende verskil is tussen die gemiddelde jaarringwydtes van twee teenoogestelde radiusse teenoor vier radiusse nie. In praktyk beteken dit dat vir jaarringstudies, monsterneming van twee teenoorstaande inkrementboorsels per boom genoegsaam sal wees om gemiddelde jaarringvariasie te bepaal oor die radius van 'n boom. 'n Studie van jaarringwydtes is gebruik om te bepaal hoe akkuraat die jaarlikse groei by ses meter hoogte voorspel kan word vanaf groei by borshoogte. Daar is aangetoon dat kumulatiewe groei by ses meter hoogte akkuraat voorspel kan word ($R^2 = 0.96$) deur die onafhanklike veranderlikes kumulatiewe groei by borshoogte, groei-indeks, en kambiale ouderdom by borshoogte.

Analise van variansie vir die volledige datastel van jaarringwydtes wys dat daar baie groter variasie in kwaskern persentasies (die persentasie van die diameter wat deur die kwaskern beslaan word) tussen verskillende kompartemente is as binne kompartemente. Binne bome is daar beduidende verskille gevind tussen die gemiddelde kwaskern persentasies van die drie stamseksies 0-2.4m, 2.4-4.8m, en 4.8-7m. Daar is gevind dat die kwaskern persentasies hoër word vanaf die onderste seksie (49.1%) tot die boonste seksie (65.4%).

'n Enkele saagblok vanaf die gesnoeide deel van elke boom is verwyder en verwerk na gesaagde planke by 'n saagmeul. Nadat die planke gedroog is, is 'n steekproef van planke vanaf 17 stompe, een vanaf elke kompartement, gekies en gerekonstrueer na hulle relatiewe posisies binne die blok. Vanaf die gerekonstrueerde blok van elke boom is die kwaskerngrootte bepaal by 'n spesifieke hoogte deur die afstand vanaf die pit tot by die end van 'n takoorblyfsel te meet. 'n Vergelyking tussen die gemete en gemodelleerde kwaskerngrootes toon 'n matige korrelasie ($R^2 = 0.62$). Redes hiervoor mag dalk snoeikwaliteit, onakkurate plantasierekords, nodulêre swellings, en die metode om kwaskerngrootte te meet, insluit.

Kennis van die kwaskerngroottes van staande bome kan gebruik word in verskeie toepassings. Twee toepassings wat geëvalueer is en bruikbaar gevind is, sluit besluitnemingsondersteuning vir dwarssaag van blokke en saagmeul produksiebeplanning in. Sagteware vir saagmeulsimulasie is gebruik om waarde –en graadherwinning te evalueer met verskillende scenarios. Resultate dui aan dat die dwarssaag van die gesnoeide deel van bome na korter stompe hoër waarde –en graadherwinnings oplewer as wanneer die gesnoeide deel as 'n enkele stomp gehou word wanneer 'n kompartement groot binneboom-variasie in kwaskerne het. Daar is ook aangetoon dat gesnoeide stompe vanaf kompartmente met relatief klein kwaskerne aansienlik hoër graadherwinnings oplewer as stompe vanaf kompartmente met relatief groot kwaskerne (hierdie inligting sal bruikbaar wees vir produksiebeplanning doeleindes). Die gevolgtrekking kan gemaak word dat die metode wat voorgestel word om kwaskerne te rekonstrueer vanaf jaarringmetings die potensiaal het om gebruik te word as 'n besluitnemingshulp in die bosproduktebedryf.

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Abbreviations & Acronyms

ANOVA	Analysis of Variance
Avg	Average
CI	Confidence Interval
cm	Centimetres
^{o}C	Degrees Celsius
DBH	Diameter at breast height (i.e. at 1.3m)
et al.	et alii
Fig.	Figure
JPEG	Joint Photographic Experts Group
MOE	Modulus of Elasticity
MS	Microsoft
Rad	Radius
SALMA	South African Lumber Millers Association
SAS	Statistical Analysis Software
SI	Site Index
SPSS	Statistical Package for Social Sciences
SRS	Simple Random Sampling
VIF	Variance Inflation Factor

Glossary of Terms

Annual Ring Layer of wood growth put on a tree during a single growing season.

Breast Height The usual point of measurement of standing tree diameter, i.e. 1.3m above ground level on the uphill side of the tree.

Butt Log The log directly above the stump. The biggest diameter log and usually having the greatest unit value of all logs in the tree.

Clearwood Wood having no (or negligible) defects caused by knots, resin pockets or mechanical damage and usually displaying straight and even grain patterns.

DBH An acronym for "Diameter Breast Height". A term used to describe a tree diameter measurement taken at the standard height of 1.3m above ground level.

Defect core The central core of a pruned tree outside of which clearwood is laid down and which contains pith, branch stubs and any occlusion defects.

Dendrochronology The method of scientific dating based on the analysis of tree-ring growth patterns.

Earlywood Portion of the annual growth ring that is formed during the early part of the growing season; it is usually less dense and mechanically weaker than latewood.

Growth is the biological phenomenon of increase in size with time.

Increment is the quantitative increase in size in a specified time interval due to growth.

Knot That portion of a branch that has become incorporated in the bole of a tree.

Knotty core (see defect core).

Latewood Portion of the annual growth ring that is formed after the earlywood formation has ceased; it is usually denser and mechanically stronger than earlywood.

Lumber or **timber** is wood in any of its stages from felling through readiness for use as structural material for construction or wood pulp for paper production.

Model A simplified representation of something we wish to describe or explain or understand.

Non-destructive evaluation (NDE) is the science of identifying the physical and mechanical properties of a material without altering its end-use capabilities and then using this information to make decisions regarding appropriate applications.

Pruning is the process of removing certain above-ground elements from a plant.

Sawlog A log considered suitable in size and quality for production of lumber

Site index (SI) A measure of the productivity of a forest site expressed in terms of the height attained by trees at a reference age.

Stand A block of trees of the same age, species and silvicultural regime

Stochastic A stochastic process is one whose behavior is non-deterministic, in that a system's subsequent state is determined both by the process's predictable actions and by a random element.

Timber That part of the forest's vegetative inventory which is available or prospectively available for harvesting and conversion to wood products.

Tolerance is a measure of collinearity reported by most statistical programs such SPSS

Tree A perennial woody plant at least 6 metres in height at maturity, having an erect stem or trunk and a well-developed crown or leaf canopy

Variance Numerical value describing the variability of a set of data

Wood The secondary xylem of trees and shrubs, lying beneath the bark and consisting largely of cellulose and lignin

1 Introduction

A variety of log types is available from plantations for conversion into sawn wood. In some cases this gives log buyers an opportunity to specify the physical and other features the raw material should possess in order to satisfy end-product requirements. However, sufficient knowledge of log properties is not always available from the growers of trees. In the highly competitive market where logs can also be imported from other countries and locations, knowledge of the raw material qualities can and should be used to improve the efficiency and profitability of growers and processors of trees. As stated by Oja *et al.* (2003), the successful running of a sawmill is dependent on its ability to achieve the highest possible value recovery from the sawlogs. On the product side, the challenge for the use of timber as an engineering material is that it does not have consistent, reproducible and uniform properties. The great variability between individual trees, as well as within and between stands, indicates that there is real necessity for more efficient and optimised forest and log utilisation (Johansson and Kliger, 1999).

1.1 The value of accurately predicting wood quality of standing trees

Prediction and information on the quality of the wood of standing trees can provide valuable information for several purposes. It can be used for selecting the appropriate raw material for each end use, for assessing and optimising the potential product recovery from different stands (production planning and optimisation), for comparing wood quality under different silvicultural management regimes, and in log pricing decisions.

The key to the appropriate use of logs is to recognise and quantify the quality variation associated with each log and to match these to the intended conversion process and end-product. Timber buyers nowadays increasingly demand sawn products with special properties regarding dimension, moisture content, warp and biological features (Grundberg and Grönlund, 1996). To be able to meet these requirements, the right logs have to be selected for a certain product before the sawing process. The assessment of the resource should make it possible to allocate the raw material to appropriate end uses.

According to Lyhykäinen *et al.* (2009), prediction of the end product distribution of the stand permits us to take into account not only of the yield but also timber quality, and further the value of end-products, at the time of harvest. Cost effective production requires that a sawmill is able to sort logs according the expected grade of the sawn products, i.e. the sawmill must be able to predict the properties of the sawn products before the actual sawing operation. The sawmill production planning and optimisation process will never be very efficient without suitable quality information of the raw material. Advanced production planning optimisation systems exist but the solutions provided by these are only as good as the information input.

Where silvicultural actions influence wood quality and properties, it might take many years before the effect (end product quality and price) of any action can be assessed. In this case the accurate prediction of tree, log and wood quality will be valuable information to evaluate silvicultural operations.

A price differential of logs based on the value potential of end-products should be fairly logical. However, because many variables influencing end product value are internal and not visible, these cannot be used in pricing decisions. Accurate prediction of these variables will enable fair and just pricing decisions.

1.2 Pruned butt logs

The major determinant of a sawn product grade and value in South Africa are the knot properties (South African Bureau of Standards, 2004). Knot properties for furniture and industrial grades are obviously important as these products are often used in an application where aesthetics are essential. Knots in structural products are viewed as strength reducing defects and the visual structural grading system used in South Africa focuses on the knot properties to assign a grade to a board. In South Africa, the bottom or butt section of sawlog trees are, in most cases, pruned in order to increase the value of logs and end-products. The value of this pruning operation is often, not always, acknowledged in the log pricing system where pruned logs are sold at a premium to saw and veneer mills. The pruned butt log section (6.6m length) typically accounts for about 65% of the total value of the tree stem (Wessels *et al.*, 2006). When considering wood quality in South Africa in standing trees, the knot properties and specifically the pruned quality of the butt log should be considered.

One of the problems encountered when grading pruned logs is that the knotty core is not visible. Experience has shown that knotty core diameters can vary dramatically, resulting in marked differences in the quality of logs, which otherwise appear externally the same. As predicted by Park (1980) in New Zealand, most parties involved in the trading and utilisation of pruned logs have come to recognise the need to evaluate the pruned components of stands before prices are negotiated (Park, 2002). It is now appreciated that pruned log quality cannot be determined from external appearance alone. Internal assessment is a vital component.

In South Africa and Zambia, for example, the current log specification systems do not acknowledge wood quality differences resulting from differences in knotty core sizes in the pruned section of the stem. Because of this shortcoming the quality outturn is unpredictable. Most logs are currently sold solely on the basis of size, i.e. small end diameter (SED) and length and whether it was pruned or not. The inherent value of logs may differ considerably, even with identical external characteristics. Sorting classification based on size results in the production of boards with the correct dimension but with a large variation in grade.

There has been an attempt in South Africa to introduce a system to quantify the quality of pruned logs (Turner and Price, 1996, and Wessels et al., 2006). Reasons for the development of this method, called the Pre-Harvest Quality Assessment method, included the use of it as a tool for determining equitable pricing, as well as for production planning and optimization purposes. The method, however, requires the destructive sampling of a representative sample of trees.

1.3 Objectives of the study

This study investigates a novel method of assessing pruned log quality, making use of ring width measurements on increment cores and pruning records. The method involves measuring ring widths at breast height of individual trees and dating each ring. When the pruning record of the compartment is known, differences in the knotty core along the pruned section of a tree can be modelled. Seventeen pruned *Pinus patula* compartments from the Mpumalanga area were assessed using the method. The suitability of the method, results of the specific study compartments and possible applications of the results were examined and discussed in this thesis.

The objective of this study was to develop and assess a methodology of using tree ring measurements together with the pruning history (age and height of pruning) of standing pruned *Pinus patula* trees to model the internal knotty cores of these trees. This will help to improve the competitiveness and profitability of the solid wood supply chain in Southern Africa (especially South Africa and Zambia). When applied in the field, the method involves the use of increment cores. These cores are obtained from breast height. Increment cores are used because they are regarded as being non-destructive.

To accomplish this objective, the following needed to be established:

1: To assess the practical applicability of the methodology developed to predict the knotty core sizes of standing *Pinus patula* trees.

Specific questions that needed to be answered are the following:

I. *Are accurate measurements of tree rings of this species possible in terms of the visibility of rings?*
II. *Can dating of year rings be performed accurately and do missing or extra rings cause problems?*
III. *Is the specific methodology developed practical and efficient?*

2: To establish a suitable within-tree core sampling strategy.

The following specific questions needed to be answered:

I. *How many increment cores are required per tree?*
II. *What is the relationship between growth ring widths at breast height and ring widths on the upper pruned section (i.e. 6m height)? In other words, can growth through the full pruned section of the stem be accurately predicted from breast height measurements?*

3: To establish the variation of knotty core sizes in a typical pruned *Pinus patula* resource.

Specific questions that needed to be answered are the following:

I. *What is the knotty core size variation within trees?*
II. *What is the knotty core size variation between trees?*
III. *What is the knotty core size variation among compartments?*

4: To evaluate some applications of knotty core data from standing trees.

Specific questions that needed to be answered are the following:

I. *How can within-tree variation in knotty core sizes be used to assist cross-cutting decisions?*
II. *What is the difference in end product grades and value recovery from compartments with large differences in knotty core sizes?*

Chapter 2

2 Literature review

For the purposes of this study, literature pertaining to the following topics was studied:

- Wood formation and tree growth in relation to variability of year ring widths;
- The effect of the knotty core size in the pruned section of a tree stem on the quality of the sawn output;
- Assessment methods of the knotty core sizes in pruned tree stems.

2.1 Tree growth

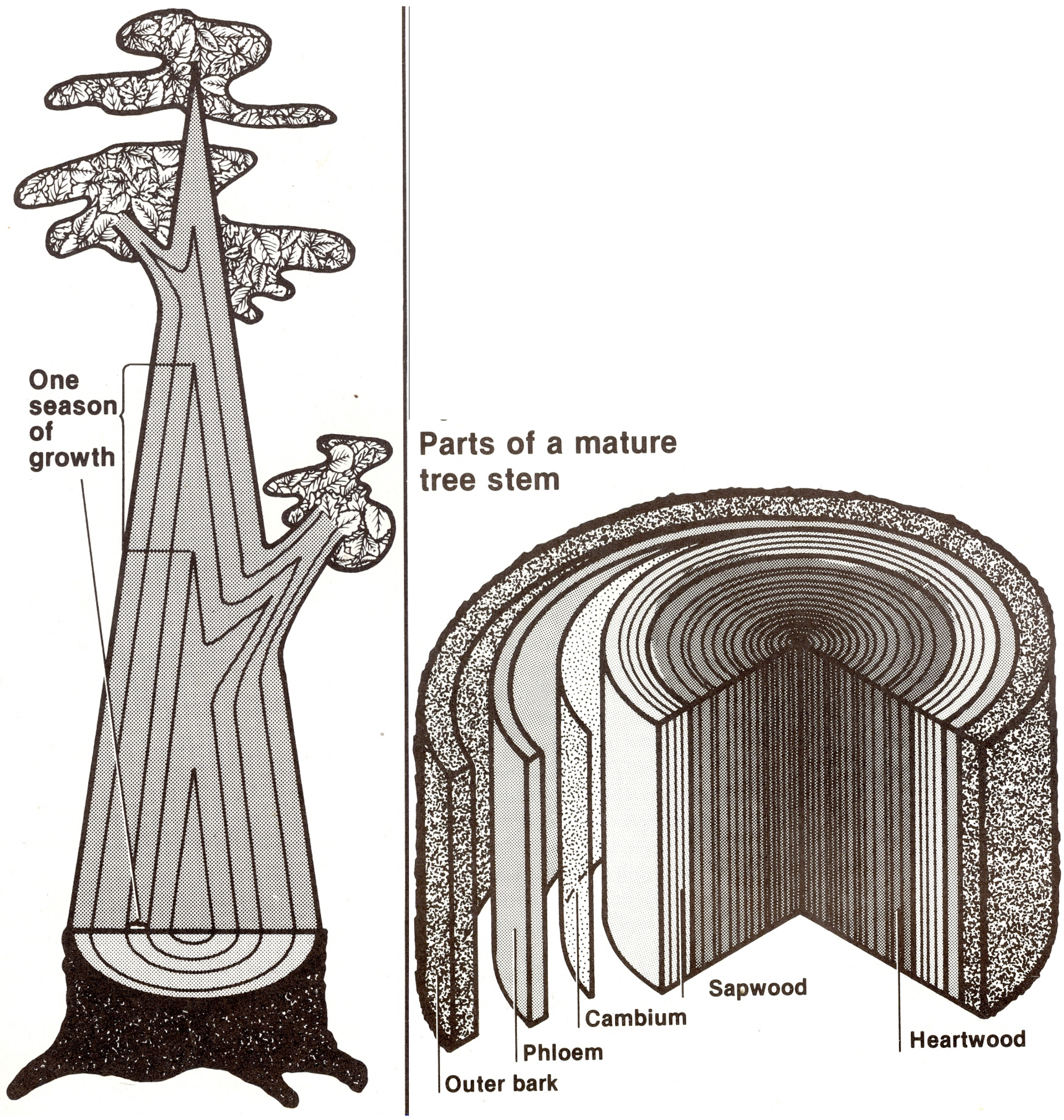

Figure 2.1 Tree rings and wood formation (Haygreen and Bowyer, 1982)

Understanding of how a tree grows is the basis for predicting not only sustainable wood production but also wood quality (Spiecker, 2002). Diameter growth is of particular importance because the width of annual rings and the relative proportions of early- and latewood in each ring have important effects on the quantity and quality of wood formed (Kramer and Kozlowski, 1960). Tree ring research has been used to understand how trees grow and respond to changes in factors that determine their growth (Downes *et al.*, 2002). In recent years tree rings as a record of tree growth have become even more attractive because analytical tools for extracting information from trees rings have improved (Fritts, 1976; Spiecker, 2002). Studying the relationships between tree growth and its effect on wood formation has lead to a much better understanding of the growth factors controlling wood properties, and wood quality in general.

A horizontal cross-section of the stem of a tree consists of a number of concentric annuli, known as growth rings (Fig. 2.1). A growth ring is a growth layer that the tree forms under its bark during the vegetation period. It consists of large diameter, thin-walled cells that are formed during the beginning of the annual growth period and small diameter thick-walled cells formed at the end of the growth period (Brown *et al.*, 1979; Haygreen and Bowyer, 1982; Wenk, 2003). The formation of growth rings in woody plants results from seasonal periodicity of growth processes (Brown *et al.*, 1979; Dinwoodie, 1981; Davis *et al.*, 2002). The expression of these seasonal rhythms depends on the woody plant species and the local conditions where the plant is growing. In temperate climates the characteristic annual cycle includes a growing and a dormant season (Hoadley, 2000). This results in a similarly cyclic nature of wood cell formation, resulting in visible growth layers. These rings may vary in width as characteristic of the species and as a result of growth conditions. The growth ring marks the position of the vascular cambium at the cessation of the previous year’s growth (Spiecker, 2002). In general, the greatest proportion of the growth ring is formed during spring when water is less limiting and temperatures are moderate (Downes *et al.*, 2002)

The growth of a woody plant represents an increase in the weight and volume of the whole plant or its parts as the result of the formation of new cells and the increase in their size (Vaganov *et al.*, 2006). In the growing tree, wood is formed by the addition of new cells through the activity of the apical and lateral meristems (Hoadley, 2000; Desch, 1996). The cells which make up meristems retain the ability to divide and produce new cells throughout the life of the tree. The apical meristem is located at the top of the main stem and also occur at the tips of branches and are responsible for the height growth of the tree whereas the lateral meristem or vascular cambium, which completely surrounds the stem, is found between existing wood and bark and is responsible for stem diameter growth.

2.1.1 Growth variation

Variation in growth is found among species and genera, among geographic sources within a species, between trees of the same stand and between stands, as well as within each individual tree along the different planes (Brown *et al.*, 1979; Wilson and White, 1986).

Trees generally produce a sheath of xylem which varies in thickness and structure at different stem or branch heights. At a given stem height, it often varies on different sides of the tree (Kozlowski, 1971). The rate of cambial growth, the distribution of earlywood and latewood, and the anatomy of cambial derivatives often vary greatly at different stem heights. In any tree, the tree ring width must of necessity vary at different heights (Brown *et al.*, 1979). The changes in vertical distribution of the xylem sheath of plantation-grown conifers as they age was discussed by Farrar (1961). When the trees are very young, the width of the annual ring decreases from the tree apex to the base (Fig. 2.2). As the trees age, however, their crowns begin to close and competition among trees increases. At that time a point of greatest ring width becomes apparent at the stem height where there is the maximum amount of foliage. Below this point, the annual xylem thickness decreases progressively to the stem base.

The annual xylem sheath laid down by the cambium varies in thickness at different stem heights in a consistent way. Kozlowski (1971) explained that below the crown, the variation in ring thickness with stem height depends on crown development. In dominant trees, the ring narrows below the crown and widens again near the stem base. In suppressed trees, the whole ring is narrower than in dominant trees, the point of maximum ring thickness is at a greater relative stem height, and below the point of maximum thickness the annual ring narrows rapidly and does not show thickening near the base of the tree.

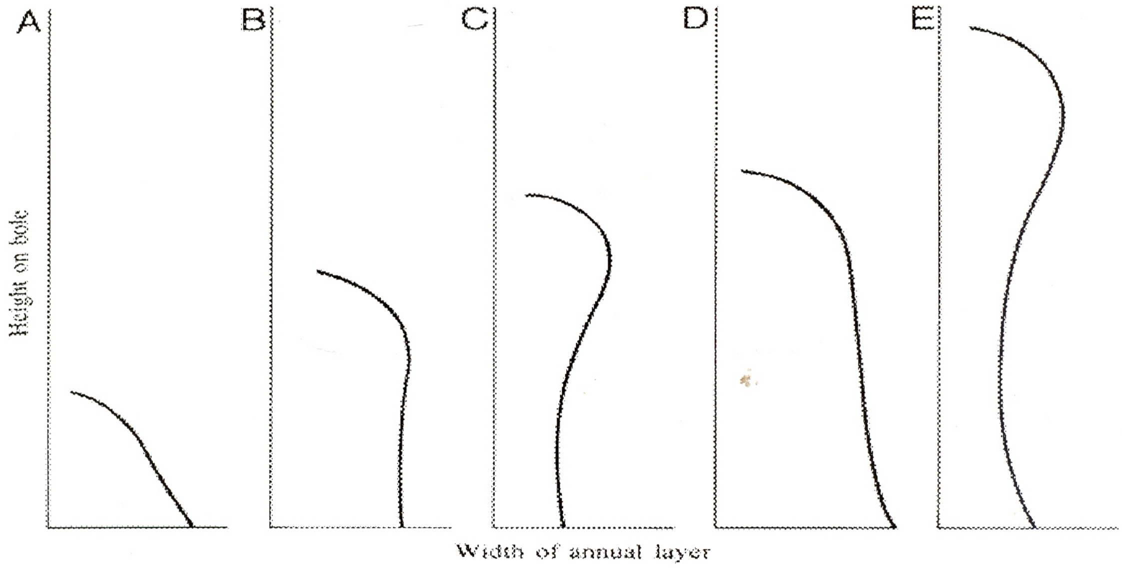

Figure 2.2 Variations in thickness of annual ring at various stem heights in plantation-grown conifers of varying age: (A) at 8 years, when crowns extend to the base of the tree; (B) crowns closing; (C) lower branches are dead; (D) shortly after thinning when crowns have been exposed to full light; (E) competition is again severe and crowns have closed. The horizontal scale is greatly exaggerated. From Farrar (1961).

Existence of vertical variation should be expected since, at different levels, wood is composed of growth rings of different structure (Tsoumis, 1968)

2.1.2 Causes of growth variation

All variation in growth can be traced to variations in limiting and interacting plant processes which can vary in time and throughout the particular tree (Brown *et al.,* 1979; Dinwoodie, 1981; Downes *et al.,* 2002; Cherubini *et al.,* 2003). Variations in ring width are not only due to fluctuations in environmental conditions but also due to systematic changes with tree age, height within the stem, and condition and productivity of the site (Fritts, 1976; Wilson and White, 1986; Husch, Beers *et al.*, 2003).

