Higher initial planting densities for South African-grown *Pinus patula* sawlog trees: the effect on stem form and land expectation value

By

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Thesis presented in partial fulfilment of the requirements for the degree Master of Science in Forestry (Wood Products Science) in the Faculty of Agri Sciences at Stellenbosch University

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March 2018

Declaration

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March 2018

Summary

There are concerns that the modulus of elasticity (MOE) of *Pinus patula* lumber in South Africa has decreased mainly due to faster growth and reduced rotation ages. However, a number of recent studies have shown that increased planting densities can improve mean stiffness of wood from several softwood species. Additionally, stem form could possibly also improve with higher planting densities. The objectives of this study were to evaluate the effect of *Pinus patula* saw log management regimes, based on higher initial planting densities, on land expectation value (LEV) and stem form. Stem form has a large influence on volume and value recovery in sawmills and the influence of stem form characteristics can be considered when calculating log values using software programmes such as Simsaw.

This study was conducted using an 18 year-old *Pinus patula* experimental spacing trial. The trial was located near Barberton on the Mpumalanga escarpment. The experiment consisted of two replications of four planting densities (403, 1 097, 1 808, and 2 981 spha). Stem form characteristics (ovality, straightness, sinuosity, butt-flare, and taper) from each spacing treatment were assessed from Lidar scanning data. The trial was felled and logs processed into structural size lumber which were destructively tested for MOE and modulus of rupture (MOR). The board MOE, together with sawing simulation results, were used to assign a log value recovery to each log class from each spacing treatment. Together with South African forestry cost data, the land expectation value for a range of planting density treatments and thinning regimes were calculated.

Spacing treatment had a significant effect on all five stem form characteristics. Over the bottom nine meters of the stem, the lower spacing treatments (403 and 1 097 spha) had mean stem deviations of 132.1 mm and 109.3 mm respectively while the higher planting densities (1 808 and 2 981 spha) had mean stem deviations of 76.4 mm and 82.1 mm respectively. Taper and butt-flare also had a decreasing trend from 403 spha to 2 981 spha. Ovality, on the other hand, increased with increasing planting density and also increased with increasing height along the tree stem.

There was an increase in mean MOE of lumber with increasing planting density. Similarly, the structural grade recoveries of similar board positions increased with planting density. This, in turn, resulted in increased log value recovery, for the same log sizes, with increased planting

density. The best management regimes for each of the three lower planting densities (403, 1 097, and 1 808 spha) all returned LEV values relatively close to each other. The best LEV was from a spacing treatment of 1 808 spha, thinned at 12 years to 300 spha, and clearfelled at 19 years (R47 693.02/ha. The second best management regime was for the 1 097 spha planting density, thinned to 250 spha at 13 years, and clearfelled at 18 years (R46 677.59/ha). Despite the results showing that higher planting densities result in better value recoveries for the same log sizes, the best LEV was not obtained from the highest planting density but with a medium high planting density and a late thinning.

Opsomming

Daar is kommer dat die modulus van elastisiteit (MOE) van *Pinus patula* hout in Suid-Afrika afneem weens vinniger groeikoerse en laer rotasie-ouderdomme. Onlangse studies het egter getoon dat verhoogde plantdigthede die gemiddelde MOE van verskeie naaldhoutspesies kan verbeter. Die doelwitte van hierdie studie was om die effek van *Pinus patula* bosbestuursregimes, gebaseer op hoër aanvanklike plantdigthede, op die landverwagtingswaarde en stamvorm te evalueer. Stamvorm het 'n groot invloed op volume -en waardeherwinning in saagmeule en die invloed van stamvorm-eienskappe kan oorweeg word wanneer boomwaardes bereken word met die gebruik van sagtewareprogramme soos Simsaw.

Hierdie studie is uitgevoer met behulp van 'n 18-jarige *Pinus patula* eksperimentele spasiëringproef geleë naby Barberton op die Mpumalanga platorand. Die eksperiment het bestaan uit twee herhalings van vier plantdigthede (403, 1097, 1808 en 2981 stamme per hektaar). Stamvorm-eienskappe (ovaalvormigheid, kromming, sinuositeid, onderentverdikking, en spitsing) van elke spasiëringsbehandeling is beoordeel met Lidar skanderingsdata. Die proef is afgekap en stompe verwerk in strukturele hout wat vernietigend getoets was vir MOE en die breekmodulus. Die plank MOE, tesame met saagsimulasieresultate, is gebruik om 'n stomp waardeherwinning vir elke stompklas uit elke spasiëringsbehandeling te bereken. Suid-Afrikaanse bosbou kostedata is gebruik om die landverwagtingswaarde vir 'n verskeidenheid van plantdigtheidbehandelings en dunning regimes te bereken.

Spasiëring behandeling het 'n beduidende effek op al vyf stamvorm-eienskappe gehad. Oor die onderste nege meter van die stam het die laer spasiëringbehandelings (403 en 1 097 spha) ‘n gemiddelde kromming van 132.1 en 109.3 mm onderskeidelik gehad terwyl die hoër plantdigthede (1 808 en 2 981 spha) gemiddelde kromming van 76.4 en 82.1 mm onderskeidelik gehad het. Spitsing en onderentverdikking het ook 'n dalende tendens van 403 spha na 2 981 spha gehad. Ovaalvormigheid, in teenstelling, het verhoog met toenemende plantdigtheid en ook verhoog met toenemende hoogte.

Daar was 'n toename in gemiddelde MOE van hout met toenemende plantdigtheid. Die strukturele graadherwinning het ook toegeneem met plantdigtheid. Dit het gelei tot

verhoogde waardeherwinning vir die ooreenstemmende stompklasse, met verhoogde plantdigtheid. Die beste bosbestuurregimes vir elk van die drie laer plantdigthede (403, 1 097, en 1 808 spha) het landverwagtingswaardes relatief naby aan mekaar gehad. Die beste landverwagtingswaarde was van 'n spasiëringbehandeling van 1 808 spha, gedun op ouderdom 12 tot 300 spha, en kaalgekap op ouderdom 19 (R47 693.02/ha) die tweede beste bosbestuursregime was vir die 1 097 spha plantdigtheid, gedun tot 250 spha op ouderdom 13, en kaalgekap op ouderdom 18 (R46 677.59/ha). Ten spyte van die resultate wat toon dat hoër plantdigthede beter waardeherwinning vir soortgelyke stompklasse gee, was die beste landverwagtingswaarde nie verkry vanaf die hoogste plantdigtheid nie, maar vanaf 'n medium plantdigtheid en 'n laat dunning.

Acknowledgements

I would like to thank my supervisor, Dr. Brand Wessels, for his support and guidance throughout this study. I have learned and gained much knowledge from you.

I would also like to thank Prof. Thomas Seifert for the development and use of the Stemfit programme.

Thanks to Dr. Stefan Seifert for his time and effort in creating the Stemfit program and supporting me during the analysis.

Thank you to the Hans Merensky Foundation for funding my studies.

Thanks to Sappi for the test material used in this study and processing of the tress.

I would also like to thank Anton Kunneke for his data collection using the Lidar scanner on the Highlands trial.

Thank you to Safcol for use of the FORSAT software.

Lastly, I would like to thank my brothers and my parents to whom I dedicate this thesis. Thanks for all the support and encouragement you have given throughout my studies.

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MOE	Modulus of elasticity
MOR	Modulus of rupture
LEV	Land expectation value
Spha	Stems per hectare
FES	Forest Economic Services
FORSAT	Forestry Scenario Analysis Tool
MPa	Mega Pascal
MFA	Micro-fibril angle
ANOVA	Analysis of variance
XXX, S5	South African visual grading system for sawn timber
SANS	South African National Standard
SED	Small end diameter
IRR	Internal rate of return

Chapter 1

1. Introduction

1.1 Background

Forestry plantations in South Africa during 2014/2015 covered a total of 1,224,456 hectares of which 619,311 ha was softwood plantations (DAFF, 2016). *Pinus patula* is by far the most popular softwood grown in the country. It makes up 50.45 % of the total softwood plantation area in South Africa, consisting of 312,447 hectares (DAFF, 2016). In 2015, 72.6% (4,676,652 m^3) of the total harvested softwood was classified as saw logs, while the remainder was classified as pulp logs (DAFF, 2016).