(a) Climate

Ring width has been shown to vary from one year to the next in a more or less irregular manner, with a large portion of this variation being a function of fluctuating climatic conditions prior to and during the growing period when the rings were formed (Fritts, 1976). The crown, trunk and roots of a tree are capable of reacting to environmental factors (Schweingruber, 1983). Environmental factors that govern tree growth can vary from periodic and/or predictable changes in temperature, precipitation and anthropogenic stress factors to occasional 'one off' events like fire, landslides or storm (Cherubini *et al.,* 2003; Husch *et al.,* 2003). Dinwoodie (1981) states that a physiological process initiated by a change in the environment eventually becomes directly measurable as a growth change, or is evident in the variation of tree features such as ring width. Favorable growing conditions result in trees with wide rings, which are associated with low density, and hence poor wood quality.

(b) Site

Site refers to the sum of the effective environmental conditions under which a plant or plant community lives. As with climate, the site will also influence growth variability. Soil type, inclination, wind exposure, and other site specific properties have an influence on the stem growth. Tsoumis (1968) states that variation of wood structure between trees of the same species exists because the micro-climate in which each tree grows is different. These differences occur in the same site, as well as between sites – in the same or in different geographical localities and altitudes. Edaphic, physiographic and climatic factors, for example, will determine how fast tree growth is. The rate at which a tree grows has a direct effect on the quality of the wood produced. Silvicultural measures (e.g. spacing of plantations, thinning and pruning) will change this environment. As a result, adjacent trees may differ in pattern of ring width and ring structure.

(c) Within-site variation

Even within the same site significant growth variation exists. Some species, for example, do not thrive when overtopped by others. Under such conditions, the resulting rings are narrower than usual. Brown *et al.*, (1949) established that on the same site and at the same age, individuals of a given tree species may exhibit appreciable differences in ring width depending on the crown class, i.e. according to their competitive class. According to Brown *et al.* (1949) and Desch (1981), a moisture-loving species on a dry site may manage to survive under conditions imposed, but its struggle for existence is then reflected in the stem by narrower growth rings. It should be noted that while variability can be attributed to the influence of site on the rate and nature of tree growth (Brown *et al.,* 1979), other variations fall within the category of normal anatomical departures from the mean in different individuals of a species. This means that although much of the variability of wood may be attributed to varying conditions under which the wood has been formed, some variability is inherent in trees in a way substantially independent of external circumstances. This is due to genetic effects.

(d) Genetics and within-tree variation

Aside from environmental effects, Tsoumis (1968) further adds that an important factor for between-tree variation is that trees of the same species may differ in genetic makeup. Differences between the wood of individual trees of the same species will arise due to causes similar to those influencing the growth of any one tree (Wilson and White 1986; Seifert, 2003). Additionally, there may be other intrinsic differences between them, such as those of genetic or ecotypic origin.

Wood quality and uniformity are primary objectives of a forest tree improvement program. A considerable amount of wood variation is under genetic control and thus genetic manipulation is an effective tool to change wood properties. Wood is controlled genetically both directly in the developmental or internal process of wood formation and indirectly by the control of form and growth.

It is important to try and understand the variation that occurs in timber, the causes of this variation and the effects of different wood properties on utilization (Zobel and van Buijtenen, 1989; Downes *et al.,* 2002). The greater the uniformity of wood, the more efficient will be the manufacturing and quality of the final product (Grabner 2005).

2.2 Effect of knotty core size on wood quality

The classical definition of wood quality is the suitability of a given piece of wood for a specific end use (Barbour, 2004). Mitchell (1961) defines quality as being the result of physical, chemical and other characteristics possessed by a tree or a part of the tree that enables it to meet the property requirements for different end products. Because of this, the intrinsic quality of wood is thus evaluated solely in terms of its suitability for various products or end uses.

The quality of wood is judged by one or more of the variable factors which affect its structure and in turn its physical properties (Panshin and de Zeeuw, 1970). Quality depends on the physical, chemical, anatomical and mechanical properties involved in the end-use as well as the between- and within-tree variation in these properties. As Barbour (2004) and Bowyer *et al.* (2003) explain, characteristics important in wood to be used for one product are often different from those for another product. Accordingly, individual wood characteristics are not usually seen as universally good or bad. Improved quality, however, results only when the properties of timber results in the increased satisfaction of the needs of the end-user and exhibit relatively less variability than before.

2.2.1 Factors affecting log and tree quality

The properties of stem wood are inherent and depend on the growth of the crown and stem as controlled by environment and management (Kellomäki *et al.*, 1999; Ikonen *et al.*, 2003)

The factors that determine the internal properties of a tree can be divided into two main categories: predetermined factors such as species and site, and silviculture (Björklund, Bengtsson *et al.*, 1996). Silvicultural practices affect virtually all these factors. Predetermined factors result in basic growing patterns.

2.2.1.1 The environment

Environmental factors affecting wood quality include climatic parameters such as photoperiod, temperature, wind, and precipitation, soil fertility, site inclination and related factors (Kramer and Kozlowski, 1960). Also of importance are abiotic and biotic stress factors that significantly affect tree diameter growth (Wipfler *et al.*, 2005; Seifert, 2007).

Kramer *et al.* (1960) explains that in terms of physiological processes, the environmental requirements are conditions favourable for the manufacture of sufficient food for growth and maintenance of internal water balance. In recent years it has become apparent that there is often no direct relation between a single environmental factor and plant growth. This is especially true in forest trees, where there may be many factors operative at one time. The study of the effect on tree growth of the environment is complicated by the perennial nature of trees, where many factors may not be effective until several months or even years later, and where the size of the experimental materials might considerably modify techniques used in individual studies.

I. Light

The effects of light on plant growth depend on its intensity, its quality or wavelength, and its duration and periodicity. Variation in any of these characteristics can modify both the quantity and quality of growth. Exposure to short days brings about a cessation of cambial activity in some species of trees, while exposure to long days prolongs it (Wareing, 1956 cited in Kramer *et al*, 1960)

II. Temperature

Fluctuations in soil and air temperature influence growth and distribution of trees by altering rates of various important physiological processes such as photosynthesis, respiration, cell division and elongation, enzymatic activity, chlorophyll synthesis, and transpiration. Low temperatures slow down physiological activity. Exposure to relatively high temperatures often causes reduced growth and injury in trees.

III. Soil moisture

Soil moisture often becomes a limiting factor because of its effects on the internal water balance, which in turn affects the processes controlling growth. In any discussion on the relation between soil moisture and growth it must be remembered that growth is not only controlled by soil moisture content or soil moisture stress but by the water balance of the plant.

IV. Competitition

Trees in dense stands compete above ground for light and below ground for water, minerals and oxygen (Kramer *et al.*, 1960). The competitive ability of every tree is reflected in the quantity and quality of the wood produced.

2.2.1.2 Silviculture

The control of timber quality begins in the plantations. Silviculture, i.e. the practice of caring for and cultivating forest trees, embraces a variety of management practices aimed at enhancing log quality (Shepherd, 1986). According to Montagu *et al.* (2003), silvicultural management involves drawing together all aspects of planted (and natural) forests to achieve a desired objective.

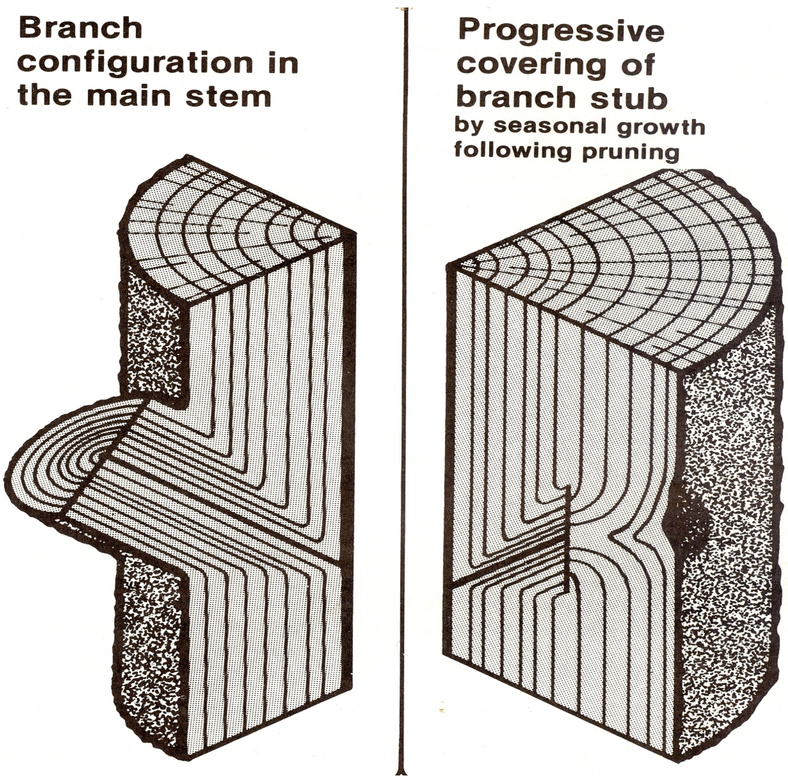

Figure 2.3 Branch after pruning (Haygreen and Bowyer, 1982)

The silvicultural intervention of main interest for purposes of this study is pruning. Pruning (Fig. 2.3) is the practice of trimming branches from chosen portions of standing trees to eliminate the occurrence of knots in subsequently produced wood, apart from epicormic shoots which may develop in special instances. Sawtimber stands are pruned to maximise the quality and value of logs. Kotze (2004) explains that through timely pruning, the formation of dead knots is prevented and the knotty core is limited to less than 20 cm, and with that the clearwood radius is also maximised. If pruning is delayed (Todoroki, 2003), the knotty core expands and clearwood conversion reduces. In many cases the last pruning defines the knotty core diameter for the stem (Cunningham and Price, 1996). A large knotty core results if a tree is already large in diameter when pruned, if sweep or other irregularities displace the alignment or pruned whorls, if poor pruning leaves stubs protruding beyond the stem surface, if the tree has swollen branch collars, or if defects develop at stub ends which degrade what would have otherwise been clear wood. Some species, such as P. taeda, tend to leave long pruning scars.

According to Viquez and Perez (2005), yield and market prices decrease considerably for trees without pruning interventions since timber must be almost knot-free in order to obtain a high monetary value. Pruning increases value by encouraging clearwood growth. Investment in pruning should be supported by long-term profit evaluations (Somerville, 1985). Two underlying assumptions in these evaluations are that pruning improves log quality, and that clearwood resulting from pruning can be traded as a high-value commodity.

2.3 The knotty core of a pruned stem

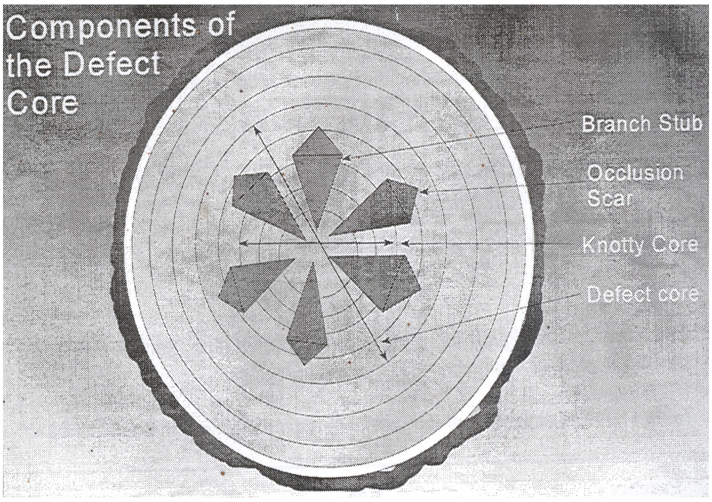

Figure 2.4 The defect knotty core (Cunningham and Price, 1996)

The knotty core is the product of diameter over pruned branch stubs (DOS) plus the additional growth that takes place to cover the occlusion scar to give diameter over occlusion (DOO) before clear wood is produced (Park, 1980; Petruncio *et al.*, 1997). Fig. 2.4 shows the components of the defect knotty core.

DOS is the maximum diameter of a single whorl measured immediately after it is pruned. It consists of the diameter under bark at the time of pruning plus additional diameter due to bark thickness, branch collars or nodal swellings, and protruding branch ends not cut flush with the stem (Petruncio *et al.*, 1997). DOO adds to DOS the amount of wood required to cover any pith, bark or other defects that may occur at the stub end. As shown in Fig. 2.4, the defect core, therefore, is the smallest cylinder that contains all occluded branches within a log and combines the effects of DOO, misalignment of whorls due to stem sweep and sinuosity, and differences between successive pruning lifts. Park (1982) found a strong relationship between the defect core and DOS. The relationship, with a correlation coefficient of 0.94, is valid for logs that are nominally straight and between 4.9m and 5.5m.

Ideally, the defect core of a pruned log should be as small as possible (Cahill *et al.*, 1988). A large defect core relative to the final diameter of the log limits clear product recovery and revenue (Petruncio *et al.*, 1997). Results of studies in New Zealand by Todoroki (2003) showed that each 1cm increase in defect beyond that initially targeted size causes an estimated value loss of 2.5%.

The importance of maintaining the defect core through pruning lifts is illustrated by the two logs in Fig. 2.5. The logs have identical external characteristics and are pruned in the same number of lifts. The delayed pruning of log A (on the left) has resulted in an enlarged defect core. As explained by Todoroki (2003), while it is clear from this example that the inherent value of pruned logs can differ considerably, even with identical external characteristics, both logs would attract the same grade if their volume or size is the only criterion for determining quality or price.

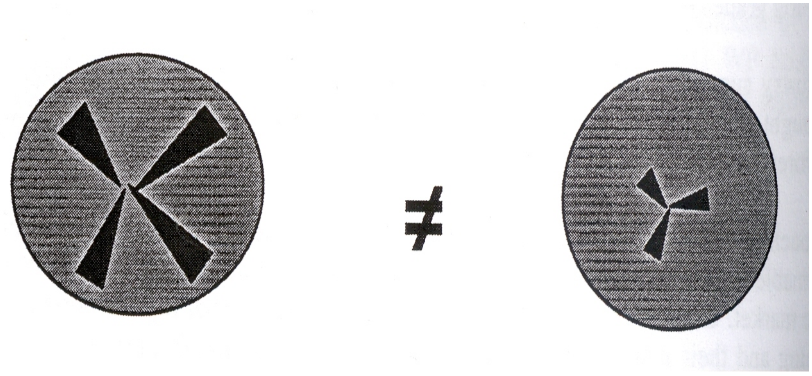

Figure 2.5 Differences in internal features between two logs of the same diameter (Price *et al.*, 2003)

2.4 Log and tree quality assessment

Lumber recovery, which depends highly upon resource characteristics (Tong and Zhang, 2008), is one of the most important measures to appraise the performance of a mill. Maximising product recovery and economic value of the forest resource requires an understanding of the variability of stem quality attributes. The successful running of a sawmill depends on its ability to achieve the highest possible value recovery from sawlogs, i.e. to optimise the use of the raw material (Oja *et al.*, 2003). The same holds true in veneer mills and with many other primary log conversion processes. Substantial economic gains (by quality improvement) could be achieved by acquiring knowledge about the internal structure of logs (Rinnhofer *et al.*, 2003)

To increase yield in most modern sawmills, it is a requirement that the mill is able to carry out an accurate measurement of the outer log characteristics such as length, diameter, sweep (Mahler and Hauffe, 2009). Manufacturers sometimes find it difficult to process wood into quality products consistently because of wood's variation in properties (Pellerin and Ross, 2002).

2.4.1 Reasons for log and tree quality assessment

To recoup the investment made by forest owners on the pruned resource, it is vital that pruned logs with a defined quality are marketed on the value associated with their clear wood content.

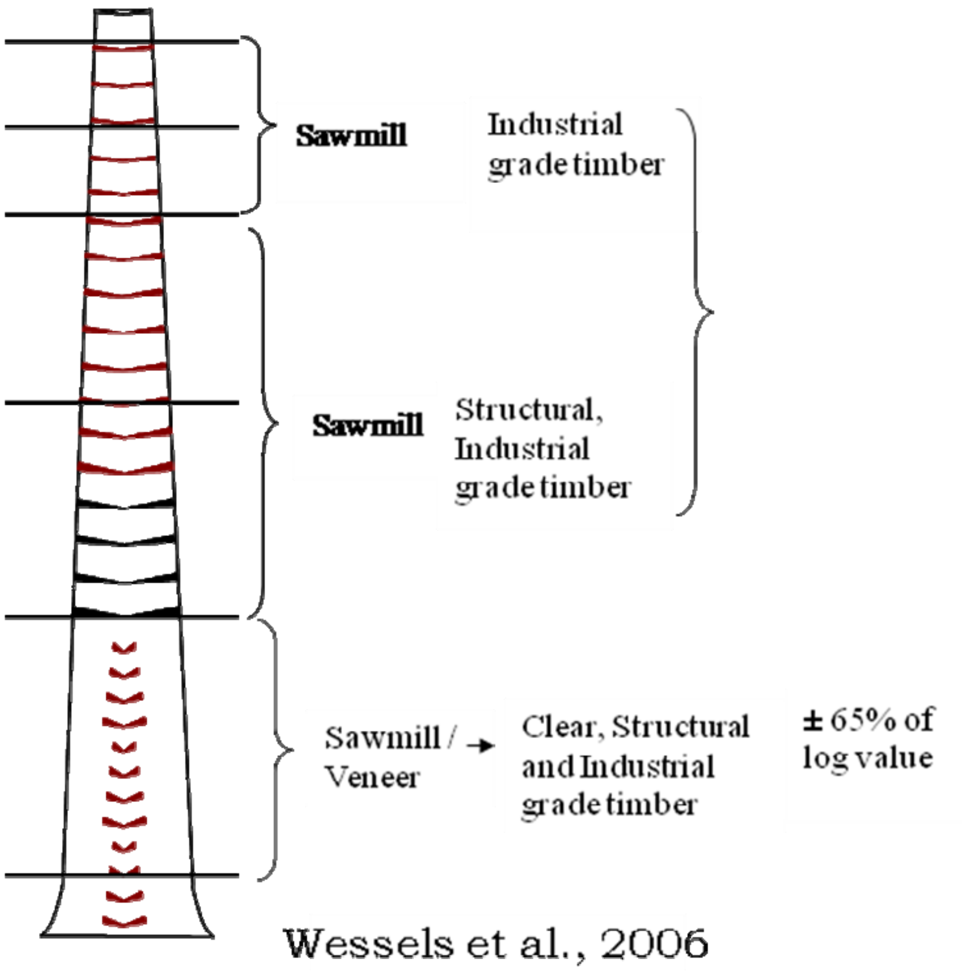

Figure 2.6 Stem classification (Wessels *et al.*, 2006)

The aim of raw material evaluation is to match the quality needs or specifications of individual products with the properties of the raw material. This information can be used to maximise the value of the products by choosing the optimal bucking and sawing patterns. Within a stem, there are defined quality zones which need to be recognised during processing if value recovery is to be enhanced (see Fig. 2.6). The wood quality of a stem in the longitudinal direction is the main factor that determines the qualities and quantities of the different wood pieces that a log can be divided into (Han and Birkeland, 1992). For this reason, it is important to be able to judge the inner quality of a log.

A traditional sawmill, which only sorts logs according to diameter and species, will produce boards with the correct dimension but with a large variation in grade (Oja *et al.*, 2003). Certain board grades will then be difficult to sell, obtain low prices and result in a low value recovery for the sawmill. The sawmill must be able to predict the properties of the sawn products before the actual production, if it is to be cost effective.

Timber growers need to assess the properties to know which stands are best suited for marketing to timber producers. Before felling a compartment, it is useful to understand its potential in terms of the proportion of each different quality product that can be made from the resource found there (Wang and Ross, 2002). In a well managed, well-pruned stand (Somerville *et al.*, 1985), the butt log may be worth more than the aggregate value of all other logs. As shown in Fig. 2.7, a higher price is not only paid for the pruned butt logs but also for the resulting timber from such high grade logs (Park, 2002). In terms of sawlogs, some grading systems segregate those logs containing an indicated and predictable minimum volume of clear sawn board from logs having lower clear-board content (Park, 2002; Cunningham and Price, 1996).

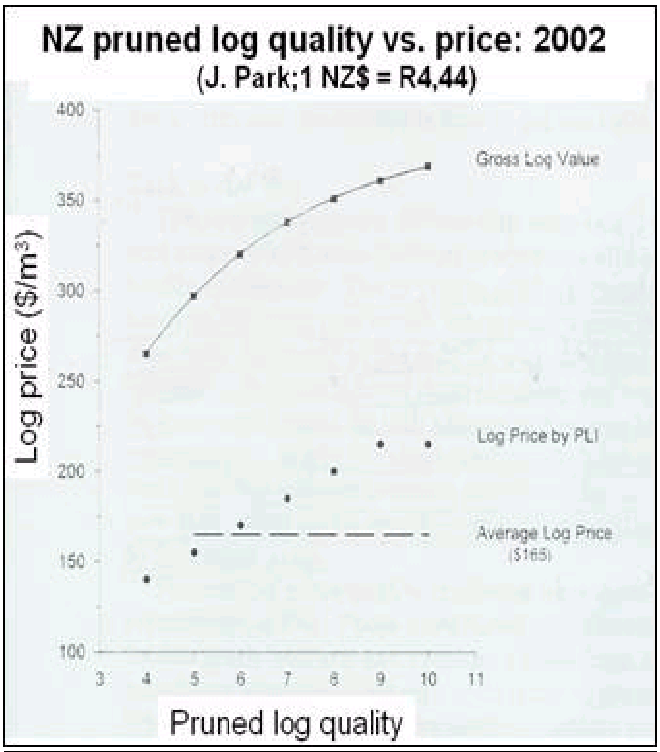

Figure 2.7 Price differences for graded and ungraded logs and for products from such logs (Park, 2002)

Evaluation of the pruned timber resource is not restricted to providing data for pending log sales. Other objectives may include long-range planning and comparisons of theoretical regimes (Somerville *et al.*, 1985). The information available and the purpose of the evaluation determine the amount of effort required and level of precision possible.

2.4.2 Log and tree quality assessment methods

According to Lönner (1994), the most severe limitation in trying to achieve optimised log use in the past has been the difficulty in predicting the inner quality parameters of trees due to measurement difficulties.

There are several methods or techniques that can be used in the evaluation of a forest resource. These include the sawing study method (Park and Leman, 1983), the cross-sectional analysis system (Somerville, 1985; Wessels *et al.*, 2006), use of the Pruned Log Index (Park, 1989) or the use of a modelling system (e.g. Cunningham and Price, 1996).

To understand the complexities of evaluating logs (Somerville *et al.*, 2004), it is important to understand that each characteristic can assume a different importance under a different primary process.

2.4.2.1 Sawing study method

The sawing study method developed by Park and Leman (1983) can be divided into four stages:

I. Log measurement;
II. Sawing (including board identification and recording of sawing patterns);
III. Log "reconstruction" from boards, and mapping of defect cores; and
IV. Timber grading and tallying

According to this method, details of the knotty core are recorded by "reconstructing" logs from their sawn produce.

Prior to sawing, each log is marked with a log end template. Sheets of A3 paper with the log number printed all over the sheet are glued to the one end of a log using PVA glue. The logs are then processed using a cant sawing pattern.

Reconstruction is done in two stages. First the full cant is reassembled and placed on its edge. A measuring stick, which is graduated in 0.1m intervals, is laid on top of the cant. By lifting back boards one at a time, the heights and positions of occlusion scars and branch stubs, as well as the path of the pith, are recorded on a diagram that gives an X-ray type view. The distance of defects from the butt end is recorded to the nearest tenth of a metre. The radial reach of branch stubs and occlusions are drawn in at each whorl; at any one whorl it is necessary to trace only the longest branch stubs and occlusion on either side of the pith. The ends of defects are often concealed within boards, but it is usually possible to estimate these to within less than one-quarter of board thickness (Park, 1982). If boards are thicker than 25mm this may become difficult to accurately estimate the position of the occlusion scars. In such case it may be necessary to cross-cut at defects to reveal their actual sizes if a higher degree of precision is required. The size of the knotty core is determined by adding the diameter of stubs and diameter over occlusion.

2.4.2.2 Cross-sectional analysis

The cross-sectional analysis method by Somerville (1985) can be applied in the field. The system provides a detailed internal and external log description without the need for sawing a log in the longitudinal direction. In this method, a study log is cross-cut at all nodes and some internodes, and dimensions and locations of internal and external features are mapped according to a coordinate system. From this information an internal model of the log can be reconstructed.

2.4.2.3 Pruned log index (PLI) and pre-harvest quality assessment

The Pruned Log Index is a single measure of basic pruned sawlog quality and clearwood potential and is calculated from measures of log size, log shape and the size of the knotty core (Park, 1989). To establish the Pruned Log Index, a PLI survey is undertaken by felling a sample of trees and cutting open the pruned logs to measure the clearwood component. The number of trees sampled depends on the area of the pruned stand but is generally about 18. A similar method developed by the CSIR in South Africa is the pre-harvest quality assessment (PHQA) method (Wessels *et al.*, 2006). The PHQA is aimed at calculating the defect core of a pruned stand. It can also be used to evaluate the presence of other characteristics that affect quality. With the PHQA method the diameter, sweep and defect core size along the length of a sample tree is measured. Sawmill simulation software was used to produce clear board recovery curves for different log and defect core sizes and sweep levels. Each measured log is then graded according to its clear board recovery potential.

2.4.2.4 Equations

From analysis carried out on the results from sawing a wide range of swept, 5.5m pruned radiata pine (*Pinus radiata* D. Don) butt logs, Gosnell (1987) developed equations to predict diameter over occlusion (DOO), log defect core size, and partial defect core size. Predictions of DOO were based on either diameter over stubs (DOS) or DOS and maximum branch size. For radiata pine, DOO can be predicted from DOS measurements as all branches occlude at approximately the same time. Log and partial defect cores were derived by adding an allowance validated with independent data and found to give adequate precision for a range of silvicultural regimes. For straight logs (4.9m and 5.5m long) Gosnell (1987) found an excellent linear relationship between DOS and the defect core (R^2=0.94).

2.4.2.5 Some non-destructive evaluation techniques

Ross *et al.* (1998) explain that, by definition, non-destructive materials evaluation is the science of identifying the physical and mechanical properties of a piece of material without altering its end-use capabilities and using this information to make decisions regarding appropriate applications. Such evaluations rely upon non-destructive testing (NDT) technologies to provide accurate information pertaining to the properties, performance, or condition of the material in question.

Non-destructive evaluation (NDE) of the properties of wood aims to promote the efficient use of wood and has its origin in the need to solve practical problems without destruction of the integrity of the object under review (Bucur, 2003). The development of NDE techniques has as its principal purpose the reduction of uncertainty regarding the characteristics of wood products as influenced by wood's biological nature. Non-destructive testing, according to Resch (2005), is needed as an integral part of manufacturing for optimization of volume and quality output from each tree.

Historically, the wood products community has used non-destructive evaluation (NDE) techniques almost exclusively for sorting or grading of structural products (Ross *et al.*, 1997).

Evaluation of the quality of standing trees in plantations can be performed by acoustic non-destructive methods involving impact stress waves or ultrasonic waves (Pellerin and Ross, 2002). These methods are an invaluable tool, as they can be used to assess important mechanical properties of wood prior to processing. As non-destructive evaluation (NDE) techniques have evolved the emphasis has shifted from product assessment and quality control to the evaluation of logs and standing trees, e.g. by measuring the 'time of flight' of an acoustic stress wave in a column of the outer wood of a tree (Auty and Achim, 2008). This provides information that can help make economic and environmental management decisions on treatments for individual trees and forest stands, improve thinning and harvesting operations, and efficiently allocate timber resources for optimal utilization. For example, the information could be used to sort and grade trees and logs according to their suitability for structural applications and for a range of fibre properties of interest to paper makers.

NDE includes both non-destructive and quasi-destructive techniques, and is often done in conjunction with destructive tests for data verification (Wang, Ross *et al.*, 2000)

Visual assessment is probably one of the most widely used non-destructive techniques in the forest products industry (Ross *et al.*, 1998). Traditionally, trees have been chosen for harvesting, based on a visual assessment of tree quality attributes such as diameter, height, observable defects and on stand characteristics such as age, species composition and management objectives.

In visual grading, assessment of wood quality is based on the size and distribution of anomalies that can be seen on the surface (Falk *et al.*, 1990). Stem form is one of the most important external quality parameters, often used as log assortment criterion (Tong and Zhang, 2008). Inferior stem form, such as larger taper, sweep, and crookedness is usually related to low lumber recovery, poor mechanical properties, and high processing cost.

2.4.2.6 Internal modelling

Several modelling systems are used to study wood product recovery from an existing or simulated resource. These modelling systems that are used in resource evaluation may have different principles, and they may have been developed for different coniferous species but they all provide a means of establishing a connection between product requirements and raw material properties (Barbour and Kellogg, 1990; Briggs and Fight, 1992; Moberg 2000, 2006). The description of stem geometry and internal defects, providing the raw material input into the system, can either be supplied directly through empirical data, or generated through individual tree growth and defect-description models (Seifert, 2003).

The recent development of measuring and computing technology has vastly improved the possibilities of predicting timber quality from the raw material (Mäkelä, 2003). One drawback of using scanning is that, though the process does not result in destruction of the log, it deals with felled logs and not standing trees. This means that scanning can only support decisions after harvesting of the trees. One cannot, for instance, use this method to help decide which compartments to harvest for required end-product properties.

2.4.2.7 Internal log scanning

There are several methods available for scanning internal defects of logs. Han and Birkeland (1992) cite among others scanning by X-rays, gamma rays, infrared rays, microwaves, nuclear magnetic resonance (NMR) and ultrasound. X-ray computed tomography has been the most successful and is the most used technique for imaging inner properties of logs (Oja *et al.*, 2003; Rinnhofer *et al.*, 2003: Seifert *et al.*, 2010).

All the scanning methods have certain advantages and disadvantages. One drawback of using scanning is that, though the process does not result in destruction of the log, it deals with felled logs and not standing trees. For this reason, logs that do not meet end-product requirements can lead to excessive wastage. Ross *et al.* (1997) state that apart from being costly, scanning currently has limited application due to the low operational speeds.

3 Materials and Methods

The objective of this study was to investigate the possibility to develop a method that would be capable of predicting knotty core sizes along the pruned section of standing trees, by combining ring width information determined at breast height and available information on the pruning history (pruning height and ages of pruning). Disc samples, taken as part of another study, was used to carry out the ring width measurements, but it is envisaged that this can be done just as effectively and non-destructively by extracting increment cores at breast height from standing trees.

3.1 Study material

The compartments from which sample material was obtained are located on the Mpumalanga escarpment. This region falls within the summer rainfall area of South Africa. The mean annual rainfall on the selected compartments ranges from 840 mm to 1299 mm and is distributed from October to April. The mean annual temperatures for the compartments vary between 13.7^{o}C and 19.4^{o}C.

The study is based on 170 stems sampled from 17 *Pinus patula* compartments. The compartments (shown in Table 3.1) were chosen to represent the growth condition variability in the study area. These sample plots represented part of 31 sample plots originally chosen to study the influence of site factors on nitrogen mineralization in forest soils of the Mpumalanga escarpment area in South Africa. A detailed description of the study area and how the plots for sampling were selected are given in Louw and Scholes (2002). At the time of sampling, tree age among the compartments varied from 16 to 20 years. The stands had a mean diameter of 31.6 cm. The mean height for all the trees was 21.2m. The site index at base year 20 ranged from 17.9 to 29.6. All trees were pruned up to a height of 5m and most up to 7m. Because of differences in timing of pruning, numbers of stems pruned, number of pruning lifts, final pruning heights, the timing and numbers of thinning, and final crop stockings, large variation in pruned log quality is expected among the stands.

Table 3.1 Diameter and height measurements of trees in sample stands

Site ID	Plantation	Compt	Planted	Diameter (Breast Height) (cm)				Tree Height (m)			
				Mean	STDev	Min	Max	Mean	STDev	Min	Max
F	Uitsoek	E55a	1989	32.3	3.62	25	36	20.08	1.06	18.5	21.3
J	Berlin	E15a	1989	37.4	4.45	29	45	23.75	1.44	21.9	26.5
L	Blyde	C22	1989	34.0	5.51	24	42	27.01	2.79	21.8	29.7
I	Berlin	E5	1989	36.5	4.79	28	43	23.77	1.64	20.4	25.5
B	Nelshoogte	E28a	1990	33.8	3.23	27	38	21.94	0.88	20.3	22.7
G	Uitsoek	E36c	1990	31.9	4.88	24	41	22.98	1.92	20.3	26.4
N	Morgenzon	D74	1990	26.9	4.20	18	32	16.39	1.26	14.1	17.9
P	Wilgeboom	D11	1990	29.4	5.06	22	39	22.78	1.37	20.0	25.0
R	Wilgeboom	J20	1990	33.4	4.58	24	41	22.78	1.33	22.3	25.7
A	Nelshoogte	E66	1991	36.0	4.66	27	44	20.92	1.04	19.4	22.8
M	Morgenzon	E3	1991	31.4	4.06	24	37	20.57	1.54	18.2	22.3
D	Uitsoek	D1	1992	32.7	4.94	25	42	22.33	1.84	19.5	24.6
E	Uitsoek	D88	1992	30.2	3.88	27	37	18.37	1.52	16.2	19.9
H	Uitsoek	E22a	1992	27.6	3.53	21	33	22.24	1.70	18.5	33
O	Morgenzon	A1a	1992	27.8	5.02	17	34	19.01	1.43	16.8	21.2
C	Nelshoogte	G21	1993	26.2	4.36	21	36	18.41	1.32	16.8	21.5
K	Berlin	E35	1993	29.1	4.98	21	37	17.97	1.04	16.3	20
Mean				**31.6**	**4.5**	**23.8**	**38.6**	**21.25**	**1.48**	**18.8**	**23.8**

3.2 Research methods

3.2.1 Field sampling

3.2.1.1 Sampling strategy

Sample trees were chosen using stratified sampling. This is the most commonly used probability sampling method and it is superior to straightforward random sampling as it reduces sampling error. In stratified sampling (Köhl *et al.,* 2006; Kangas and Maltamo, 2007), certain auxiliary information is used to stratify the population into homogeneous groups or strata. In an ideal scenario, a single sample from each stratum would be suffice to gain complete knowledge about the population parameter of interest since there is no within-stratum variance as all elements or units would have the same attribute value (Köhl *et al.,* 2006).

There are several potential benefits to stratified sampling (Pedhazur and Schmelkin 1991; Köhl *et al.,* 2006). One such benefit is that dividing the population into distinct, independent strata can enable researchers to draw inferences about specific subgroups that may be lost in a more generalised random sample.

A second benefit is that utilising a stratified sampling method can lead to more efficient statistical estimates (provided that strata are selected based upon relevance to the criterion in question, instead of availability of the samples). It is important to note that even if a stratified sampling approach does not lead to increased statistical efficiency such a tactic will not result in less efficiency than would simple random sampling, provided that each stratum is proportional to the group's size in the population.

Thirdly, sometimes data for individual, pre-existing strata within a population are more readily available than for the overall population. In such cases, using a stratified sampling approach may be more convenient than aggregating data across groups.

Finally, different sampling approaches can be applied to different strata, since each stratum is treated as an independent population. This enables researchers to use the approach best suited (or most cost-effective) for each identified subgroup within the population.

There are, however, some potential drawbacks to using stratified sampling. First, identifying strata and implementing such an approach can increase the cost and complexity of sample selection, as well as leading to increased complexity of population estimates. Second, when examining multiple criteria, stratifying variables may be related to some, but not to others, further complicating the design, and reducing the utility of the strata. Finally, in some cases (such as designs with a large number of strata, or those with a specified minimum sample size per group), stratified sampling can require a larger sample than would other methods (although in most cases, the required sample size would be no larger than would be required for simple random sampling (Pedhazur and Schmelkin, 1991).

3.2.1.2 Sampling procedure

Sample trees were selected to represent the utilisable timber volume available from the compartments in terms of tree diameters. The diameter at breast height (dbh), i.e. at a height of 1.3m from the ground, of 100 trees in a circular plot on the study site was measured and recorded. The circular plot was situated at the place where soil data for the site was collected (the soil data was used in a different study). The tree diameters were then sorted in ascending order and the quartile values determined. One tree (small diameter) was selected from the first quartile, two trees from the second quartile, three from the third quartile, and four large diameter trees from the fourth quartile. More trees were selected from the quartile with the larger diameter trees because large trees contribute more to total volume than small ones. This resulted in a total of 10 trees per compartment that had to be felled. The sample trees came from within the circular plot described above.

3.2.1.3 Sample disc collection

After felling a tree, the trunk was de-limbed. Points at which cross-cutting was to be done were marked, after which the height of the tree and height to first branch whorl were measured. For purposes of this study, the first sawlog, measuring 2.1m, was removed from the pruned section of the tree for use in the sawing study (Fig.

3.1). Disc samples were taken at breast height, at 6m and at 11m above ground level. The choice of sample disc heights was based on representing equal volume sections of the useable section of the trunk. The useable volume of an average *P. patula* tree trunk aged 17 years and with a DBH of 29.2cm was calculated using the Max and Burkhart taper function (Bredenkamp, 2000). If the trunk was divided into three logs of equal volume, the sample discs would roughly be at the centre of each log. The bottom disc had to be shifted a little lower, however, to fit in with samples from other studies.

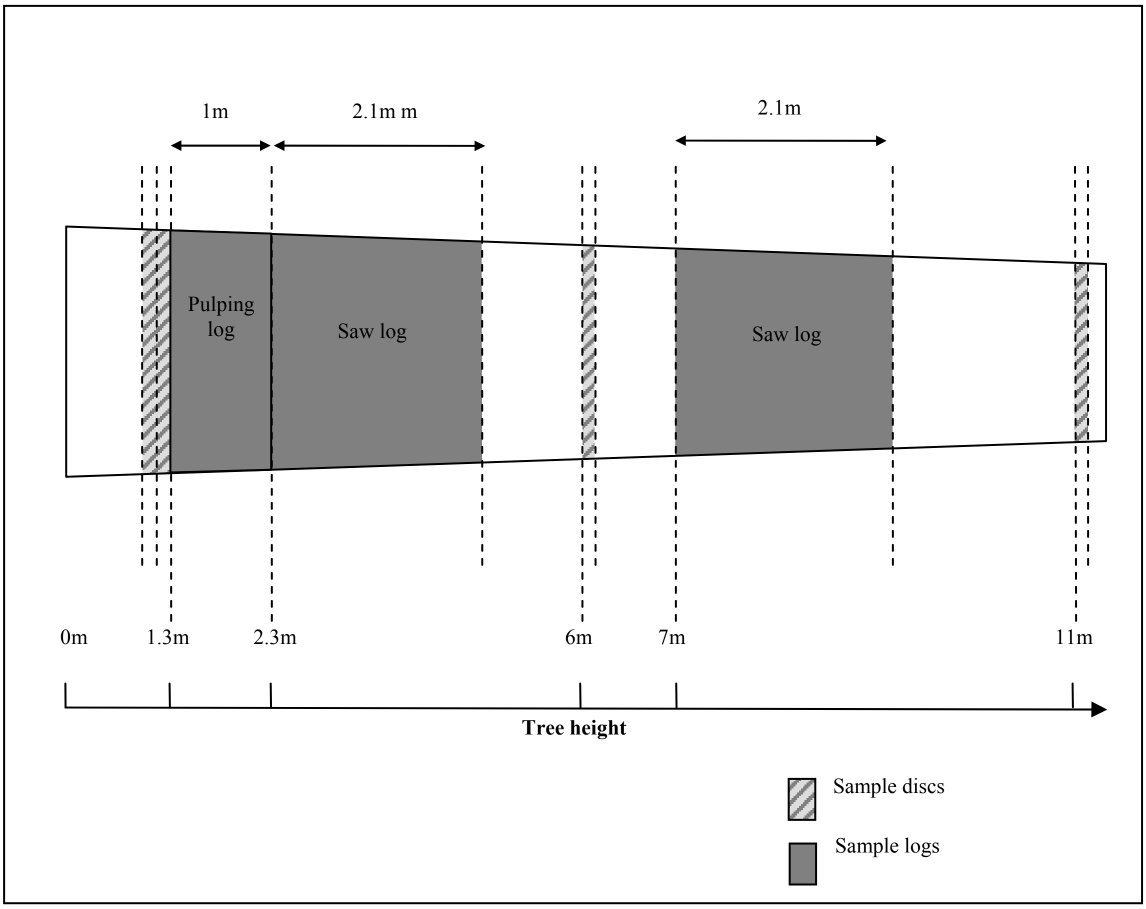

Figure 3.1 Samples removed from each tree stem. Discs taken at 1.3 and 6 m were used in this study.

The compartment, tree and height from which the discs were obtained were marked with a lumber crayon on each disc for ease of identification.

3.2.2 Ring width measurement methods

3.2.2.1 Disc preparation

Prior to transportation to Stellenbosch, the discs were air-dried at ambient temperature for several months to a target moisture content below 15%. Proper surface preparation of the stem cross section disc was essential to ensure high quality output digital images. As stated by Soille and Misson (2001), the better the quality of an input digital image, the simpler and more reliable is the image processing operation. Once dry, one surface on each of the discs (170 from breast height and 170 from 6.0m height) was sanded with a belt sander to a smooth, clear surface, by applying successively finer grit sizes, i.e. 80, 100 and 120.

3.2.2.2 Ring width measurement

A preliminary study, using discs from three randomly selected compartments (C, L and M), was undertaken to determine whether to use four or two radii per disc for the tree ring analysis. In practice this is the difference between using 2 or 4 increment cores per tree. It was assumed that two radii will be the minimum number to use in order to cancel the effect of pith eccentricity. Only the breast height discs (30 in all) from these 3 compartments were used.

Only half a disc from each tree was available for this study – the other half was used in a different study. After sanding, four tracks (radii) were drawn across the image on the sanded surface (Fig. 3.2). The lengths of all radii were measured using a calliper and recorded. Each radius was scanned as shown in Fig 3.3 using an HP ScanJet document scanner at a spatial resolution of 300 dots per inch (dpi) and the image saved in JPEG format. Ring widths were measured from the digital images of wood surfaces using an image analysis program, ImageJ. The recorded length of each radius was used to calibrate *ImageJ*. In *ImageJ*, the known (measured) distance was used as input together with the units of measure (pixels). Measurements of each annual radial increment (ring width) were recorded using these pixel units. The measurement started with the outer-most ring, i.e. the last ring to be formed by the tree and ended with the first ring at the pith. Ring width was expressed as the distance between successive boundaries. After measuring the last ring, all measurements for that radius were saved in MS Excel. The sum total of the ring width measurements were used to verify the accuracy of the measurements, by comparing it with the total radius length. When serious discrepancies occurred, the section (radius) was re-measured. Using MS Excel, the average ring width for all the four radii and the average ring width for the first and last (opposite) radius for all the test sample discs were determined. A typical output of the ring width measurements is shown in Table 3.2.

Figure 3.2 Sanded disc with 4 radii

Figure 3.3 Scanned portion of the disc surface with line for ring width measurement

Table 3.2 Ring width measurements for disc from tree 1, Compartment C[1]

Compt	Tree	Disc	Ring	Rad_1	Rad_2	Rad_3	Rad_4	Avg (all)	Avg (1&4)
C	1	1	1	5.8	5.5	6.2	6.5	6.0	6.2
C	1	1	2	3.8	3.6	4.2	3.2	3.7	3.5
C	1	1	3	6.2	6.7	6.2	6.7	6.5	6.4
C	1	1	4	6.5	7.4	6.9	8.6	7.3	7.4
C	1	1	5	8.2	8.6	9.3	9.1	8.8	8.6
C	1	1	6	5.8	5.5	5.5	7.6	6.1	6.8
C	1	1	7	6.8	7.9	6.6	9.2	7.6	8.1
C	1	1	8	10.8	12.9	11.5	17.7	13.2	14.2
C	1	1	9	11.4	12.0	12.4	13.7	12.4	12.6
C	1	1	10	9.2	12.3	8.2	12.9	10.6	11.1
C	1	1	11	18.9	21.5	18.2	20.4	19.8	19.6
C	1	1	12	19.6	21.8	18.2	20.2	19.9	19.9
C	1	1	13	20.7	20.1	18.8	20.9	20.1	20.8
C	1	1	14	7.7	7.6	6.6	6.5	7.1	7.1

The same sanding and measurement process was followed for the two discs per tree, i.e. one from breast height and one from 6.0m. In total 340 discs were prepared and ring widths measured. Ring width measurements from breast height (1.3m) and 6.0m were used to determine the relationship between growth at these heights.

3.2.2.3 Data analysis and modelling

The knotty core structure of the pruned section of each tree was estimated using the ring width data and pruning records. The actual mean ring widths from the discs at 1.3m and 6m were used for reconstruction of a tree's ring structure. Figure 3.5 shows an example of the modelled knotty core of a pruned tree. Ring width measurements at 1.3m and 6m will give both the width of each year ring at a specific height as well as the gradient of each ring relative to the pith. For year rings where only one measurement at 1.3m was available (e.g. rings 1 to 7 in Figure 3.5), the ring width was kept constant until it reached the pith. When the pruning age and height for each pruning lift is known, it is a simple procedure of drawing a line along the year-ring where pruning occurred up to the pruning height to determine the exact radial distance where the knotty core will stop along the length of the log. The sample tree in Figure 3.5 was pruned at 4 years to 1.5m height, at 7 years to 3m height, at 9 years to 5m height and at 12 years to 7m height. Excel spreadsheets and simple trigonometric calculations were used to calculate the knotty core sizes along the length of a log.

[1] These are not official compartment numbers but IDs allocated to each sampling site for simplicity reasons.

For purposes of analysis each pruned section of a tree was separated into three logs: A bottom log from 0 – 2.4m, a middle log from 2.4 – 4.8m and a top log of 4.8 – 7m. For each log the maximum knotty core diameter was calculated as an absolute value as well as a percentage of the small-end diameter of the log.

It should be emphasized that nodal swelling, branch protrusion after pruning and the occlusion scar were not considered in this study. For the model described above it is assumed that the knotty core stops at the year-ring where pruning occurred.