Sustainable forestry is strongly linked to wood quality improvement (Harding, 1996) and the application of sound silvicultural practices (Malan 2003). Aggressive silvicultural and genetic improvement of tree resources has resulted in considerably reduced rotation lengths of saw-log resources (Wessels et al., 2014). Structural lumber stiffness would be lower as a result of reduced rotation ages because a higher percentage of juvenile wood present in the final product. A number of studies have concluded that the stiffness (MOE) of *Pinus patula* in South Africa has been reduced and is considerably lower than the limits set for S5 grade timber (Burdzik 2004; Dowse 2010; Wessels et al. 2011 and Wessels et al. 2014).

Although the stiffness of *Pinus patula* has been reduced, studies have been done to test whether the MOE or stiffness properties can be improved. Erasmus (2016) studied the effect of planting density on *Pinus patula* stem form, wood properties and lumber strength and stiffness. His results show a significant increase in stiffness properties of young *Pinus patula* lumber with higher initial planting densities. According to his results micro-fibril angle (MFA) has a greater effect on MOE than density and MFA is also significantly influenced by planting density. A study by Froneman (2014) showed a significant increase in stiffness properties of young *Pinus elliottii* and *Pinus radiata* with higher initial planting densities.

Erasmus (2016) determined the stiffness of 18y old *Pinus patula* from two compartments planted at 1 667 and 1 334 spha respectively and thinned to 827 spha. The lumber from the compartment with the higher initial planting density had a much higher mean MOE (8 967 MPa) than the other (7 134 MPa). According to these studies, increasing initial planting density seems to be a possible answer to improving the stiffness of *Pinus* lumber in South Africa.

Research has showed that stiffness could be increased through higher planting densities for some species. However, no study has been conducted on the economics of *Pinus patula* plantation management regimes to evaluate whether planting at much higher initial densities has a financial advantage. One aspect of higher initial planting densities that has an influence on the economic returns of the saw log processing value chain, but has not been sufficiently investigated, is the effect on stem form (Erasmus, 2016). Both the yield and quality of lumber is greatly affected by crooked stems (Cown et al., 1984; Monserud et al., 2004; Ivković et al., 2007; Lachenbruch et al., 2010) and some studies suggest value losses in the sawmill process of roughly 10% due to poor stem straightness (Carino et al., 2006). It is not clear though whether higher planting densities will result in less stem deviation in trees as there are conflicting results from literature (del Rio et al., 2004; Egbäck et al., 2012; Liziniewicz et al., 2012; Belley et al., 2013; Theron and Bredenkamp, 2004).

1.2 Objectives

There were two objectives for this study. The first objective was to perform an economic evaluation of South African grown *Pinus patula* saw log management regimes based on higher initial planting densities, using land expectation value as a measurable. The second objective was to determine the effect that planting density has on stem form. Stem form indirectly influence the economic performance of management regimes through its effect on log volume recovery in sawmills.

Chapter 2

2. Literature review

2.1 Wood properties

Malan, Retief and Male (1997) carried out a study to determine the influence that planting spacing has on wood density from a *Pinus patula* trial in in Southern Kwa-Zulu Natal. The planting densities used were 125 spha, 371 spha, 1483 spha, and 2965 spha. Four sample discs were cut at four different heights from trees in each espacement. Finally, a 2x20 mm strip was then cut along the full radius of each disc and used for wood density analysis. Results from their study showed that the annual ring density and radial gradient increased with increasing intensity of suppression (Malan et al. 1997). Ring number, effect of spacing densities and their interaction accounted for most of the variation in annual ring density.

Erasmus (2016) studied the effect of planting density on *Pinus patula* stem form, microfibril angle and wood density. His material was sampled from a plantation near Barberton on the Mpumalanga escarpment. Again, four sample plots were used, planted at 403 spha, 1097 spha, 1808 spha, and 2981 spha. Instead of cutting sample strips from discs obtained from trees, Erasmus removed increment cores from randomly selected trees to measure density and MFA. His results proved similar to that of Malan, Retief and Male (1997). The mean MFA and wood density was improved with increasing planting density. He also found that juvenile wood transitioned earlier into mature wood in trees from denser spacing treatments based on the MFA starting to stabilise at the age of approximately 7-8 y (Figure 1). Wessels et al. (2015) showed that MFA and wood density were the most influential wood properties in determining wood stiffness (MOE) of *Pinus patula* lumber. However, Erasmus (2016) found that MFA was the most influential and therefore more important than wood density during early growth. Lasserre et al. (2009) showed that denser initial stand spacing reduced the MFA for *Pinus radiata* D. Don corewood.

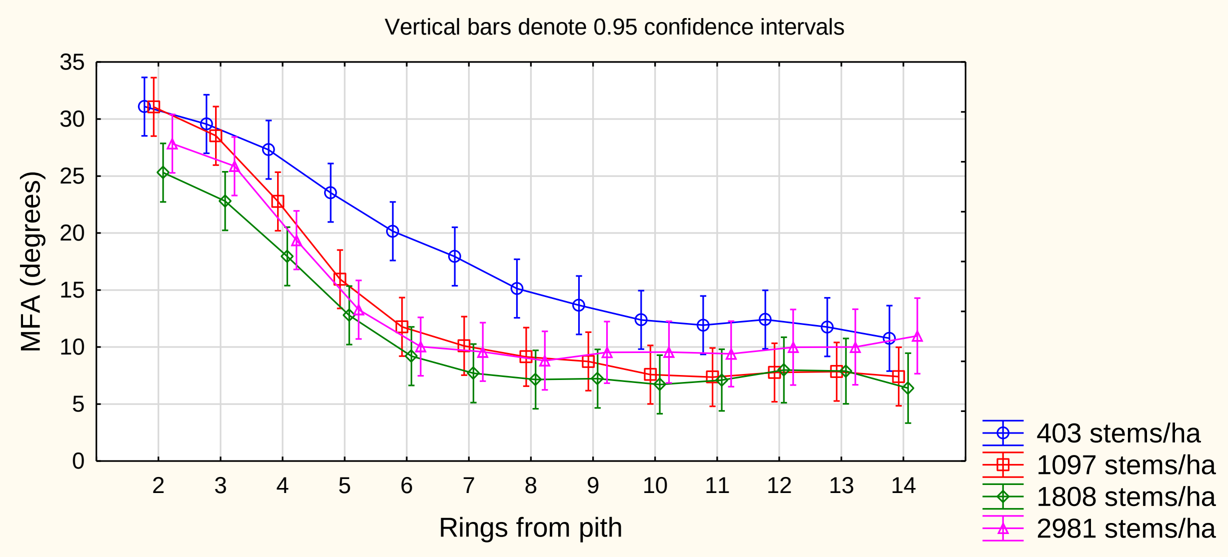


Figure 1: MFA from Pinus patula annual rings from different spacing treatments

2.2 Stem form

Erasmus (2016) reported on the effect of planting density on stem form. The stem form characteristic he was interested in was stem curvature or stem straightness. His results showed that trees planted at 403 spha were less straight than trees from the other spacing treatments. Although tree straightness improved with increasing planting density, he stated that the inconsistent trend in stem straightness from 403 to 2 981 spha in his results was only in partial agreement with results from other similar studies. Liziniewicz et al. (2012) and Belley et al. (2013) showed that stem curvature and timber quality increased with increasing initial density. However, their results conflicted with the results from a study done by del Rio et al. (2004) where the rate of bent trees was higher in the higher density plots, although their results were influenced by heavy snowfall. Studies by Erasmus (2016) and Waghorn et al. (2007) showed that planting density significantly affected stem slenderness (ratio of tree height and DBH) of *Pinus patula and P. radiata*, with increases with increasing initial planting density. Research from New Zealand has shown that ambient temperature and stem slenderness together are responsible for 75% of the variation in green MOE (Watt et al. 2006). Sinuosity is thought to negatively impact wood quality (Spicer et al., 2000). Spicer et al. (2000) did research on sinuous stem growth in a Douglas-fir plantation and found that highly sinuous trees developed more slope of grain defects than less sinuous trees.

2.3 Economic evaluation:

From experience (Dowse, 2010) we know that MOE is the limiting property for our structural grades and South Africa sawmills only grade to S5 while non-conforming boards fall into the utility grade (XXX).

Wessels et al. (2014) obtained saw logs from 17 different *Pinus patula* compartments in Mpumalanga ranging between 16 to 20 years. They found an increase in MOE and MOR from the inner boards to the outer boards influenced by increasing density from pith to bark (MFA was not measured).