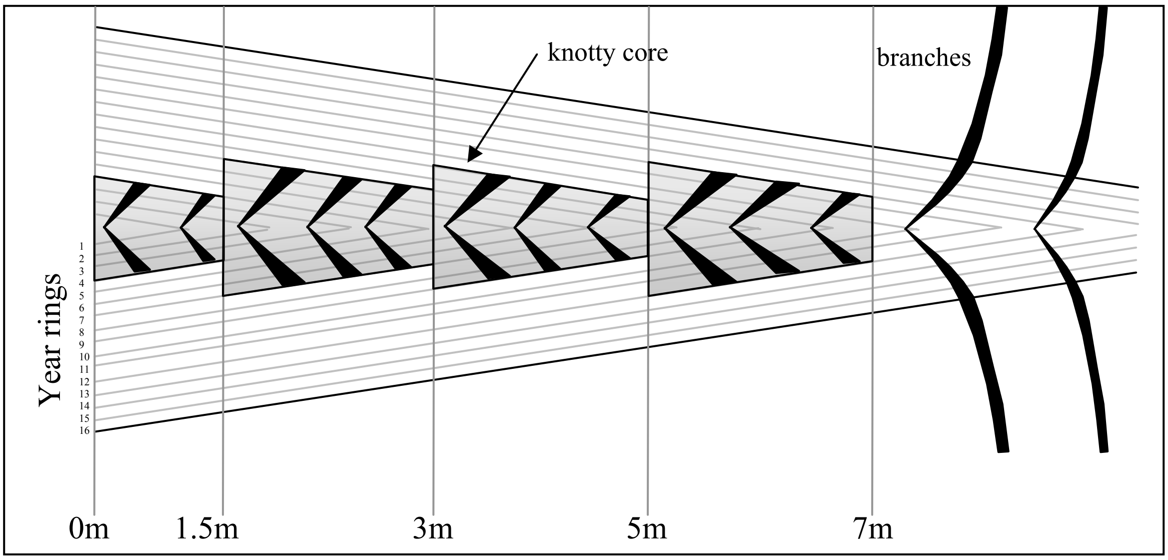

Figure 3.4 Knotty core reconstruction using ring width data and pruning records

3.3 Sawmill processing

To validate the results of the ring width method (explained in section 3.2.2.2) for determining knotty core size, a method similar to the one proposed by Park and Leman (1983) was used. According to this method, details of the knotty core are recorded by "reconstructing" logs from their sawn produce.

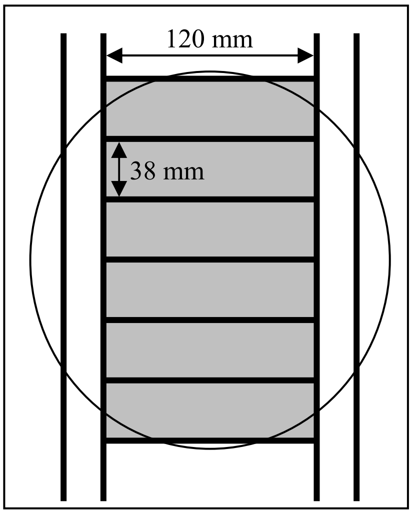

Figure 3.5 The centre boards from cant sawing

After obtaining a disc from breast height, a 2.1m sawlog was cut from the pruned section of each stem (Fig. 3.1). Prior to sawing, each log was marked with a log end template similar to the method described by Smith *et al.* (2003). Sheets of A3 paper with the log number printed all over the sheet were glued to the one end of a log, using PVA glue. The logs were then processed using a cant sawing pattern (see Figure 3.5). Both primary and secondary breakdown were achieved using frame saws. The sawing pattern for each log was such that the location of each board within the log could be traced to its relative position within the cross-section of the log. Each piece of timber produced was assigned a unique identification number associating it with the log from which it was sawn and its location within the log. Each log was turned in a way that resulted in a vertical plane of curvature before entering the head-rig (primary breakdown saw). The log was centred and some boards were then removed from the sides by the primary breakdown saw. A cant with a wet thickness of 120 mm remained. The cant was then centred and broken down using a secondary breakdown saw into boards with a wet thickness of 40 mm. The secondary breakdown saw was fitted with a curve-sawing device so that the boards could be cut more or less parallel to the pith. All the boards were marked on the wide faces with a log number. Only the boards produced from the cant were used in this study. The timber was then kiln-dried to a target moisture content of 15%.

One board from a pruned log from each compartment was selected for use in our experiment to compare with results of knotty core determination using ring width measurements – 17 logs and boards in total. The fairly low sample number resulted from problems experienced during the processing of the boards. In the sawmilling process boards with large pieces of wane are discarded. That resulted in many smaller logs from compartments where the knotty cores were relatively large not producing a board where an occluded knot was visible since these boards had wane on. Additionally, roughly one in five boards was lost by the sawmill after the sawmilling and drying process was completed. When a cant is missing a board or more than one board it was difficult to reconstruct it and measure the knotty core with a relatively high degree of accuracy.

Each of the sampled boards contained occluded branch stubs. The exact height in the tree where each knot occurred was recorded and the knotty radius where pruning occurred was calculated. Distance from the pith to the longest branch stubs and occlusion on either side of the pith was used to estimate the size of the knotty core. Pith eccentricity was not very pronounced, and was, for purposes of this study, ignored. Radial shrinkage during drying (at 3%) as well as the saw blade kerf (4mm) was accounted for in the calculation.

It was also attempted to link a year-ring number to the pruned branch stub and compare it with the pruning record – to confirm whether the pruning record was accurate. This proved to be impossible and the year-ring numbers obtained did not relate well with the pruning record. The reason for this is probably that the branch stub length and the nodal swelling added to the radial position of the knotty core. When the year-rings at the board-ends are inspected (where nodal swelling and branch stub length cannot be quantified) one then select a year-ring that is probably much older than that of the actual year of pruning.

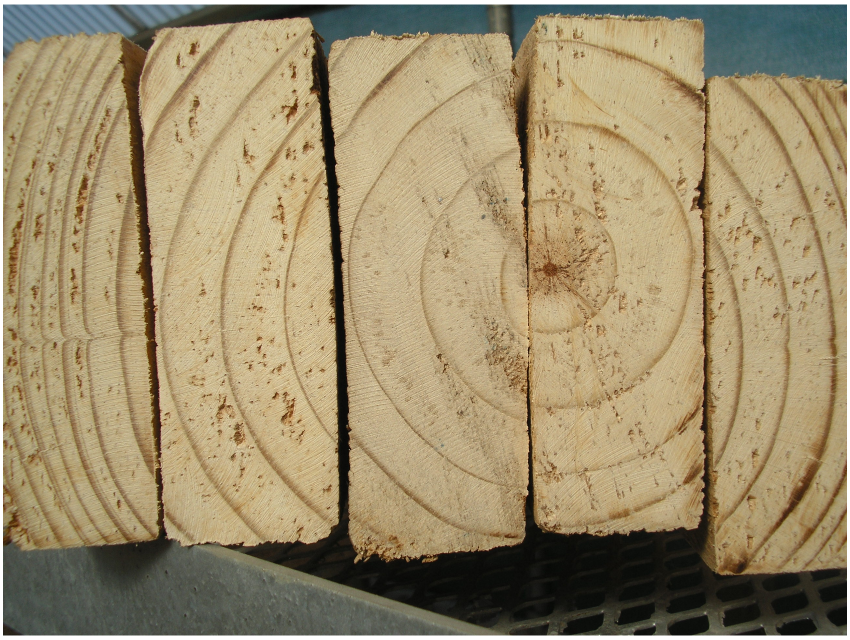

Figure 3.6 End-view of "reconstructed" log

3.3.1.1. Effect of knotty core on grade/value and processing decisions

The knotty core diameters were used to predict the product grades to be expected from logs of varying knotty percentages. The results from the knotty core modelling were used as inputs for SIMSAW, a sawmill simulation software which uses a stochastic method to link log quality with product grades. In this way many different processing options may be analysed without doing a sawmilling trial for each.

I. Simulation trial to evaluate cross-cutting decisions

In order to determine the effect of cross-cutting decisions on value recovery when knotty core data is available, two scenarios were simulated. The ten sample trees from compartment O were used for the simulation since compartment O had fairly large within-tree differences in estimated knotty core sizes. In the first scenario the pruned section of a tree was kept as a single log of 6.6m and the sawing simulator Simsaw6R was used to determine value and grade recoveries. In the second scenario each pruned section was cut into two logs: a 2.4m bottom log and a 4.2m second log and value and grade recovery were determined. The following inputs and assumptions were made (also see Appendix 2 for Simsaw6R report which lists the input values used):

- It was assumed that trees will be harvested at about 28 years of age and the growth was predicted using the yield table for *P. patula* from the South African Forestry Handbook (Kassier and Kotze, 2000, p178) for a medium SI site. In effect 46% was added to diameter growth for each tree;
- The knotty core sizes for each tree and log section as determined in this study were used and an additional 2cm was added to the knotty core diameter to account for the occlusion scar;

- The same sawing patterns and other processing variables were used as inputs to the simulation software for both scenarios. Only 38mm and 25mm thickness products were cut – 38mm in centre and 25mm on edges. Cant sizes were set to roughly 2/3 of the diameter for each log sorting class with cant widths of 120, 160, and 240mm;
- Logs were assumed to have sweep of 7mm/m and no ovality. The actual measured diameter and taper values were used;
- Log prices were kept constant since the same log inputs were used for both scenarios;
- The inputs to the stochastic grading method used by Simsaw 6R were as follows: If a 25mm or 38mm board contained no wood from the knotty core zone, it was graded as a clear board. If less than 50% of the volume of a 25mm thickness board contained wood from the knotty core, then there was an 80% probability that the board will be an industrial grade, and 20% chance that it will be crating grade. If more than 50% of a 25mm thickness board came from the knotty core, then there is a 50% probability that the board will be an industrial grade, and 50% chance that it will be crating grade. If less than 50% of the volume of a 38mm thickness board comes from the knotty core, then there is a 90% probability that the board will be an S5 grade, and 10% chance that it will be XXX grade. If more than 50% of a 38mm thickness board comes from the knotty core, then there is an 70% probability that the board will be an S5 grade, and 30% chance that it will be XXX grade. These probabilities were predictions by the author – actual data was not available at the time of this study;
- Timber prices were obtained from the South African Lumber Index, August 2009 (Crickmay and Associates, 2009). Gauteng average prices per grade were used. Where a specific dimension's price was not available (i.e. 25x152mm) the price of the dimension closest to that (i.e. 25x114mm) was used.

Since Simsaw6R uses a stochastic process for board grading, two simulation runs using the same input variables might result in two different output values. In order to minimise the risk of getting outliers, the simulation run for each scenario was repeated 10 times and averages of the 10 runs were used for comparative purposes.

II. Between-compartment variation of knotty core sizes: Simulation trial to compare value and grade recoveries

Where there are large differences in knotty core sizes between different compartments, processing decisions can be based on this knowledge. Log allocation decisions might be influenced i.e. small defect core logs might be sent to veneer processors or sawmills which focus on recovery of furniture and clear grade timber. Production and harvest planning might be influenced i.e. when large orders for high quality timber (clear or furniture grades) exist, one might decide to harvest small knotty core compartments. In order to quantify the effect the knotty core differences might have on product and value recovery, a simulation trial was performed. Sawmill processing of pruned logs from two compartments with large differences in knotty core sizes was simulated. The bottom pruned logs of compartments M (small knotty core) and G (large knotty core) was used for the simulation. These compartments had very similar mean diameters. The same assumptions and input variables were used as for the previous cross-cutting simulation trial (see previous section) except for the following:

- Processing of a single pruned log of 5.4m was simulated for each of the ten sampled trees per compartment, the reason being that compartment M was only pruned up to 5.5m;
- A sweep of 32mm/m was assumed for all the logs.

3.4 Data analysis and hypothesis testing

The statistical methods used for data analysis and hypothesis testing were multiple regression and ANOVA.

3.4.1 Multiple regression

Multiple regression was used to predict cumulative growth prediction at 6m height from tree ring measurements at breast height. Certain tests of hypotheses about the model parameter are helpful in measuring the applicability of the resulting multiple regression model. The test for significance of the regression was used to determine if there was a linear relationship between the response variable y and a subset of the regressor variables $X_1, X_2, \ldots X_k$.

The following regression model was tested:

$$CumRad_{6.0m} = \alpha + \beta * CumRad_{1.3m} + c * CamAge_{1.3m} + d * SI10 \quad [1]$$

Where,

α = Constant;
$CumRad_{6.0m}$ = Cumulative growth in radius at 6.0m for a given cambial age (mm);
$CumRad_{1.3m}$ = Cumulative radial growth at breast height (mm);
CamAge = Cambial age, labelled from the pith outwards (years);
SI10 = Site Index at age base year 10 (m).

The two diagnostic factors examined were tolerance and the Variation Inflation Factor (VIF).

Possibility of multicollinearity was assessed by examining two collinearity diagnostic factors, tolerance and Variance Inflation Factor (VIF). Collinearity refers to a linear relationship between two explanatory variables. Multicollinearity is a statistical phenomenon in which two or more explanatory variables in a multiple regression model are highly correlated. Tolerance is a measure of collinearity reported by most statistical programs such as SPSS. The VIF measures the impact of collinearity among the variables in a regression model.

$$Tolerance = 1 - R^2 \quad [3]$$

VIF = 1/Tolerance [4]

A tolerance of less than 0.20 or 0.10 and/or a VIF of 5 or 10 and above indicates a multicollinearity problem (O'Brien, 2007)

When there is a problem of multicollinearity in the regression model, two or more of the explanatory variables are significantly alike, i.e. they correlate. It then becomes impossible to determine which of the variables accounts for variance in the dependent variable.

3.4.2 ANOVA

The significance of the differences in knotty core percentage among compartments was analysed using analysis of variance (ANOVA). ANOVA is a process of splitting the total variation of a set of experimental data into meaningful components that measure different sources of variation.

The purpose of analysis of variance is to test for significance of the different effects in the experiment by evaluating the contribution of each to the overall variance in the experiment. These quantities are known as mean sums of squares, and are compared to the natural variance or mean square error (abbreviated as MSE or s^2) by construction of an F-ratio for each. The last quantity is a pooled variance, meaning that all the data in the data set were used for its calculation. The validity of this estimate of the error variance would be affected in the case of heterogeneity of variance.

The F-ratio should be interpreted as a test for the null hypothesis that the means of two or more treatments do not differ from each other. Small p-values would lead to rejection of the null-hypothesis, and large p-values to its acceptance.

ANOVA was used to determine whether there is evidence of differences between the sample means.

4 Results and discussion

4.1 General observations on the year-ring measurement method

In this study discs were used for tree ring measurement. However, for standing trees increment cores will be the most likely method of sample extraction. Sample preparation methodology of increment cores for tree ring measurement is well developed and several books describe the methodology (i.e. Fritts, 1976; Schweingruber, 1983).

As long as boundaries between early- and latewood were clear, it was easy to carry out the measurements – and with the sample material this was mostly the case. As with any measurement procedure, there is a possibility of human error since tree ring width measurement depends on a personal judgement of the ring boundary.

The method of using a normal computer document scanner to scan discs and the use of an image analysis program, *ImageJ*, for ring width measurements, worked well. This methodology was tested for accuracy by Munalula (2008) and was found to be highly accurate provided the same operator performs the measurements.

The rings for most trees were easy to distinguish and date. Of the 340 discs there were few cases where measurements had to be corrected after cross-dating indicated missing or false rings.

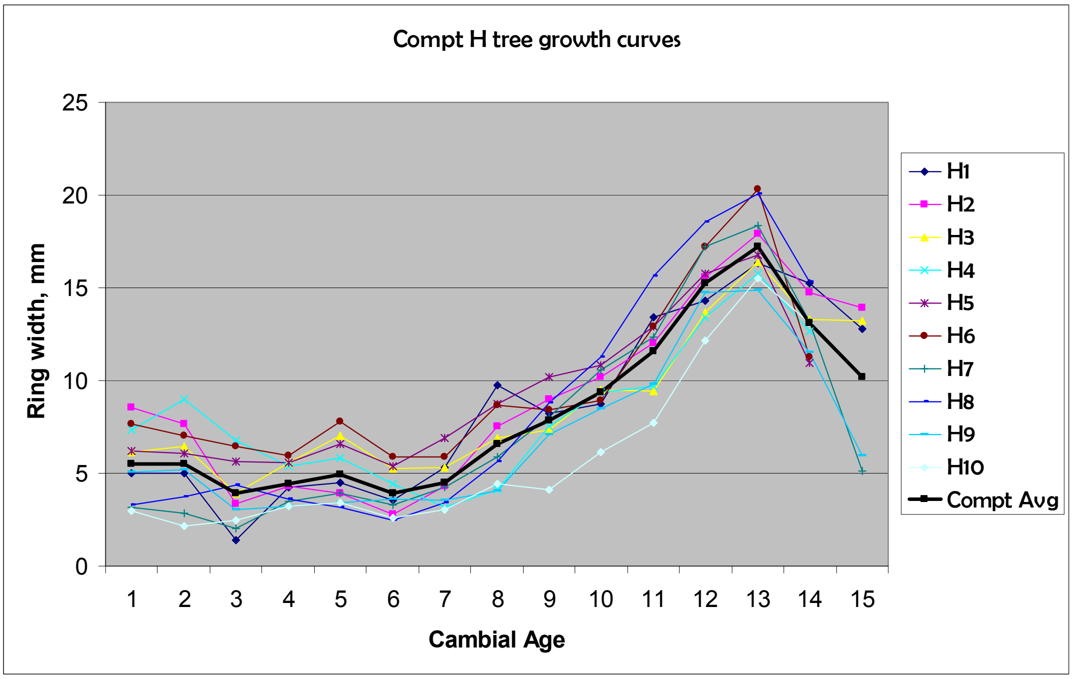

Figure 4.1 Example of graph used for cross-dating. The curves are for individual trees and the thick line is the compartment average.

Ring patterns were matched using signature years in the growth curves, such as the one for compartment H shown in Fig. 4.1. As stated by Grabner (2005), cross dating from ring widths is possible because tree growth is frequently affected by the yearly sequence of favourable and unfavourable climate (wet and dry, or warm and cold years), which is recorded by the sequence of wide and narrow rings in large numbers of trees. Through careful matching and comparison, it is easy to identify and correct problem rings. Fritts (1976) and Schweingruber (1983) explain that the matching is necessary to identify special cases where rings may be absent or where two or more apparent rings have been formed in a year. The average growth curve for each was used to check samples in which ring widths showed a marked departure from what was expected. For the example in Figure 4.1 the year rings 3, 5, 6 and 13 can be considered to be signature years since there is a change in gradient in those years. If any tree showed a gradient change before or after these signature years, it was checked for correctness.

4.2 Summary statistics for different compartments

Table 4.1 below shows the summary statistics regarding each compartment's age in years at felling, mean top height (m), mean diameter (cm), and site indices for base years 10 and 20.

Table 4.1 General data for each compartment

Site ID	PLANT	CO MPT	Age at felling (yrs)	Mean top height (m)	Mean Diameter (cm)	SI10	SI20
A	Nelshoogte	E66	17	21.7	36	14.3	23.9
B	Nelshoogte	E28a	19	22.5	33.8	14.5	23.17
C	Nelshoogte	G21	16	19.7	26.2	15.5	22.56
D	Uitsoek	D1	17	24.1	32.7	15.7	26.49
E	Uitsoek	D88	17	19.7	30.2	15.3	21.73
F	Uitsoek	E55a	20	20.9	32.3	14.6	20.9
G	Uitsoek	E36c	19	25.6	31.9	16.8	26.34
H	Uitsoek	E22	17	22.4	27.6	16.5	24.76
I	Berlin	E5	19	25.1	36.5	16.7	25.79
J	Berlin	E15	19	24.9	37.4	17.6	25.72
K	Berlin	E35	16	18.8	29.1	16.5	21.57
L	Blyde	C22	20	29.6	34	18.5	29.55
M	Morgenzon	E3	17	22.1	31.4	13.5	24.29
N	Morgenzon	D74	19	17.4	26.9	9.6	17.89
O	Morgenzon	A1a	16	20.4	27.8	13.6	23.31
P	Wilgeboom	D11	18	24.1	29.4	19.6	25.57
R	Wilgeboom	J20	19	25.4	33.4	16.8	26.13

4.3 Appropriate number of radii per cross-section to measure

Table 4.2 shows a summary of the results of the test carried out to assess whether the average mean ring widths for four and two radii measured on one disc are the same. The statistics indicate total number of rings measured (N), mean ring width (mm), standard deviation (mm), and standard error of mean (mm).

Table 4.2 Results when 2 radii are measured vs. 4 radii per disc

No. of radii measured	N	Mean ring Width (mm)	Standard Deviation (mm)	Standard Error of Means (mm)
2	439	8.242	4.671	0.223
4	439	8.214	4.720	0.225
Difference		0.029		

In order to save costs it would be preferable to keep the number of growth ring measurements needed to a minimum when predicting annual growth of a tree. The results of a t-test carried out to make an inference about the difference between average mean ring width values from four radii and average mean ring width values from two radii. The null hypothesis was that there is no significant difference among the means between those from two radii and those from four radii. The p-value found is greater than our chosen alpha level of 0.05 (Table 4.3).

Table 4.3 Computed t-test statistics (p=0.05)

t Statistic	DF	Prob>|t|
1.0403	438	0.299

The results therefore show that there is no evidence to infer that the means differ when two radii are used as opposed to when four are used. Because of this, all subsequent ring width measurements were based on measuring two radii per disc. In practice, using increment coring, it will mean that two increment cores are removed from opposite sides of the pith. It will also be advisable to avoid the maximum radius, in other words don’t extract on the leaning side of the tree.

4.4 Relationship between annual radial growth at breast height and at 6 m height level

Results of a comparison of growth at 1.3m and growth at 6.0m are presented in Table 4.4. From the table, it can be seen that there were, on average, about 13 rings available at 6 m height for assessment. These 13 rings were then compared in a “paired” fashion with the 13 inner rings at 1.3 m height, testing the significance of the difference by means of a paired-sample” t-test.

Table 4.4 Within-tree growth variability summary table

	N	Mean ring width (mm)	Standard Deviation (mm)	Standard Error of Means (mm)
1.3m-heigth discs	2198	7.7126	4.4367	0.0946
6.0m-height discs	2198	9.1668	4.6092	0.0983
Difference		-1.4542		

To make an inference about the difference between increment at 1.3m and 6.0m within the same tree, a paired-sample t-test was carried out at an alpha level of 0.05. For example, the outermost ring was measured at both 1.3m and at 6m on opposite sides of t he pith and the mean value for each height determined. These two values were then compared to determine whether they differed in a statistically significant manner. The same procedure was followed for all the other rings. The results are presented in Table 4.5.

Table 4.5 Pair-wise comparison of ring widths between 1.3m and 6m growth (p=0.05)

t Statistic	DF	Prob>|t|
-18.02	2197	7.58E-68

The t-test (Table 4.5) shows that the difference in the means was found to be statistically significant. This study proved that the amount of increment that occurs in a tree in a single year or growing season will differ at different heights in the tree. The increment at 6m can be either higher or lower compared to 1.3m due to within-tree differences in annual growth. This is an effect of individual competition. As explained by Kozlowski (1971) and Brown *et al.* (1979) the ring width must of necessity vary at different heights in any tree in order for the tree to retain its shape.

4.5 Growth prediction at 6m stem height using breast height increments

One objective was to predict diameter growth at 6m from growth at 1.3m since increment cores are only practical at breast height or lower. Figure 4.2 shows the results of a nonlinear regression analysis where the individual ring width at 6m height is predicted from individual ring width data at 1.3m height. A single tree from compartment A is used to illustrate the results.

It proved to be more viable to use the accumulated increment (radius) for the prediction. It provided higher degrees of determination and stabilised the functional correlation considerably. Figure 4.3 shows the relationship between the cumulative growth at 1.3m and 6 m heights of the same tree.

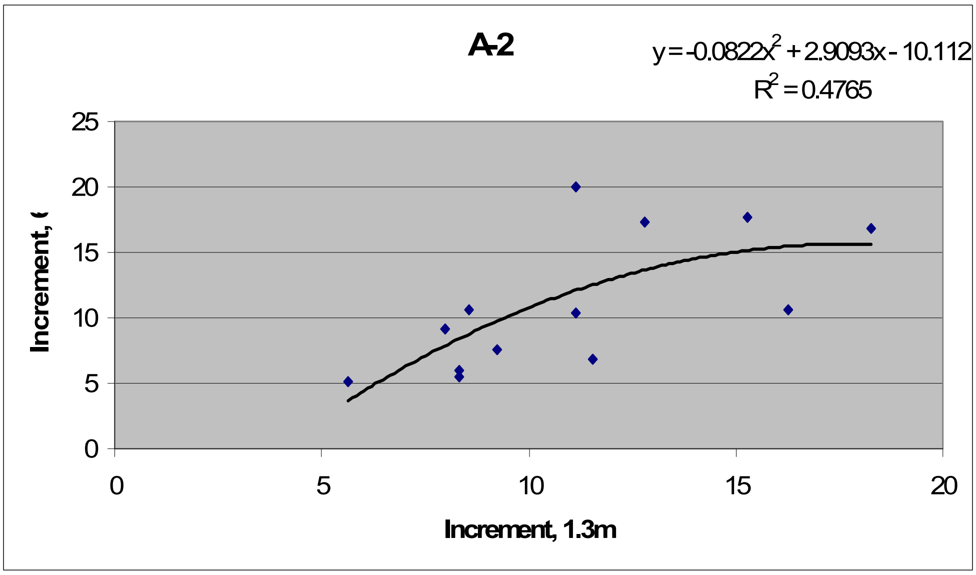

Figure 4.2 Example of the relationship between ring widths at breast height and ring width at 6 m height, and regression line that gave the best fit for tree A2.