A study by Erasmus (2016) using two commercial compartments also near Barberton comprising of a 17 and 18 year old *Pinus patula* planted at 1 667 spha and 1 334 spha respectively and thinned at age 11 to 827 spha. Results showed a significant difference for MOE and MOR in boards from different compartments as well as for board positions within the log (Figure 2) and increasing strength properties in boards obtained from higher initial planting densities.

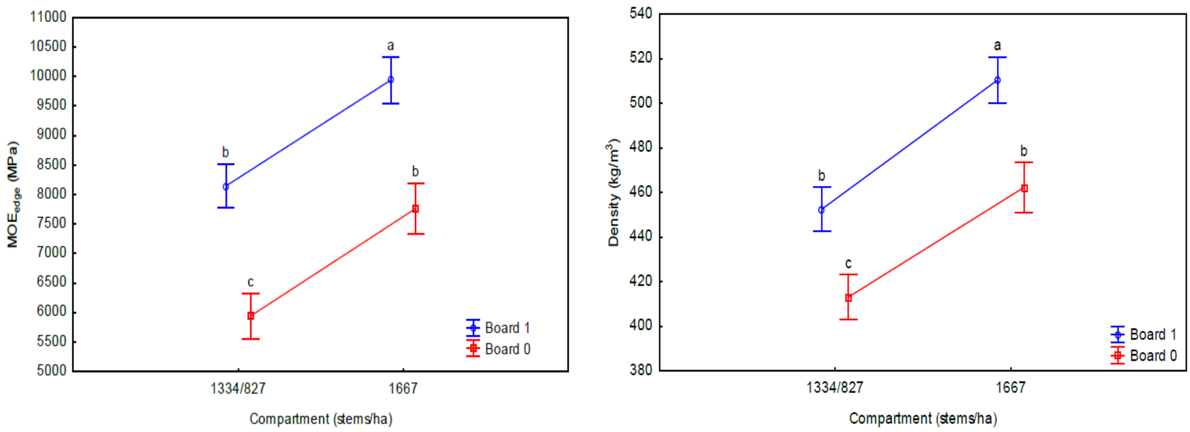


Figure 2: Means and 95% confidence intervals of MOE and density of different compartments form the top and bottom logs. Different letters denote significant differences. (Erasmus, 2016)

Research by Froneman (2014) and Froneman and Wessels (2015) found that the effect of spacing treatment and the board position for both *P. elliottii* and *P. radiata* had a significant effect on the MOE of lumber. There was an increase in MOE with increasing planting density for both *P. elliottii* and *P. radiata.* There was also an increase in MOE from the inner boards to the outer boards and an increase in MOE from each board position with increasing planting density. Figures 3 - 5 show the effect that species, site, spacing and radial variation have on stiffness (MOE). According to the building code requirements the lowest structural grade timber (S5) must have a mean MOE of 7 800 MPa. It is clear from these results that planting density influenced the MOE of lumber for different species differently (Figure 3). *Pinus patula* seem to be the species responding best to higher planting densities even to the extent that the lumber is at similar stiffness levels of Western Cape grown *Pinus radiata* (Figure 3 and 5).

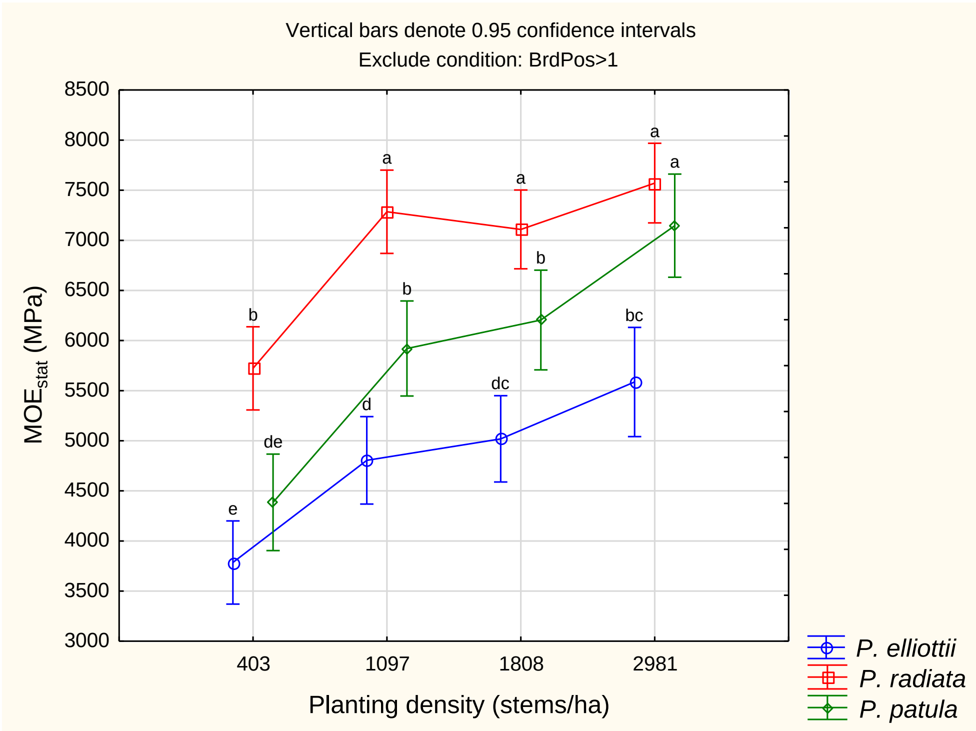


Figure 3: The means and 95% confidence interval of MOE measured on the two centre boards in a log (Froneman and Wessels 2015)

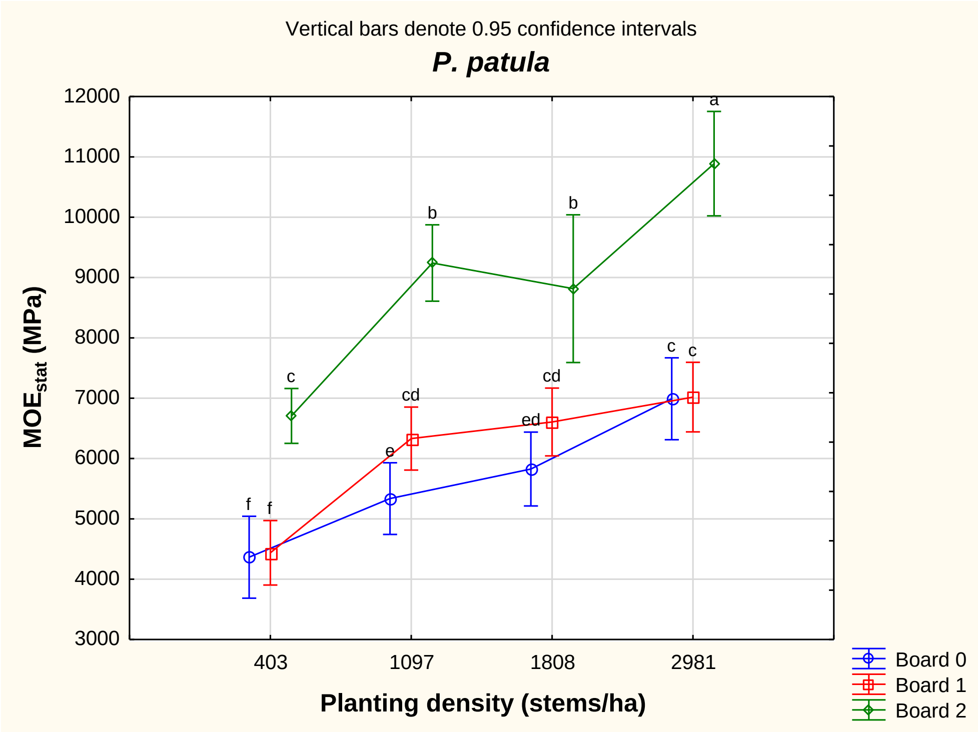


Figure 4: The means and 95% confidence intervals of MOE for Pinus patula boards at different radial positions and spacing treatments (Froneman and Wessels 2015)