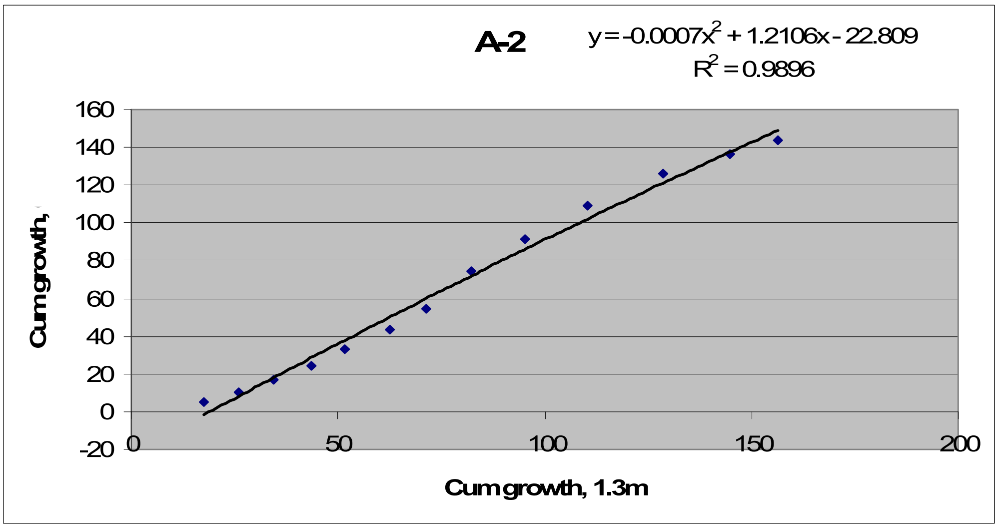

Figure 4.3 Relationship between accumulated growth at breast height and accumulated growth at 6 m height, and regression line that gave the best fit for tree A2.

Table 4.6 summarises the results of the multiple regression analysis carried out on all data to predict the cumulative radius growth at 6.0m (Cum Rad6.0m), as the dependent variable, using cambial age at 1.3m (CamAge1.3m), cumulative growth in radius at 1.3m (Cum Rad1.3m), and site index at 10 years (SI10) as the explanatory variables. The table shows the Pearson's correlation coefficient (R), which measures the degree of linear association between the dependent and explanatory variables, and the adjusted R^2, which indicates how well the model fits. A coefficient of determination adjusted for degrees of freedom and the standard error of estimate are also presented.

Table 4.6 Multiple regression model summary for predicting cumulative radius growth at 6m height[b]

R	R Squared	Adjusted R Square	Std. Error of the Estimate
0.980[a]	0.960	0.960	7.612860

a. Predictors: (Constant), SI10, CamAge1.3m, Cum Rad1.3m

b. Dependent Variable: Cum Rad6.0m

The regression analysis of variance is summarised in Table 4.7. The analysis of variance was done to split the total variation of the experimental data into a set of meaningful components that measure different sources of variation. The ANOVA table also shows F and p-values which are helpful in measuring the significance of the regression and the usefulness of the model.

Table 4.7 Analysis of Variance[b] ($p=0.05$)

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	3070164.858	3	1023388.286	17658.13	0.000[a]
Residual	126864.902	2189	57.956		
Total	3197029.761	2192			

a. Predictors: (Constant), SI10, CamAge1.3, Cum Rad1.3m

b. Dependent Variable: Cum Rad6.0m

Testing the hypotheses on the individual regression coefficients to determine the value of each of the regressor (independent) variables in the regression model produced results that are presented in Table 4.8.

Table 4.8 Regression model coefficients[a] ($p=0.05$)

Model	Unstandardised Coefficients		Standardised Coefficients		
	B	Std. Error	Beta	t	Sig.
(Constant)	-65.903	1.269		-51.917	0.000
Cum Rad1.3m	0.913	0.010	0.731	93.069	0.000
CamAge1.3	2.650	0.076	0.272	34.685	0.000
SI10	1.685	0.075	0.097	22.617	0.000

a. Dependent Variable: Cum Rad6.0m

The resultant regression model was:

$$CumRad_{6.0m}=-65.903+0.913*CumRad_{1.3m}+2.65*CamAge_{1.3m}+1.685*SI10 \quad [5]$$

Results of diagnostic tests carried out to assess multicollinearity, i.e. the possibility of the independent variables in the regression model being correlated with one another, are shown in Table 4.9.

Table 4.9 Coefficients for multicollinearity

Coefficients[a]

Model predictor variables	Collinearity Statistics	
	Tolerance	VIF
1 Cum Rad1.3m	0.294	3.400
CamAge1.3	0.295	3.389
SI10	0.994	1.006

Initially attempts were made to predict the increment of individual year rings at 6m from growth at 1.3m. This attempt did not provide satisfactory results. For example, a moderate (R^2=0.48) coefficient of determination was found when annual increment at 1.3m height was used to predict the annual increment at 6m height for an individual tree (see Figure 4.2 as an example for an individual tree). The next step was to use the cumulative growth at 1.3m instead of the individual growth per year to predict the cumulative growth at 6m. The results improved significantly (see Figure 4.3 where an R^2 value of 0.989 for an individual example tree was obtained). The reason for this improvement might be the fact that unusually high or low annual growth increments are less pronounced when cumulative growth is used. Finally, a multiple regression model was developed where the independent variables: cumulative growth in radius at 1.3m, cambial age at 1.3m and site $index_{10}$ were used to predict cumulative radius growth at 6m (Table 4.6).

To assess how well the model fits, the adjusted R^2 was used because it takes into account the sample size and the number of independent variables. The regression model had an R^2 value equal to 0.96 (Table 4.6). This value indicates that 96% of the total variation in cumulative growth at 6.0m can be explained by variation in all the three independent variables in the equation.

To test the significance of the fitted regression, an analysis of variance was carried out. Results showed that the regression was highly significant ($P<0.001$) (Table 4.6). A large value of F, such as the one that was obtained, indicates that a significant proportion of the variation in *y* is explained by the regression equation and that the model is valid. The p-value of the test confirms that there is evidence to infer that the model is valid. On the basis of the *F* and p-values, we can conclude that a strong linear relationship exists between the independent variable (growth at 6.0m) and the explanatory variables (cumulative radial growth at 1.3m, cambial age at 1.3m, and site index at year 10).

The regression coefficients in Table 4.7 indicate the value of each explanatory variable to the regression model. The p-values of the *t* tests for cumulative radius at 1.3m, cambial age at 1.3m and site index (SI) measured by height at 10 years are all below 0.00. The *F* test (Table 4.6) indicates that the complete model is valid. The adjusted coefficient of determination also tells us that the model's fit is good.

From results shown in Table 4.7, it follows that increase in cumulative radius at 1.3m, cumulative growth at 6.0m and cambial age (measured in years) at 1.3m will result in increase in tree growth at 6.0m. From the results, we learn that for each 1mm increase in cumulative radial growth at 1.3m, the tree will grow by 0.913 mm at 6.0m. For each year added to the cambial age at 1.3m, the tree grows by 2.65 mm at 6.0m. The relationship between growth at 1.3m and SI is expressed by β_3 = 1.685. For each 1 unit increase in site index, the tree grows by 1.685mm.

All the predictor variables have a significant effect on the growth prediction (see Table 4.7). Cumulative radial growth at 1.3m, cambial age at 1.3m and SI all contribute significantly to the model. The relationship between the dependent variable (growth at 6.0m) and the predictor variables (cumulative radial growth at 1.3m, cambial age at 1.3m and SI is illustrated by the mathematical model shown in equation [2]

The minimum calculated VIF in our regression model is 1.006 and the maximum 3.400 (Table 4.8). The lowest VIF is given by SI (1.006) and the highest by cumulative radial growth at 1.3m (3.389). The minimum tolerance is 0.294 and the maximum 0.994. When there is a problem of multicollinearity in the regression model, two or more of the explanatory variables are significantly alike. It then becomes impossible to determine which of the variables accounts for most of the? variance in the dependent variable. The results show that explanatory variables in the multiple regression model are not highly correlated.

From the results of the tests carried out on growth variability and growth prediction, it can be seen that though annual increment varies significantly with height, reliable predictions of cumulative growth at 6m can be made by using ring width measurements at breast height. One should be careful to use this model only in the age-range of the samples used for the study, which is 20 years. Given the fact that final pruning is usually finished by 20 years the age range should be sufficient for prediction of knotty core sizes of *P. patula* trees in South Africa.

4.6 Knotty core size variation

The average knotty core structure of each compartment is shown graphically in Appendix 3. Using percentages was preferred to the absolute knotty core size since it makes it possible to compare the pruned quality of different size trees. Results of the analysis of variation (ANOVA) in knotty core percentages of the 17 compartments are presented in Tables 4.10 to 4.12.

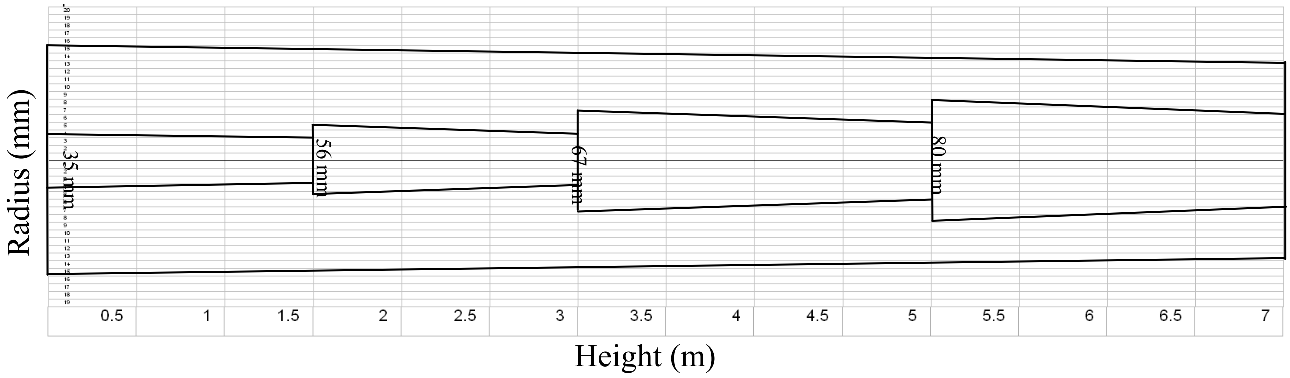

Figure 4.4 Example of pruned section with knotty cores for each pruning lift

Table 4.10 ANOVA results of the knotty core percentage variation among compartments for the 0-2.4m stem section.

Source of variation	DF	Sum of Squares (fraction)	Mean Square (fraction)	F	P-value
Intercept	1	40.37891	40.37891	8389.870	0.00
Compartment	16	1.92970	0.12061	25.059	0.00
Error	151	0.72674	0.00481		

Table 4.11 ANOVA results of the knotty core percentage variation among compartments for the 2.4-4.8m stem section

Source of variation	DF	SS	MS	F	p
Intercept	1	51.23911	51.23911	12579.39	0.00
Compartment	16	2.44074	0.15255	37.45	0.00
Error	151	0.61506	0.00407		

Table 4.12 ANOVA results of the knotty core as a percentage variation among compartments for the 4.8-7.0m

Source of variation	DF	SS	MS	F	p
Intercept	1	71.86040	71.86040	15476.90	0.00
Compartment	16	3.36512	0.21032	45.30	0.00
Error	151	0.70110	0.00464		

Table 4.13 ANOVA results of the maximum knotty core percentage among compartments for the full stem

Source of variation	DF	SS	MS	F	p
Intercept	1	60.93632	60.93632	17866.72	0.00
Compartment	16	1.97802	0.12363	36.25	0.00
Error	151	0.51500	0.00341		

Table 4.14 summarises the results of the test carried out to assess the differences between knotty core percentages at different heights.

Table 4.14 Summary statistics of the knotty core fractions at different stem sections for all the trees and compartments

Stem section	No.	Knotty core fraction Mean	Std Dev.	Std Error	Confidence Interval -95%	Confidence Interval +95%
0-2.4m	168	0.491066	0.126122	0.009731	0.471856	0.510277
2.4-4.8m	168	0.552922	0.135271	0.010436	0.532317	0.573526
4.8-7.0m	168	0.654253	0.156041	0.012039	0.630485	0.678021
0-7.0m	168	0.602924	0.122181	0.009426	0.584313	0.621534

The Shapiro Wilk test was used to test whether data was normally distributed. The knotty core percentages of the 4.8-7m section as well as the maximum knotty core percentage over the full stem were not normally distributed. Knotty core percentages of the 0-2.4m section and 2.4-4.8m section were normally distributed.

A graphical comparison of the 0-2.4m log section's knotty core (KC) percentages for each of the compartments with their confidence intervals is presented in Fig. 4.5

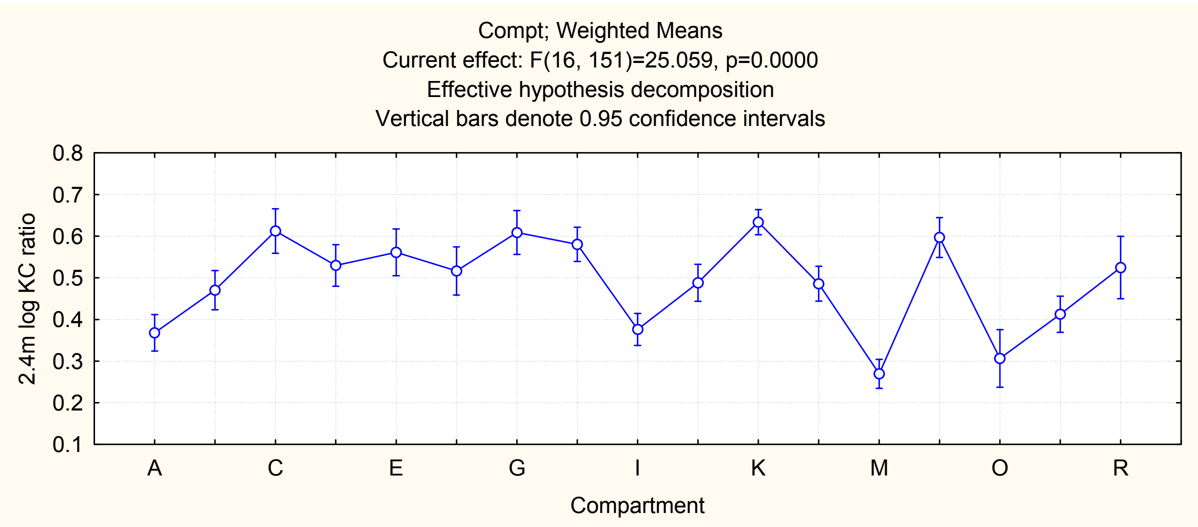

Figure 4.5 Weighted means of knotty core (KC) ratios for the 0-2.4m stem section of the different compartments

The bootstrap means for the maximum knotty core of all the compartments and stem sections are presented in Fig 4.6.

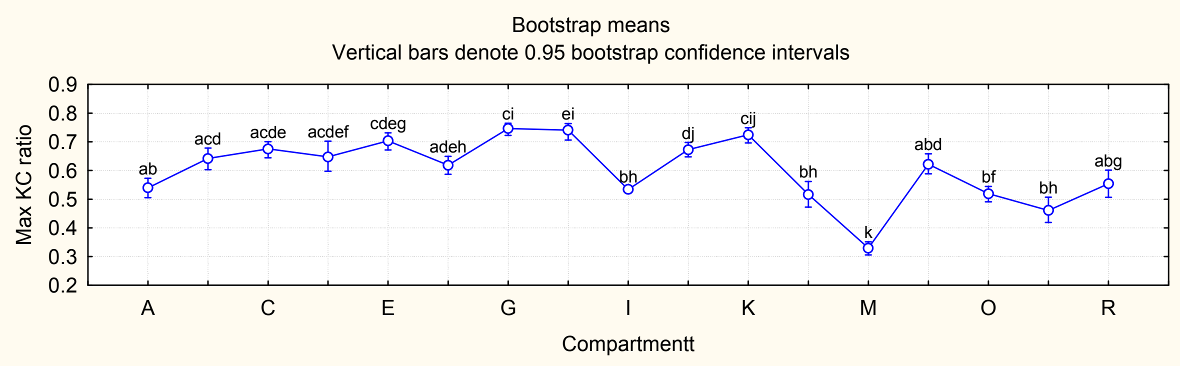

Figure 4.6 Graph showing Bootstrap means for maximum knotty core sizes among compartments

The ANOVA results in Table 4.10 for the "Max knotty core as percentage of diameter at breast height" show that the mean square for compartments (0.1236) is far larger than the mean square error (0.00341). The same trend is evident for the other two log sections (Tables 4.10-4.12). It is thus clear that differences in knotty core percentages are much larger between compartments than within compartments.

Both diameter after occlusion of the knotty core and pruning height influences the shape of the knotty core. The size of the knotty core is also dependent on the size of the branch collar (Seifert, 2003). The diameter of a branch/knot is correlated with the branch collar. The branch collar has to be occluded as well. Knotty core sizes were compared among three sections of a stem as shown in Fig. 4.3.

Results show that the maximum knotty core, expressed as a percentage of diameter of a log section, increased with increase in height. In the average butt log, i.e. the first 2.4m, 49.1% of the diameter is occupied by the knotty core (Table 4.14). For the 2.4-4.8m and 4.8-7m log sections, the knotty core takes up 55.2% and 65.4% of the diameter of the log respectively. From the 95% confidence intervals we can see that the means differ significantly between the different log sections. The mean maximum knotty core percentage over the full length of the pruned section of the stem is 60.2%.

4.7 Comparison of measured vs. calculated knotty core sizes

The method to calculate knotty core sizes from ring width data provided an internal model of knotty core sizes for each tree (Figure 4.4). The knotty core radius from one pruned knot in each log from each compartment was measured and compared to the value calculated from ring width measurements. Results of this comparison can be seen in Table 4.15 and Figure 4.7.

Table 4.15 Comparison of measured knotty core radius vs. calculated value

Compartment	Tree	Height to knot (m)	Measured radial distance from pith to knot (mm)	Calculated knotty core radius (mm)
A	9	3.44	117.4	80.2
B	5	2.89	105.7	65.1
C	9	2.78	54.0	39.8
D	4	2.39	104.6	64.5
E	7	2.5	83.0	68.3
F	9	2.66	73.5	43.8
G	1	3.8	141.1	116.1
H	9	3.03	97.3	74.0
I	8	2.53	101.9	54.8
J	10	2.8	101.9	66.9
K	6	2.43	86.0	72.4
L	3	3.72	91.7	84.6
M	3	2.85	65.1	18.1
N	6	2.61	98.5	92.0
O	8	2.94	86.8	33.1
P	6	2.56	63.4	36.4
R	3	2.6	95.6	47.2

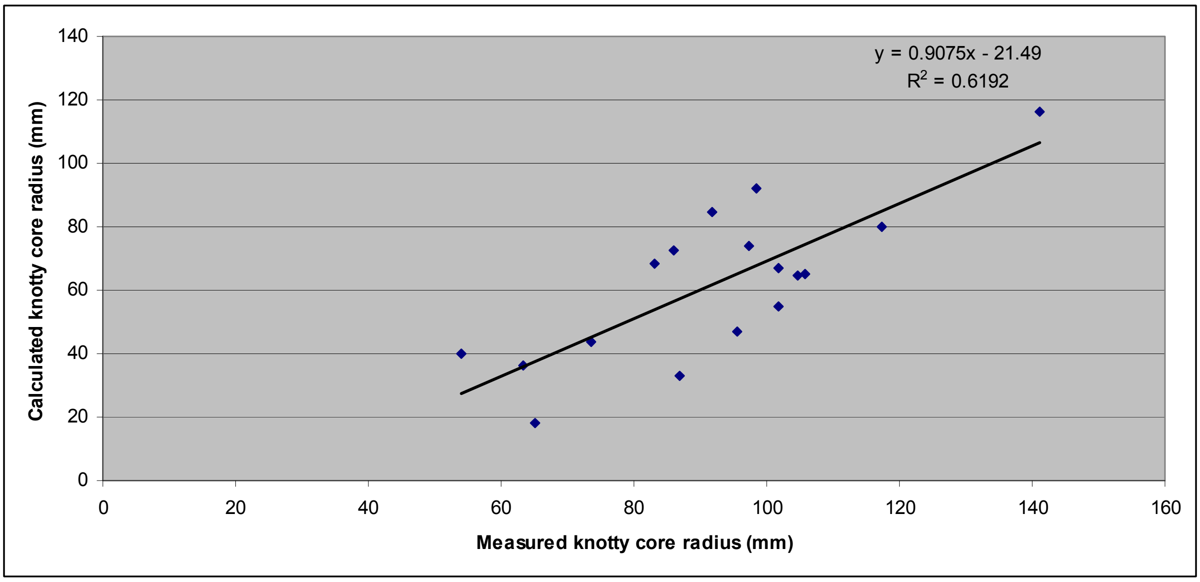

Figure 4.7. The relationship between the measured knotty core values vs. calculated values using ring widths and regression line.

A linear regression between measured knotty core values (*x*) and calculated knotty core values (*y*) provides the following relationship:

$$y = 0.9075x - 21.49$$

The coefficient of determination (R^2) for the regression line is 0.62. The relationship between the measured values and calculated values can only be described as moderate.

Variation in the size of the knotty cores of trees (excluding occlusion scar) from a single compartment will in most cases be due to variation in growth, variation in the nodal swelling, pith eccentricity and variation in the branch stub remaining after pruning. In this study only variation due to growth was considered. Additionally, if any plantation pruning records were inaccurate it will also result in errors in the knotty core model. It was, therefore, expected that a good relationship between measured and predicted values was not possible.

The method used to measure the radial distance of a pruned branch end from a reconstructed log also has some weaknesses. The variation in shrinkage during drying, exact depth of a branch stub in a board, eccentricity of the pith, and size variances of boards will cause errors in results. Cross-cutting of logs in the field on the pruning scars, and measuring knotty cores will probably be more accurate than the method employed here. This, however, is highly destructive and wasteful (which a forest manager obviously wouldn't like) and it has to be done on a representative sample of trees. At the time of harvesting, however, the difficulties associated with log reconstruction and knotty core measurements were not foreseen.

The knotty core models for the sample trees were based on actual measured growth increments at 1.3m and 6m. It is, therefore, obvious that variation in knotty core sizes due to growth variation in trees will be accounted for in the method developed here. When year-ring data at 6m is not available, the prediction of growth at 6m from growth at breast height can be performed fairly accurately (R^2 = 0.96, see Table 4.6). The moderate relationship between the measured knotty core sizes and predicted or modelled sizes is therefore probably a combination of the factors not considered in this study (nodal swelling, pith eccentricity, branch stub protrusion), inaccurate plantation records, and the weaknesses of the method of measuring knotty core sizes in sawn boards.

4.8 Application of knotty core information

In this section, results of some practical applications of variation in knotty core data that has been obtained on a compartment basis, are presented and discussed. The data obtained from the 17 sample compartments are used as an example to discuss the possible advantages of the non-destructive determination of knotty core sizes on a compartment basis.