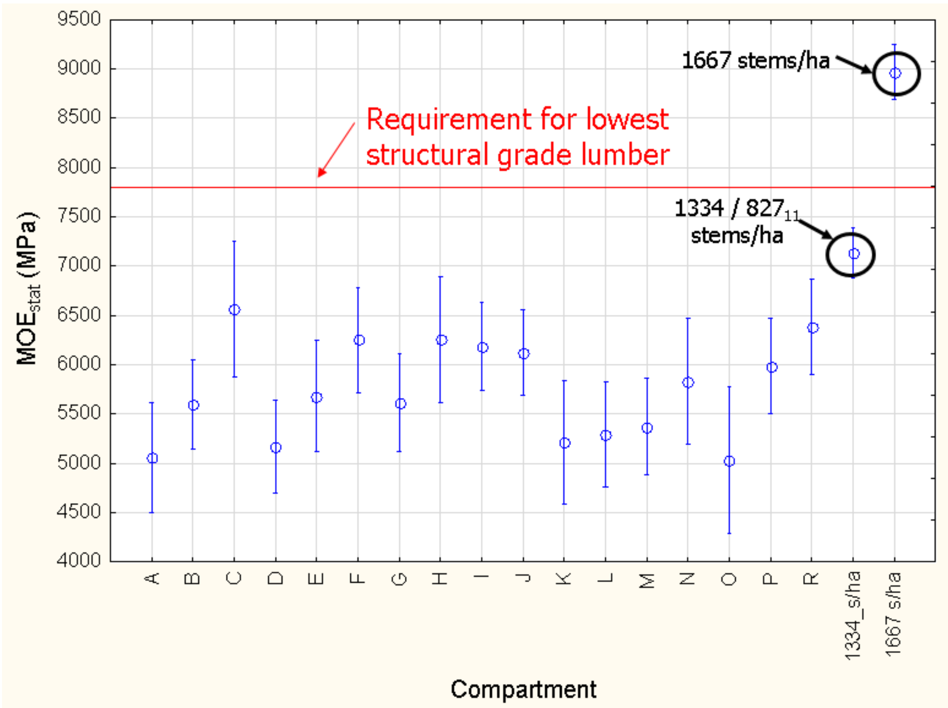


Figure 5: The means and 95% confidence intervals of MOE for lumber from different compartments (Froneman and Wessels 2015)

A number of studies have shown the effect that stem form had on volume and value recoveries of structural grade lumber (Cown et al. 1984, Monserud et al. 2004, Ivković et al. 2007). Monserud et al. (2004) studied the effect that log sweep had on the recovery of simulated sawn logs and found that conversion decreased by 10% with every 25.4mm increase in sweep and lumber value also decreased with increasing sweep deflection. Cown et al. (1984) and Ivković et al. (2007) also found that structural timber grade recovery can be increased with decreasing sweep and increasing MOE for *Pinus radiata*, while some studies suggest value losses in the sawmill process of roughly 10% due to poor stem straightness (Carino et al., 2006). For this study it was important to understand how certain stem form characteristics were affected by planting density and whether initial planting density could be used to improve stem form. It is not clear whether higher planting densities will result in less stem deviation in trees – as there are conflicting results from literature (del Rio et al., 2004; Theron and Bredenkamp, 2004; Egbäck et al., 2012; Liziniewicz et al., 2012; Belley et al., 2013).

In this study the focus was on the effect of high initial planting density on the stiffness (MOE) of South African grown *Pinus patula* and an economic evaluation, considering LEV for an economic analysis, of high planting densities based on the following four spacing treatments: 403 spha, 1 097 spha, 1 808 spha, and 2 981 spha. The effect of planting density on stem form characteristics was also evaluated. The norm in South Africa is typically planting densities between 1 111 to 1 334 spha for *Pinus patula* in the Mpumalanga area (Wessels et al. 2015). Stem form characteristics (ovality, straightness, sinuosity, butt-flare, and taper) from each spacing treatment (initial planting density) were assessed and evaluated. Each of the above were only performed on the bottom part of the tree up to nine m and for each of three sections of 3 m saw logs within that. The sample plots used were from the same trial and therefore from the same vicinity and each remained unthinned. The stem form characteristics were measured by capturing Lidar data of each plot and were not physically measured in field. Lidar was found to be an accurate measurement method for stem form in other studies with Lovell *et al.* (2011), using Lidar scanning from a fixed view point to measure stem diameters, reporting that "the diameter estimations were well correlated with the field measurements at the plot scale and that the range and bearing to trees were in excellent agreement with field data" (Lovell *et al.*, 2011).

Simsaw6 is a software programme that is used by sawmills to determine sawing patterns and machine settings for different log classes that will result in optimal volume and value recoveries. Simsaw can either generate logs for simulation based on user input such as log lengths, taper, ovality, wane specifications, etc. or it can use Lidar data from actual logs in field. Simsaw is a useful tool that takes board values and board specifications through user input into account to determine volume and value recoveries and also gives the user an idea of the type of board products to expect when applying these different sawing patterns and machine settings.