4.8.1 Within-tree knotty core variation: Simulation trial to evaluate cross-cutting decisions

The results of the simulation trial, which compared two cross-cutting scenarios using knotty core data, can be seen in Table 4.16. In the first scenario the full bottom pruned log of 6.6m was processed without making any cross-cuts. In the second scenario the pruned section of each stem was cut into two logs of 2.4m and 4.2m respectively. For each scenario 10 simulation runs were completed. Table 4.16 shows the total value of products from each simulation run. All the input variables (i.e. product pricing, log pricing, sawmill variables) was kept constant for the comparison. Appendix 4 shows the Simsaw 6R inputs and results for one of the simulation runs.

Table 4.16 Simulation Results

Simsaw6R runs	Total value Scenario 1 (R)	Total value Scenario 2 (R)
1	8824.75	9138.35
2	8889.26	9187.75
3	8945.63	9063.9
4	8810.28	9110.09
5	8861.93	9166.55
6	8866.76	9199.37
7	8908.44	9088.61
8	8663.57	9153.77
9	8857.11	9120.01
10	8829.57	9125.56
Average	8845.73	9135.396

The fact that there are significant differences of knotty core percentages **within a tree** at different heights indicates that it might be worthwhile using data on within-tree knotty core variation in processing decision support. The compartment used for this scenario had relatively large within-tree variation of knotty core sizes. Because the knotty core size of the bottom 2.4m section of this tree was much smaller than the upper sections, the hypothesis was that more value can be created if this log was processed separately. The tree sizes were adjusted for estimated growth up to a harvesting age of 28 years.

The total product value created when processing the 10 logs of compartment O as single 6.6m logs was R8845.73 (this value is the average of 10 simulation runs). When the pruned part of the stem was cross-cut into 2 logs of 2.4m and 4.2m respectively, the total value created was R9135.40. The second scenario created a total product value of 3.3% higher than the first scenario. This fairly low additional value that was created, despite a significant rise in clear grade recovery, can be ascribed to two characteristics of the South African timber market that is dominated by structural products. Firstly, there are fairly large price differences between short and long structural products, so when a longer log is cross-cut into shorter logs one might get more high-value clear products, but at the same time the prices for structural products will drop because they are now short products. Secondly, the price difference between structural products and clear products is currently not very high (i.e. less than 30% for 38x114 products).

It should be mentioned that cross-cutting decisions are also influenced by market demand, sawmill capacity and extra costs associated with higher piece counts. The simulation trial showed that extra value can be created by cross-cutting and processing shorter logs with low knotty core sizes separately. However, the extra value created is fairly small using the current South African timber pricing structure where short structural products reach lower prices than long products and a small price differential exists between structural and clear products. Where veneer processing is an option, value differences might be more pronounced when the bottom log is used for veneer production in stead of sawn timber production.

4.8.2 Between-compartment variation of knotty core sizes: Simulation trial to compare value and grade recoveries

The results of the trial where value and grade recoveries of a compartment with a relatively small knotty core (Compartment M) and a compartment with a large knotty core (Compartment G) are compared can be seen in Table 4.17. The values for each compartment are the means of 10 simulation runs each. Value recovery is the product Rand value created for each cubic metre of round log processed.

Table 4.17 The mean simulated value and product grade recoveries from the pruned logs of compartments M (small knotty core) and G (large knotty core).

	Value recovery (R/m^3)	Product recovery per grade (%)				
		Clear grade	S5 grade	Industrial grade	XXX grade	Crating grade
Compartment M	1736	53.4%	42.6%		4.0%	
Compartment G	1621	26.9%	51.1%	6.5%	14.1%	1.5%

The data from the sampled compartments showed that there are large differences in knotty core percentages **between compartments**. For example, compartments M and G have similar mean diameters at breast height but have relatively large differences in maximum knotty core percentages. The recovery of the highest grade (clear grade) timber from compartment M is roughly double that of compartment G. The value recovery of compartment M is R116/m^3 or 7.1% higher than that of compartment G. This relatively low difference in value recovery is mainly due to the relatively small price difference between different quality grades in South Africa.

The results show large differences (±100% for clear grade) in product grade recoveries between the two compartments when all sawmilling variables were kept the same. Based on the results it is clear that information on the defect core can be an advantage when used for production planning purposes. If a sawmill has, for instance, orders for high grade products the compartments with small knotty core diameters can be identified for harvesting.

4.8.3 Use of knotty core information in processing decision support

Apart from the applications mentioned above, there are many other instances where knotty core data can be used to assist decision-making. Log allocation to different processing facilities is an example of where knotty core data can be used. For instance, pruned logs from compartment M (small knotty core) may be processed at a veneer mill or saw mill where clear wood can be extracted at a premium price. If logs from compartment M are sent to a sawmill, where the focus is on extraction of structural timber, the value recovery will be less.. Conversely, if logs of compartment G are sent to a processing facility where high value clear wood is required i.e. a slicing veneer operation, expensive processing time might be wasted on logs with very little potential for clear veneer recovery.

Although current SA market conditions do not result in very high differences in value recovery in a sawmill between compartments of different pruned quality, this might not be the case in the future. In such instances log pricing decisions can be based on knotty core information and forestry companies can be rewarded for well pruned logs.

The main advantage of knotty core data on a within-tree and between-compartment basis seems to be for planning purposes. Planning of marketing strategies, product forecasting, manufacturing facilities and manufacturing processes all depend to a greater or lesser extent on the pruned quality of the resource. For some processes like veneer production it can be very important, whereas for others like structural timber production it can be less important. The pruned quality of logs can be determined at least 13 years before harvesting using the method described in this study. Decisions on future processing strategies can be made with much greater confidence when one of the big factors causing uncertainty viz. the pruned quality of a log, has been determined.

It is important to mention that some of the underlying assumptions made for this simulation study have not been tested experimentally. Although it is fairly obvious that clear grade products will only be produced from the section of the log outside of the knotty core, not all these products might be clear grade due to other defects present. The exact grade recoveries used in the study from the knotty core sections in terms of structural (S5) and utility (XXX) grades were based on average SA sawmill grade recoveries and not only from pruned log grade recoveries. The type of data available from this simulation study can also be obtained, with much more effort but also with better confidence in the results, from sawmill trials. Future studies should include sawmill trials in order to get a better understanding of the relationship between simulation and actual results.

5 Conclusions

A method of using tree rings widths for evaluating the quality of the pruned section of standing *Pinus patula* compartments was developed and evaluated. The method worked well with this species, as year ring widths could be measured and dated without significant problems. The few cases of false or extra rings were easily identified using cross-dating techniques. The method of using a normal computer document scanner to scan discs and the use of an image analysis program, *ImageJ*, for ring width measurements, was efficient and accurate.

The results of the study indicated that when ring widths are measured at breast height it makes no difference whether 4 or 2 radii are used. It can thus be concluded that when sampling standing trees using increment cores, two increment cores opposite each other will be sufficient.

It was shown that cumulative growth at 6m height can be predicted using cumulative growth at breast height, site $index_{10}$, and cambial age at breast height as independent variables (R^2 = 0.96). Ring width measurements at breast height can, therefore, be used to predict growth in the upper pruned section which in turn can be used to reconstruct the internal knotty core through the full pruned section of the log.

Analysis of variation for the 17 compartments and 170 trees sampled, showed that there was far greater variation in knotty core percentages (the percentage of diameter occupied by knotty core) between different compartments than within compartments. Within a tree, the knotty core percentages between three stem sections, 0-2.4m, 2.4 – 4.8m, and 4.8-7m, differed significantly. The knotty core percentages were found to increase from the bottom section (49.1%) to the top section (65.4%).

A comparison of the knotty core sizes measured on reconstructed logs and the modelled knotty core sizes of a sub sample of trees showed only a modest relationship (R^2 = 0.62). Reasons for this might be variability in pruning quality, inaccurate pruning records, nodal swellings, and the methodology used to measure the actual knotty core sizes.

Knowledge of knotty core sizes can be used for different purposes. Two applications that were assessed and found to be useful include decision support for cross cutting logs and for sawmill production planning purposes. Sawmill simulation software was used to evaluate value and grade recoveries under different scenarios.

It can be concluded that the methodology proposed to reconstruct knotty cores from tree ring measurements at breast height has the potential to be used as a decision aid in the forest and forest products industry. Areas that need further study include:

- The size variation in nodal swellings, branch stubs, and occlusion scars;
- The number of trees to sample per compartment;
- In-field destructive methods to verify pruning records.

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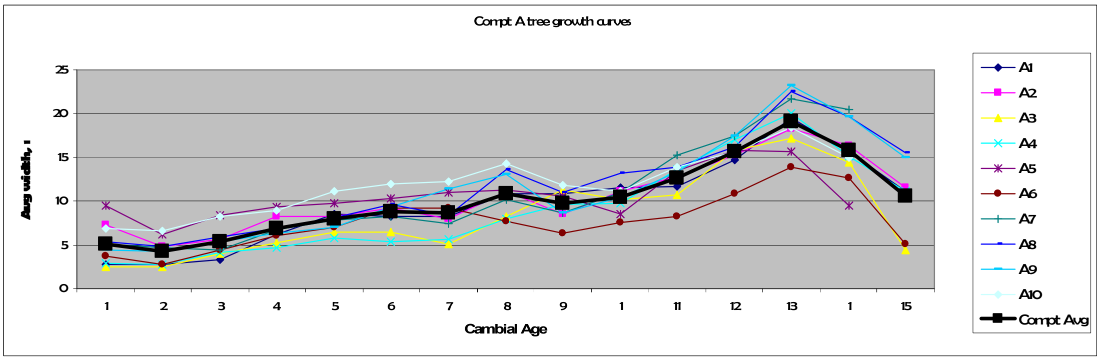
7 Appendices

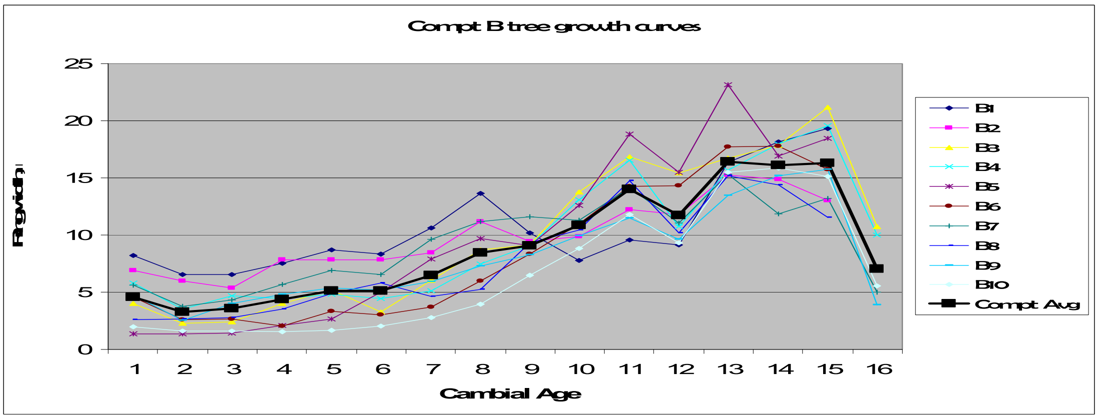
Appendix 1: Pruning records per compartment

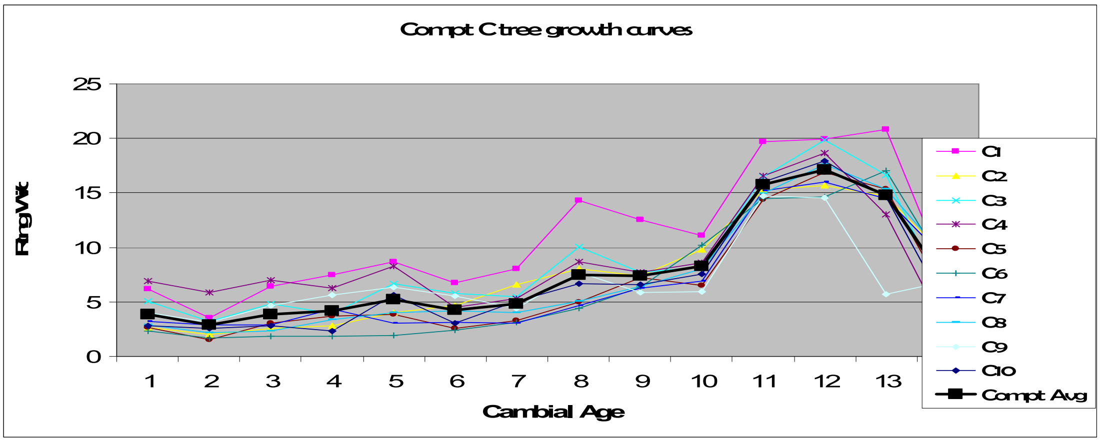
Felling date: 05/09/2008

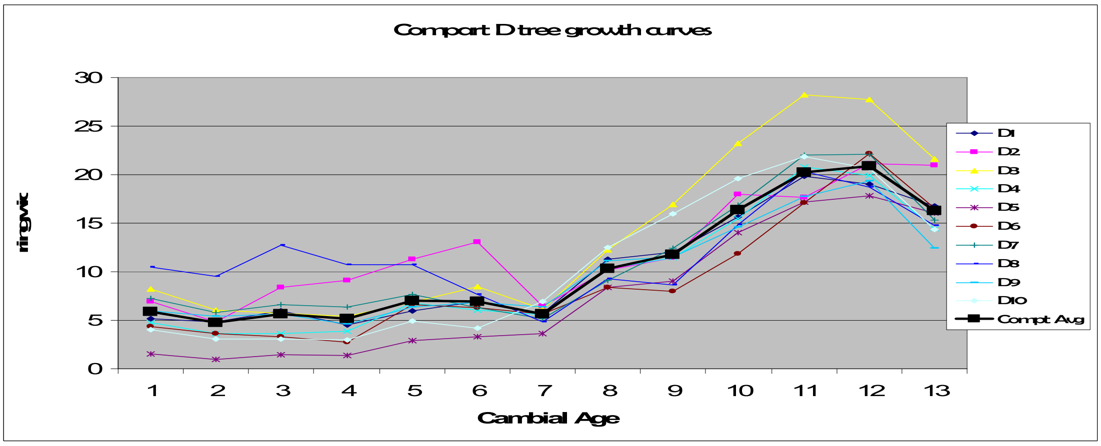
Sample	Plantation	Compt	Plantdate	Age	Pru Age	Pru Ht	Pru Age	Pru Ht	Pru Age	Pru Ht	Pru Age	Pru Ht	Pru Age	Pru Ht	Pru Age
A	Nelshoogte	E66	01/12/1991	16.8	4	1.5	6	3	8	5	10	7			
B	Nelshoogte	E28a	01/03/1990	18.5	6	1.5	7	3	8	5	11	7			
C	Nelshoogte	G21	01/02/1993	15.6	5	1.5	6	3	8	5	10	7			
D	Uitsoek	D1	01/02/1992	16.6	6	1.5	7	3	9	5	9	7			
E	Uitsoek	D88	01/01/1992	16.7	5	1.5	7	3	10	5	12	7.5			
F	Uitsoek	E55a	01/01/1989	19.7	7	3	9	5	12	7					
G	Uitsoek	E36c	01/03/1990	18.5	7	1.5	8	3	10	5	12	7			
H	Uitsoek	E22a	01/01/1992	16.7	5	1.5	7	3	10	5	12	7			
I	Berlin	E5	01/11/1989	18.9	5	1.5	6	3	8	5	10	7			
J	Berlin	E15a	01/02/1989	19.6	6	1.5	7	3	8	5	11	7			
K	Berlin	E35	01/05/1993	15.4	5	1.5	7	3	9	5	10	7	11	8.5	
L	Blyde	C22	01/03/1989	19.5	5	1.5	7	3.5	8	5.5	9	6.5	10	7.5	11
M	Morgenzon	E3	01/11/1991	16.9	3	1.5	5	3.5	7	5	8	5.5	9	6	12
N	Morgenzon	D74	01/03/1990	18.5	5	1.5	9	5.5	10	7					
O	Morgenzon	A1a	01/11/1992	15.9	4	1.5	5	2	6	3.5	8	5.5	11	7	
P	Wilgeboom	D11	01/12/1990	18	4	2	6	3.5	7	5.5	8	6.5	9	8.5	10
R	Wilgeboom	J20	01/08/1990	18.1	4	1.5	6	3.5	7	7.5	10	8.5	11	9.5	

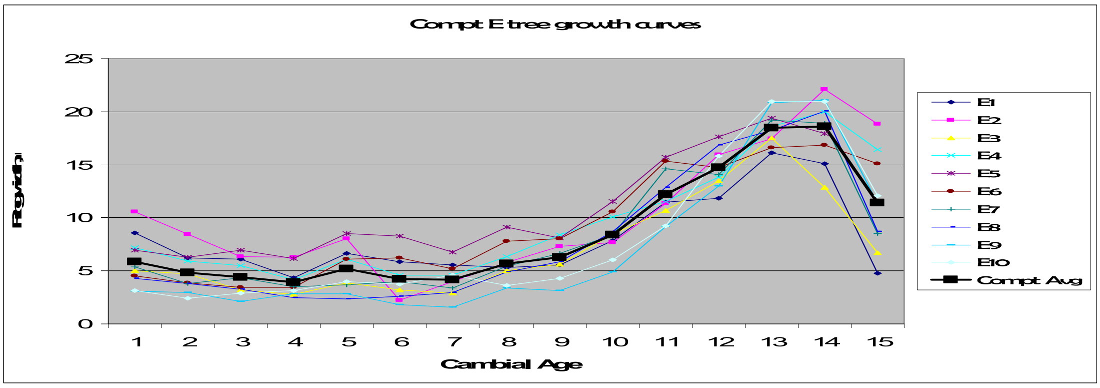
Appendix 2: Growth curves of all trees and compartments

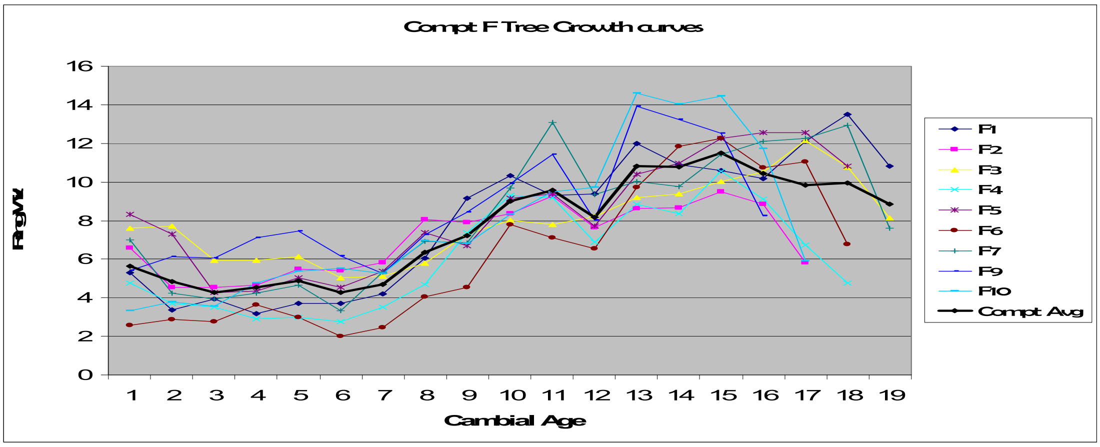









Compt E tree growth curves
Cambial Age
E1
E2
E3
E4
E5
E6
E7
E8
E9
E10
Compt Avg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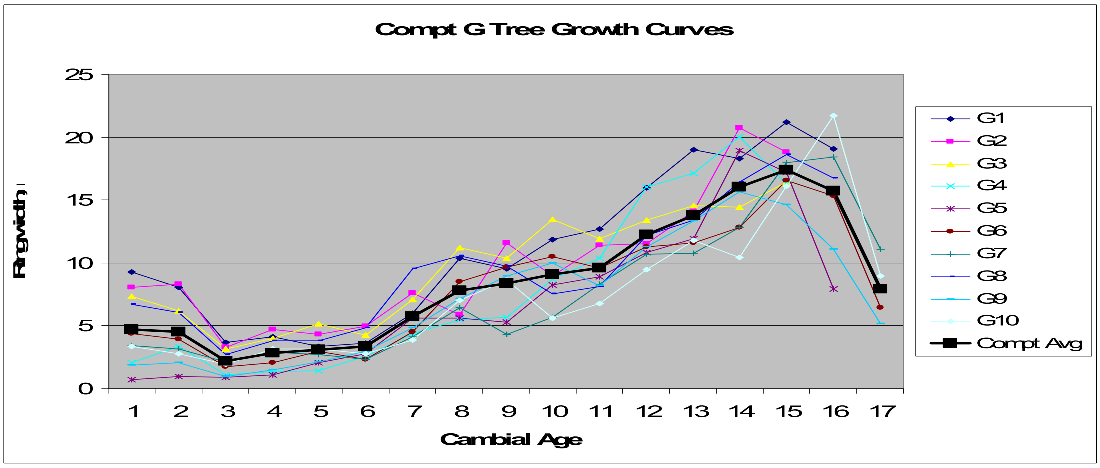
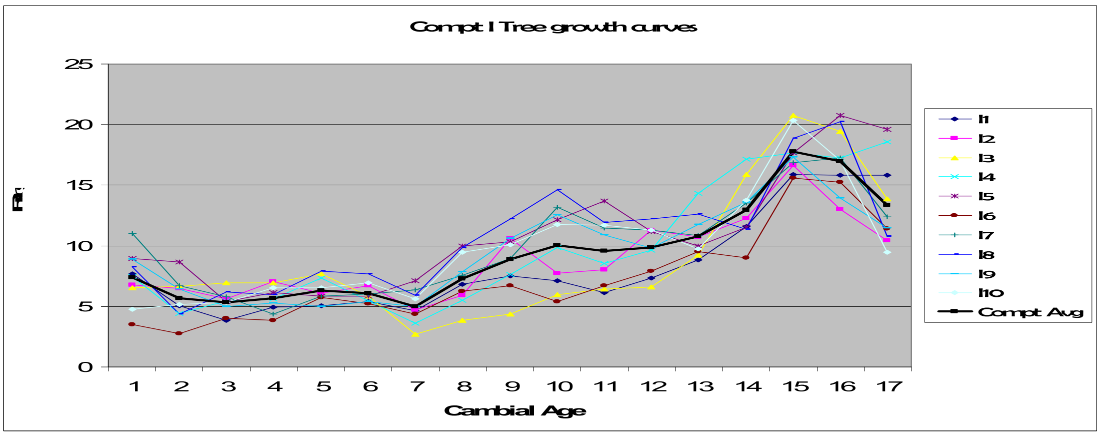
Cambial Age
F1
F2
F3
F4
F5
F6
F7
F9
F10
Compt Avg


Compt G Tree Growth Curves
Cambial Age
G1
G2
G3
G4
G5
G6
G7
G8
G9
G10
Compt Avg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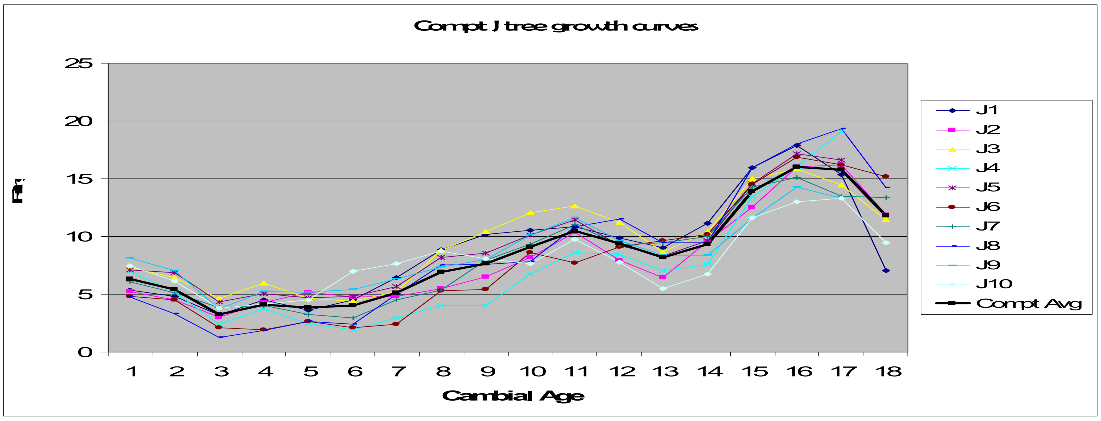
Cambial Age
I1
I2
I3
I4
I5
I6
I7
I8
I9
I10
Compt Avg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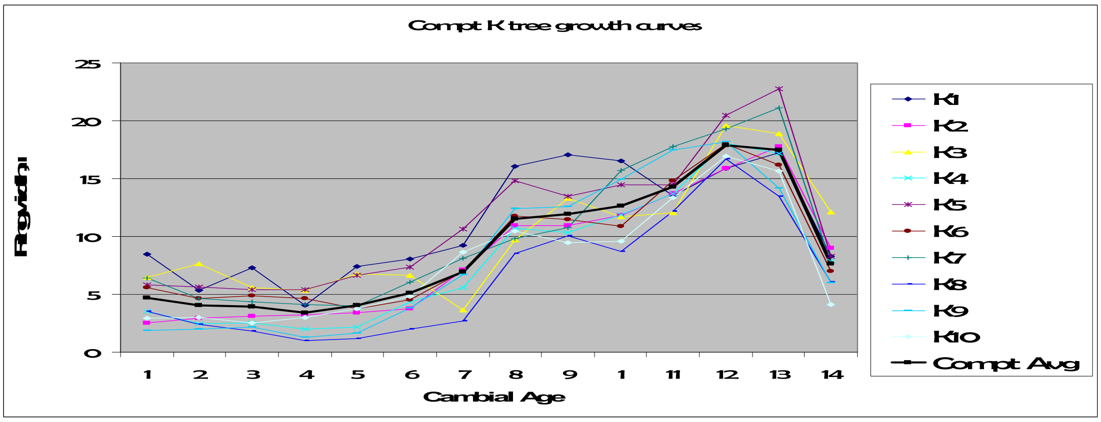
Cambial Age
J1
J2
J3
J4
J5
J6
J7
J8
J9
J10
Compt Avg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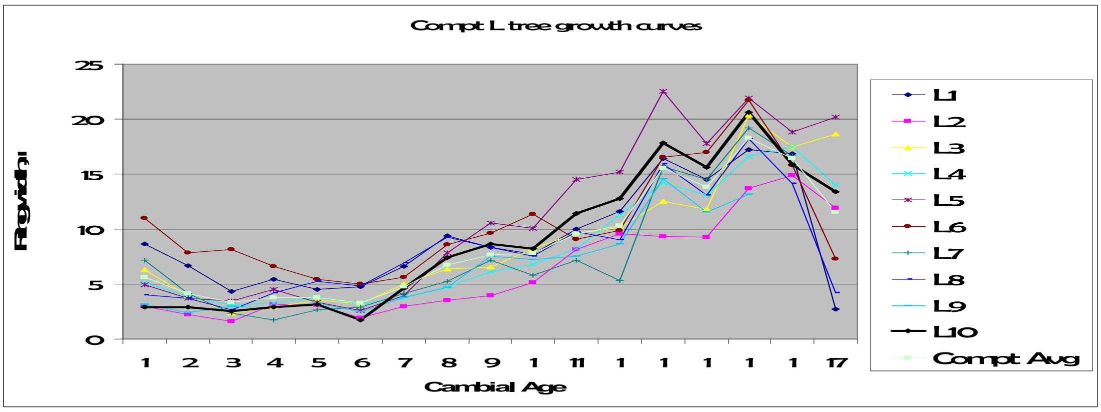
Cambial Age
Compt Avg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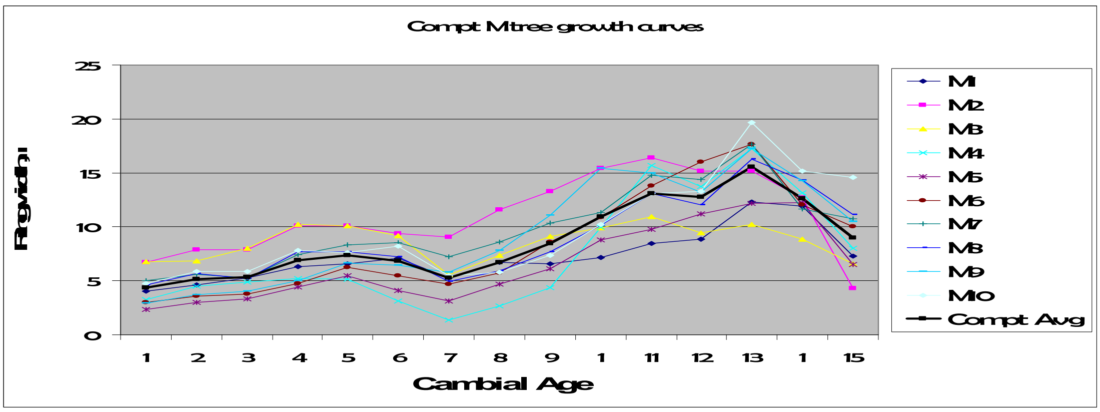
Cambial Age
Compt Avg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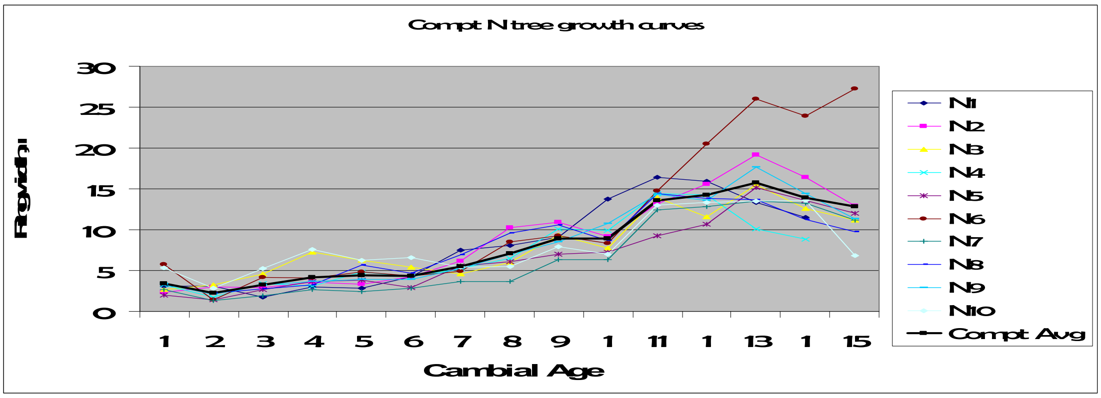
Cambial Age
Compt Avg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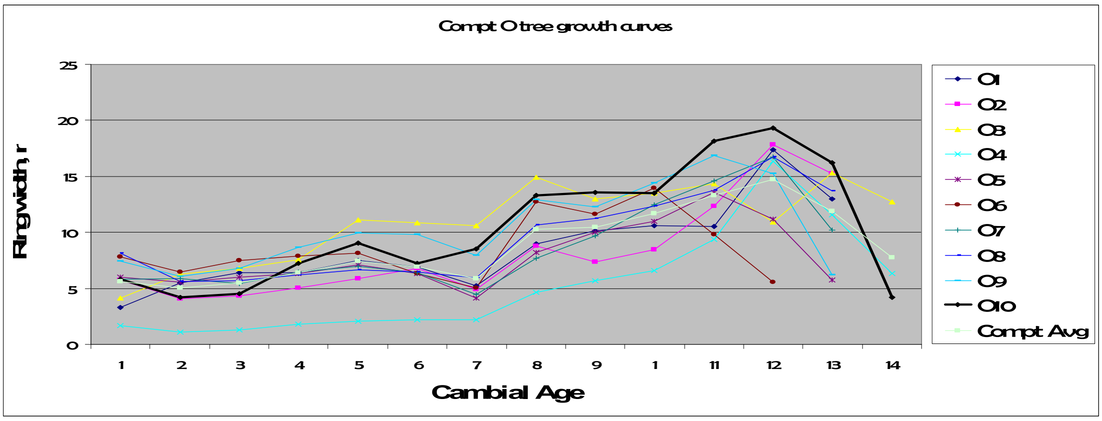
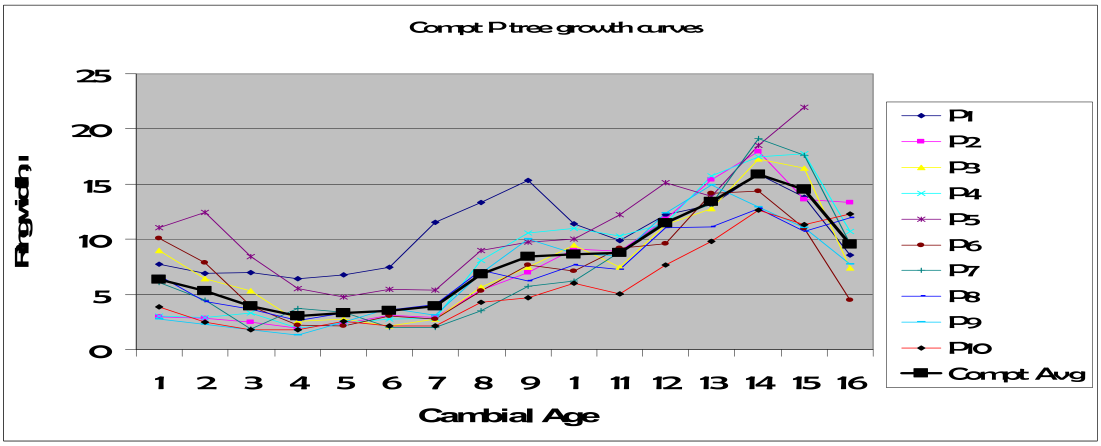
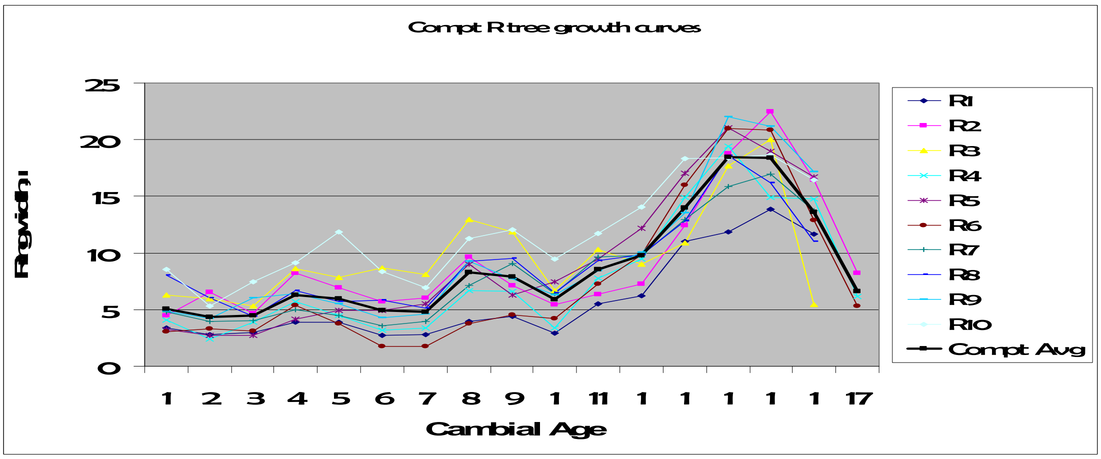
Ringwidth, r
0
5
10
15
20
25
30
1 2 3 4 5 6 7 8 9 1 11 1 13 1 15
Cambial Age
N1
N2
N3
N4
N5
N6
N7
N8
N9
N10
Compt Avg


Compt O tree growth curves
Ringwidth, r
0
5
10
15
20
25
1 2 3 4 5 6 7 8 9 1 11 12 13 14
Cambial Age
O1
O2
O3
O4
O5
O6
O7
O8
O9
O10
Compt Avg


Compt P tree growth curves
Ringwidth, r
0
5
10
15
20
25
1 2 3 4 5 6 7 8 9 1 11 12 13 14 15 16
Cambial Age
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10
Compt Avg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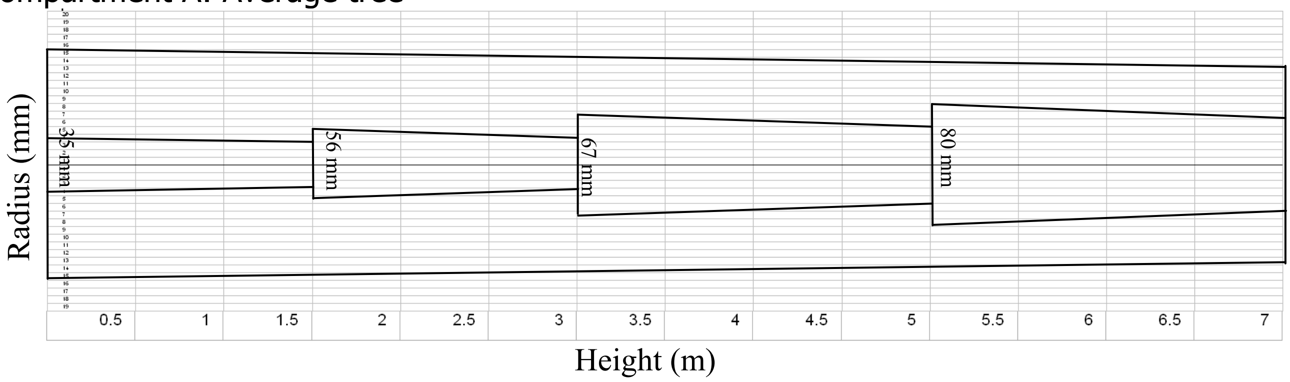
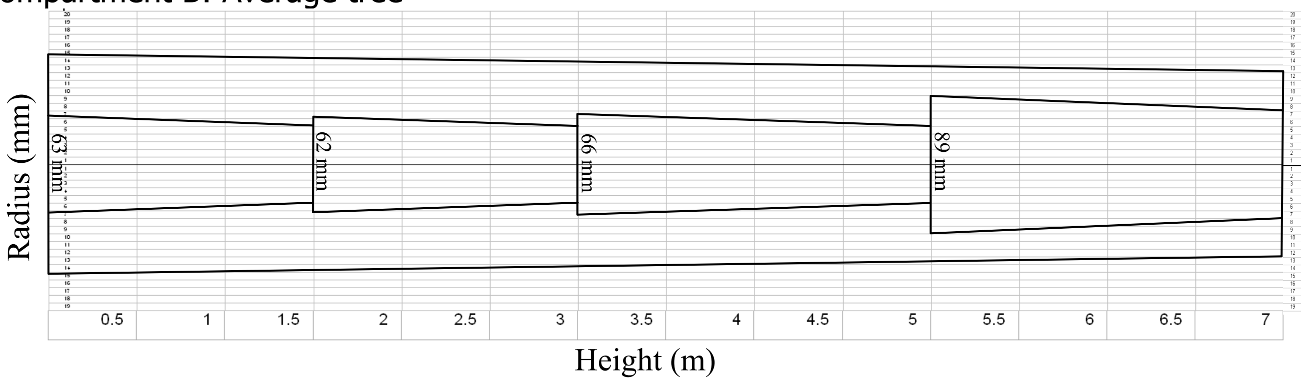
Ringwidth, r
0
5
10
15
20
25
1 2 3 4 5 6 7 8 9 1 11 1 1 1 1 1 17
Cambial Age
R1
R2
R3
R4
R5
R6
R7
R8
R9
R10
Compt Avg

Appendix 3: Average knotty core structures per compartment

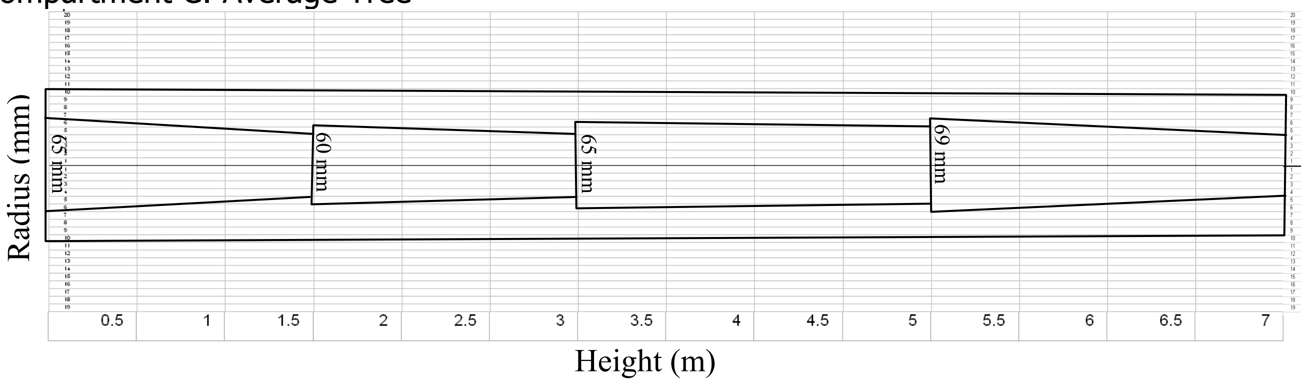
Compartment A: Average tree



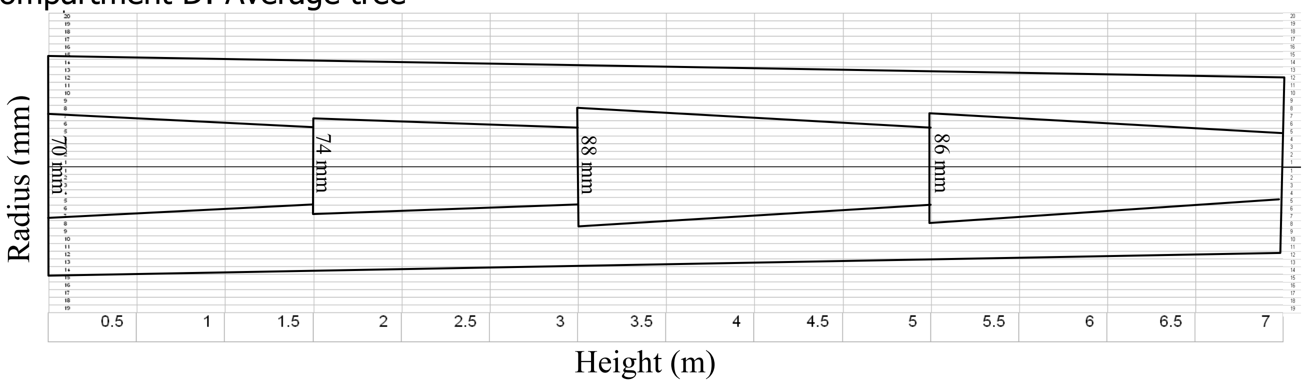
Compartment B: Average tree



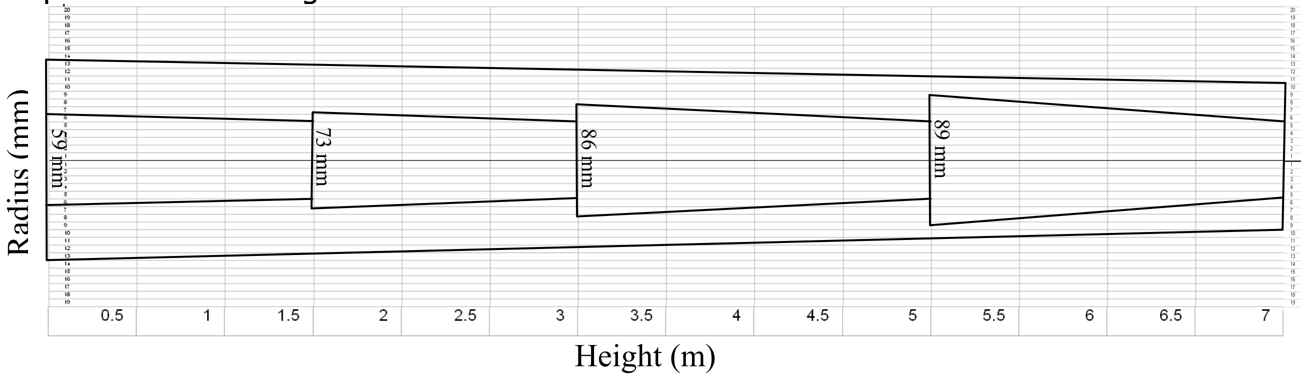
Compartment C: Average Tree



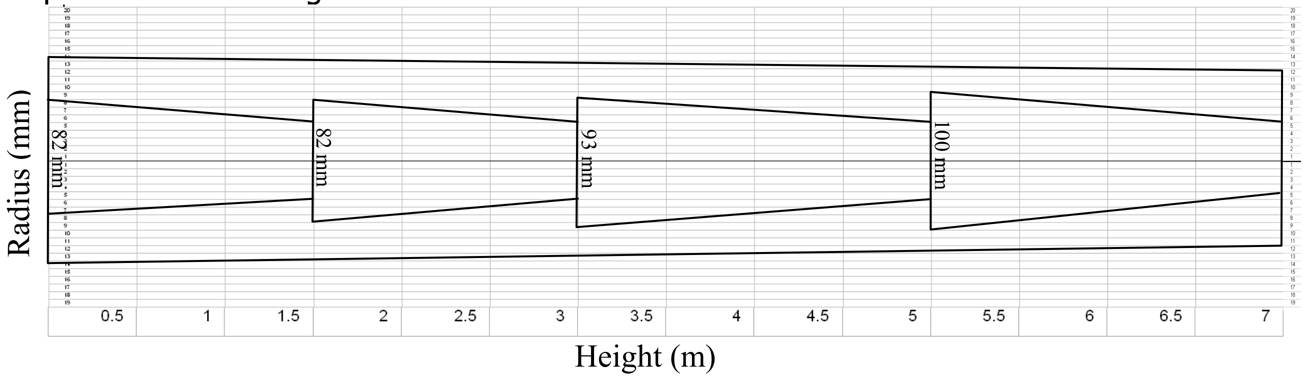
Compartment D: Average tree



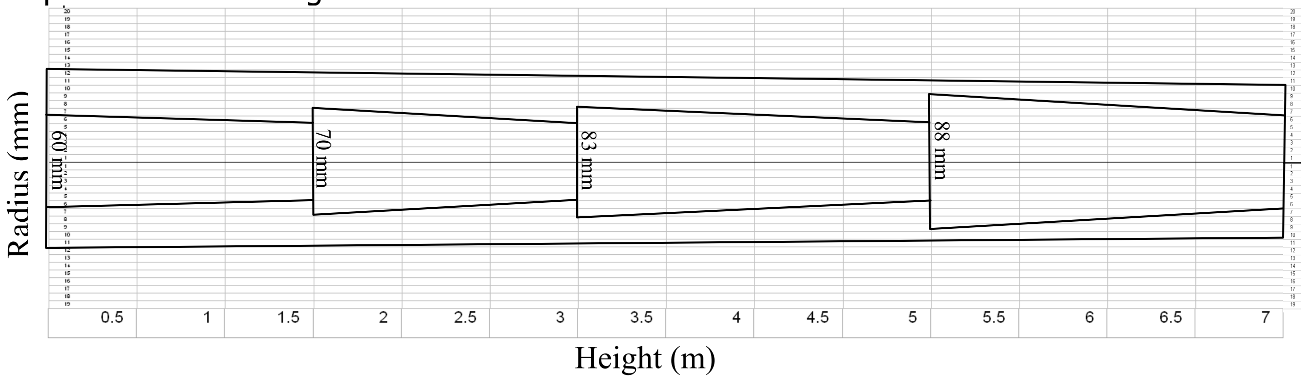
Compartment E: Average Tree



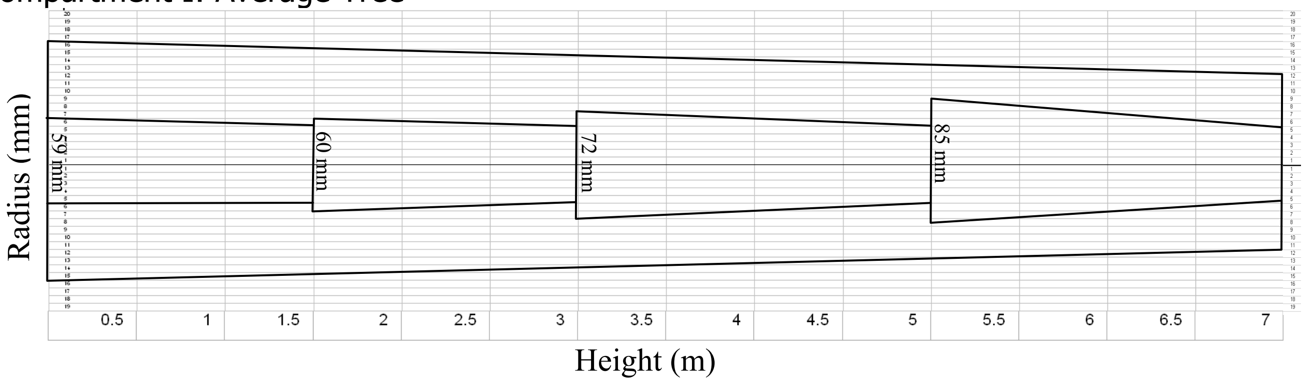
Compartment G: Average Tree



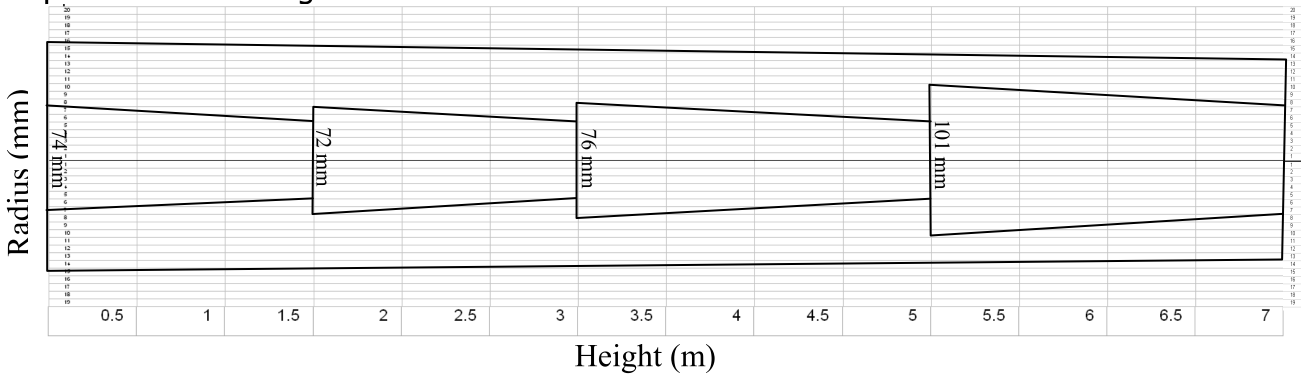
Compartment H: Average Tree



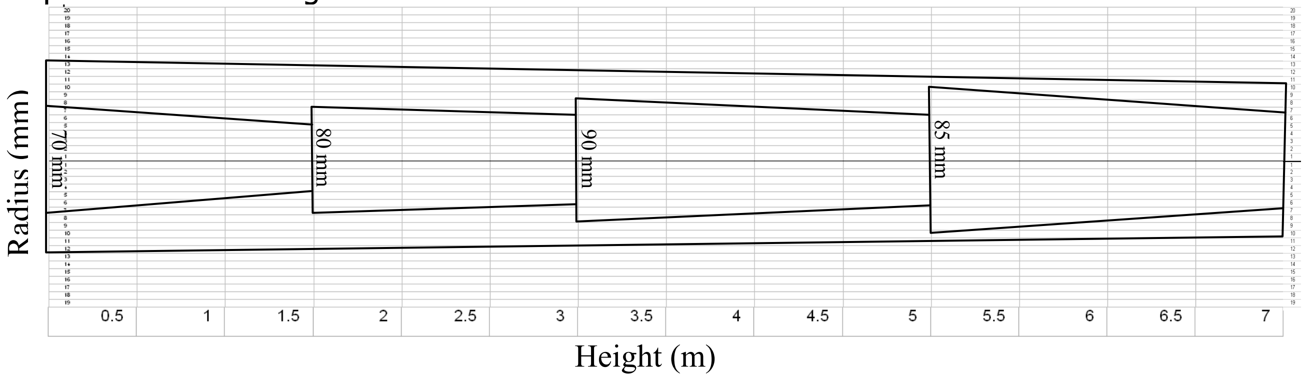
Compartment I: Average Tree



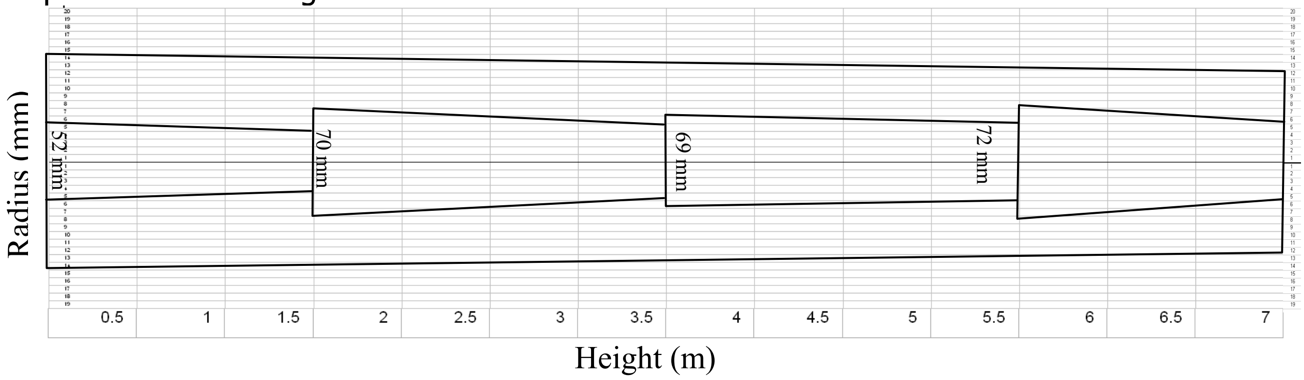
Compartment J: Average Tree



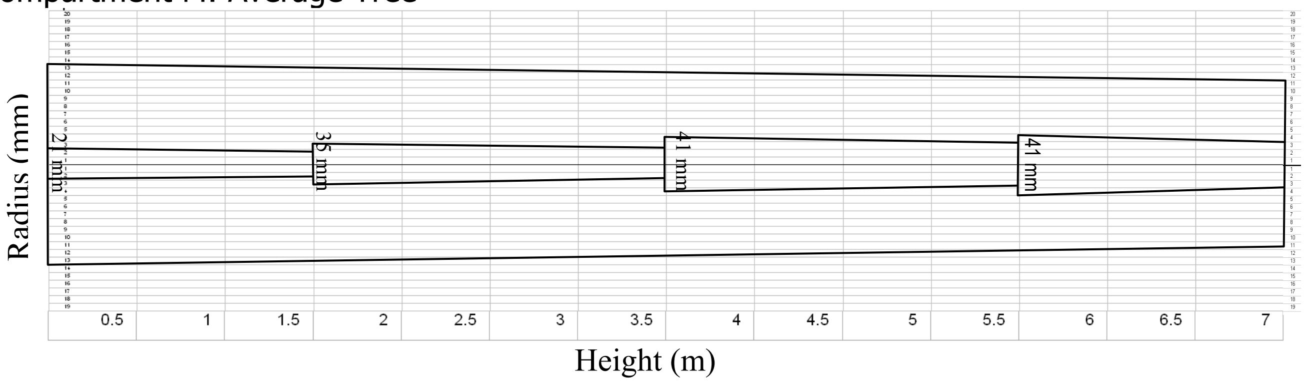
Compartment K: Average Tree



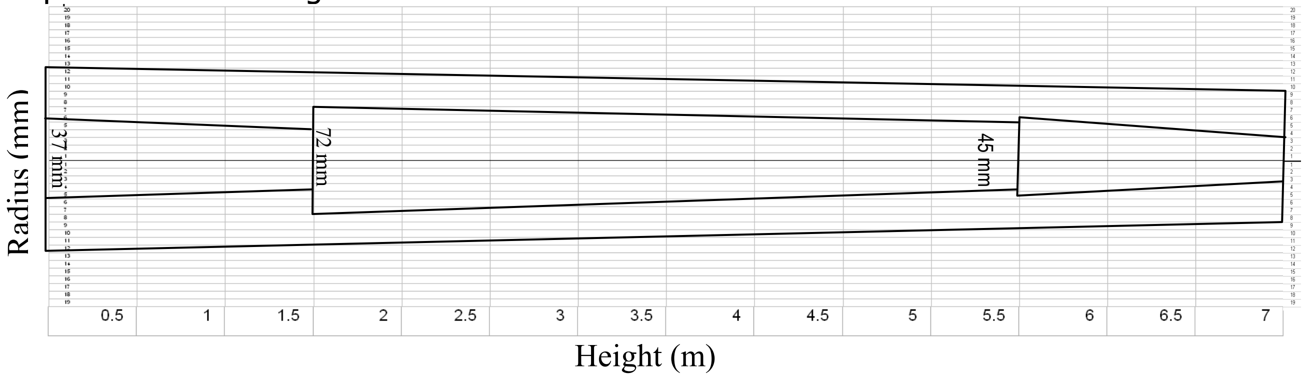
Compartment L: Average Tree



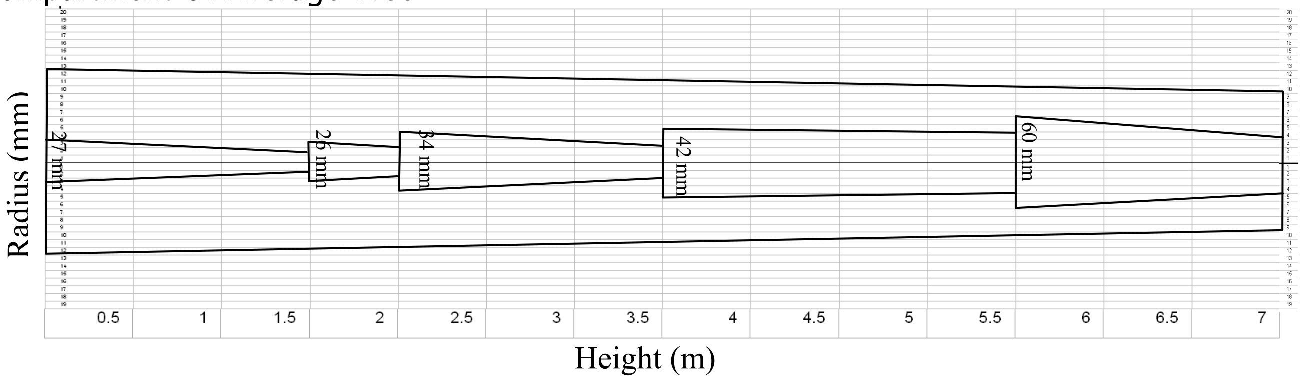
Compartment M: Average Tree



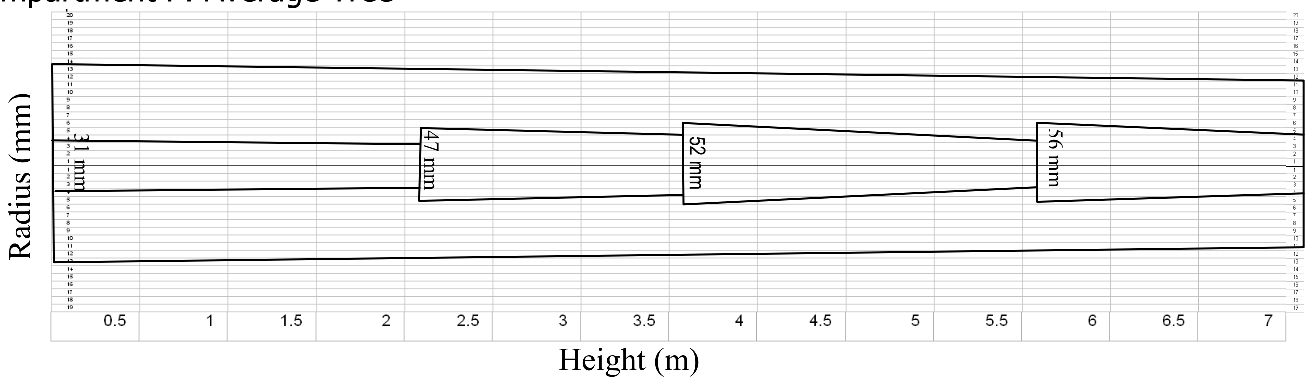
Compartment N: Average Tree



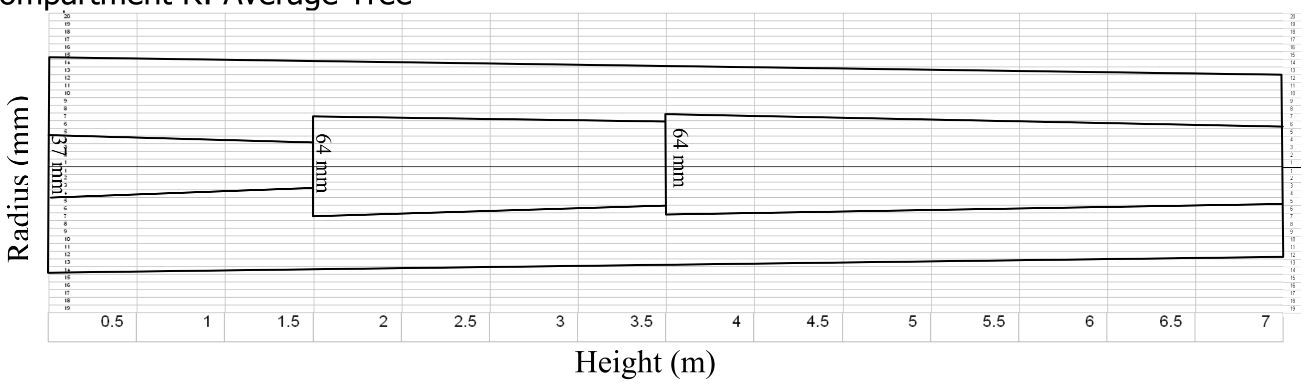
Compartment O: Average Tree



Compartment P: Average Tree



Compartment R: Average Tree



Appendix 4: Simsaw6R output for cross-cut simulation run

Simsaw Simulation Report : Board Piececount

(Ideal Logs)

Log class specifications

Log class no.	Diameter (cm) Min	Diameter (cm) Max	Length (m) Min	Length (m) Max	Length (m) Incr	Taper (mm/m) Min	Taper (mm/m) Max	Sweep (mm/m) Min	Sweep (mm/m) Max	Ovality Min	Ovality Max	Defect core (%) Min	Defect core (%) Max	Grade description	Log price (R/m^3)	No. of logs
1	16.0	17.9	2.4	6.6	0.3	0.0	20.0	0.0	20.0	0.70	1.30	0	100	All log grades	400.00	1
2	18.0	21.9	2.4	6.6	0.3	0.0	20.0	0.0	20.0	0.70	1.30	0	100	All log grades	400.00	0
3	22.0	25.9	2.4	6.6	0.3	0.0	20.0	0.0	20.0	0.70	1.30	0	100	All log grades	400.00	0
4	26.0	27.9	2.4	6.6	0.3	0.0	20.0	0.0	20.0	0.70	1.30	0	100	All log grades	400.00	3
5	28.0	31.9	2.4	6.6	0.3	0.0	20.0	0.0	20.0	0.70	1.30	0	100	All log grades	400.00	3
6	32.0	35.9	2.4	6.6	0.3	0.0	20.0	0.0	20.0	0.70	1.30	0	100	All log grades	400.00	3
7	36.0	45.0	2.4	6.6	0.3	0.0	20.0	0.0	20.0	0.70	1.30	0	100	All log grades	400.00	0

Grade Outputs

Log grade	Thickness (mm)	Width (mm)	Board grade	Precentage defect core 0 %	1-50%	51-99%	100%
All log grades	25.0	76.0	Clear	100	0	0	0
			S5	100	100	100	100
			Crating	0	20	50	50
			Industrial	0	80	50	50
			XXX	100	100	100	100
		114.0	Clear	100	0	0	0
			Crating	0	20	50	50
			Industrial	0	80	50	50
			XXX	100	100	100	100
		152.0	Clear	100	0	0	0
			Crating	0	20	50	50
			Industrial	0	80	50	50
			XXX	100	100	100	100
		228.0	Clear	100	0	0	0
			Crating	0	20	50	50
			Industrial	0	80	50	50

Run name : Francis Scen1_10 Run date : 02/11/2009 15:52:47 Report date :02/11/2009 15:58:09 Page :1

		XXX	100	100	100	100
38.0	76.0	Clear	100	0	0	0
		S5	0	90	70	70
		Crating	0	10	30	30
		Industrial	0	80	50	50
		XXX	0	10	30	30
	114.0	Clear	100	0	0	0
		S5	0	90	70	70
		XXX	0	10	30	30
	152.0	Clear	100	0	0	0
		S5	0	90	70	70
		XXX	0	10	30	30
	228.0	Clear	100	0	0	0
		S5	0	90	70	70
		XXX	0	10	30	30

Machine settings

1 Framesaw

Primary Breakdown Machine
Kerf sizes (mm) : 4.0
Log rotation (deg) : 0
Log misalignment (mm) : 0
Saw offset (mm) : 0

Secondary Breakdown Machine
Kerf sizes (mm) : 4.0
Cant guiding : Half-taper
Max sweep for RTC machine (mm):999
Cant misalignment (mm) : 0
Saw offset (mm) : 0

Edging
Edging for max : Volume
No of blades : 2
Kerf size (mm) : 5.0

Resaw
Primary : On
Kerf size (mm) :5.0
Secondary : On
Kerf size (mm) :5.0

Product specifications

Thicknesses (mm)		Widths (mm)		Lengths (m)			
Dry	Wet	Dry	Wet	Description	Min	Max	Incr
25.0	27.0	76.0	81.0	Short	0.9	2.7	0.3
38.0	41.0	114.0	120.0	Long	3.0	6.6	0.3
		152.0	160.0				
		228.0	240.0				

Combinations				
Thickness (mm)	Width (mm)	Length	Grade	Price (R/m³)
25.0	76.0	Short	Clear	3120.00
25.0	76.0	Short	Crating	1487.00
25.0	76.0	Short	Industrial	1847.00
25.0	76.0	Long	Clear	3300.00
25.0	76.0	Long	Crating	1835.00
25.0	76.0	Long	Industrial	1826.00

25.0	114.0	Short	Clear	3120.00
25.0	114.0	Short	Crating	1487.00
25.0	114.0	Short	Industrial	1847.00
25.0	114.0	Long	Clear	3300.00
25.0	114.0	Long	Crating	1835.00
25.0	114.0	Long	Industrial	1826.00
25.0	152.0	Short	Clear	3120.00
25.0	152.0	Short	Crating	1487.00
25.0	152.0	Short	Industrial	1847.00
25.0	152.0	Long	Clear	3300.00
25.0	152.0	Long	Crating	1835.00
25.0	152.0	Long	Industrial	1826.00
25.0	228.0	Short	Clear	3120.00
25.0	228.0	Short	Crating	1487.00
25.0	228.0	Short	Industrial	1847.00
25.0	228.0	Long	Clear	3300.00
25.0	228.0	Long	Crating	1835.00
25.0	228.0	Long	Industrial	1826.00
38.0	76.0	Short	Clear	3120.00
38.0	76.0	Short	S5	2215.00
38.0	76.0	Short	XXX	1474.00
38.0	76.0	Long	Clear	3300.00
38.0	76.0	Long	S5	2617.00
38.0	76.0	Long	XXX	1730.00
38.0	114.0	Short	Clear	3120.00
38.0	114.0	Short	S5	2354.00
38.0	114.0	Short	XXX	1495.00
38.0	114.0	Long	Clear	3300.00
38.0	114.0	Long	S5	2575.00
38.0	114.0	Long	XXX	2069.00
38.0	152.0	Short	Clear	3120.00
38.0	152.0	Short	S5	2354.00
38.0	152.0	Short	XXX	1495.00
38.0	152.0	Long	Clear	3300.00
38.0	152.0	Long	S5	2575.00

38.0	152.0	Long	XXX	2069.00
38.0	228.0	Short	Clear	3120.00
38.0	228.0	Short	S5	2196.00
38.0	228.0	Short	XXX	1813.00
38.0	228.0	Long	Clear	3300.00
38.0	228.0	Long	S5	3040.00
38.0	228.0	Long	XXX	2251.00

Standard boards (mm)		Centre boards (mm)	
Dry	Wet	Dry	Wet
25.0	76.0		
25.0	114.0		
25.0	152.0		
25.0	228.0		
38.0	76.0		
38.0	114.0		
38.0	152.0		
38.0	228.0		

Wane specifications

Board dimensions (mm)		Maximum wane			
Thickness	Width	Thickness (%)	Width (%)	Length	Units
25.0	76.0	0.0	0.0	0.0	%
25.0	114.0	0.0	0.0	0.0	%
25.0	152.0	0.0	0.0	0.0	%
25.0	228.0	0.0	0.0	0.0	%
38.0	76.0	0.0	0.0	0.0	%
38.0	114.0	0.0	0.0	0.0	%
38.0	152.0	0.0	0.0	0.0	%
38.0	228.0	0.0	0.0	0.0	%

Board piececount results

Total log volume (m^3) : 5.6139

Dry volume recovery (%) :	53.34	Chips volume (m^3) :	1.5699
Wet volume recovery (%) :	60.63	Chips value (R/m^3) :	0.00
Value recovery (R/m^3) :	1572.80	Sawdust volume (m^3) :	0.6405
Nett value recovery (R/m^3) :	1172.80	Sawdust value (R/m^3) :	0.00

Thickness (mm)	Width (mm)	Length	Grade	No of pieces	Volume (m^3)	Value (R)	Volume %	Value %	Pieces %
25.0	76.0	Short	Clear	10	0.0274	85.36	0.9	1.0	10.0
25.0	76.0	Long	Clear	8	0.0627	206.91	2.1	2.3	8.0
25.0	76.0	Long	Industrial	2	0.0251	45.80	0.8	0.5	2.0
25.0	114.0	Short	Clear	2	0.0103	32.01	0.3	0.4	2.0
25.0	114.0	Long	Clear	18	0.2975	981.88	9.9	11.1	18.0
25.0	152.0	Long	Clear	16	0.3830	1264.03	12.8	14.3	16.0
38.0	114.0	Long	S5	1	0.0286	73.62	1.0	0.8	1.0
38.0	114.0	Long	XXX	1	0.0286	59.16	1.0	0.7	1.0
38.0	152.0	Long	S5	10	0.3812	981.63	12.7	11.1	10.0
38.0	152.0	Long	XXX	2	0.0762	157.75	2.5	1.8	2.0
38.0	228.0	Long	Clear	6	0.3015	994.97	10.1	11.3	6.0
38.0	228.0	Long	S5	19	1.0865	3302.86	36.3	37.4	19.0
38.0	228.0	Long	XXX	5	0.2859	643.59	9.5	7.3	5.0
				100	**2.9945**	**8829.57**			