For this study the log positioning was "horns up" with round-the-curve sawing on the cant. According to a study by Wessels (2009) round-the-curve technology is mostly used in old SA framesaw sawmills. Wessels (2009) studied the benefits of individual log positioning optimization compared to the standard conventional log positioning ("horns up" and centred). His findings showed that there was a 2.51 % increase in volume recovery using individual log positioning optimization compared to the standard conventional log positioning. However, after performing a regression analysis, he concluded that it is impossible to predict whether there was a significant advantage using individual log positioning based on log characteristics such as taper, diameter, sweep etc., rather than the standard conventional log positioning method. Carino et al. (2006) showed the impact that curve sawing had on lumber volume and value yields over conventional sawing. Their study suggested that curve sawing or the improvement of stem crookedness or sweep could increase lumber value yield by approximately 9.2%.

Kotze and Malan (2009) stated that "progress to date has proven that the quality of the wood produced by *Pinus patula* can be modelled and effectively incorporated into existing growth and yield software and used on a stand-level basis". It has been proven that pruning is a powerful technique used to improve wood quality, and the predictability thereof, of wood produced in the pruned section of the tree stem (Kotze and Malan, 2009). According to Kotze and Malan (2009) results of spacing and thinning trials have proven that tree volume can be maximized by accelerated incremental growth without having any major effect on wood strength. This pruning, spacing and thinning information gathered over time has been modelled into FORSAT (Forestry Scenario Analysis Tool), an integrated software tool, "which uses a dynamic stand growth and yield modelling system to generate silvicultural and other treatment alternatives for financial analysis with a whole range of financial criteria" (Kotze, 2009). The FORSAT user manual highlights that it can be used to assist forest managers to:

- Compare alternative silvicultural, harvesting and other operational treatments
- Assess risk and damage
- Determine optimum rotation or felling age
- Determine stand or plantation value over time
- Compare forestry with alternative land-use investments

Net Present value (NPV), Expected Annual income (EAI), Benefit Cost Ratio (BCR), Internal Rate of Return (IRR) and Land Expectation Value (LEV) are financial decision criteria used to evaluate the financial feasibility of forestry projects based on discounted cash flow (Uys, 2000a; Bettinger et al., 2009;). According to Ham and Jacobson (2012), LEV (also known as Soil Expectation Value) is unique to Forestry. "LEV is also used in forestry valuation as it gives an indication of the maximum price a forestry investor could pay for bare land and still earn the minimum acceptable rate of return "(Ham and Jacobson, 2012). LEV can be used to compare forestry projects with different time periods because it accounts for an infinite time line, while NPV for example, cannot be used to compare projects with different time periods (Bettinger et al., 2009). Cubbage et al. (2010), from North Carolina State University, investigated the global forest plantation investment returns in 2008 for exotic species in selected countries. They estimated financial returns in timber investments for *Pinus patula* and *Eucalyptus grandis* in South Africa and assumed "typical forest management practices with good sites and good management" (Cubbage et al., 2010). In their calculations they included production rates, base factor costs, and timber stumpage costs. However, they excluded land prices/costs to make sure that it was possible to compare results for investment returns among different countries. These investment returns were based on factor costs and prices and timber productivity. The returns to these investments were analysed using standard capital budgeting techniques and criteria which included Land expectation value (LEV), net present value (NPV), and internal rate of return (IRR) with an 8% discount rate. Their results indicated an estimated LEV of 1 862 $/ha (approximately 15 361 R/ha, based on the exchange rate in 2008) for *Pinus patula* and 2 872 $/ha (approximately 23 694 R/ha) for *Eucalyptus grandis* in South Africa. These results were quite poor and much lower compared to results from other countries. FORSAT was a tool used in this study to perform an economic analysis of different management regimes for each spacing treatment to determine the best land expectation value (LEV).

Falcão and Uys (1999) performed an economic evaluation to determine the minimum required yield for profitable sawtimber production for *Pinus patula* on the Mpumalanga escarpment. They used NPV as their financial criteria. Their results showed that a minimum yield of 14, 17 and 20 m^3/ha/annum at a discount rate of 2, 3.5 and 5% respectively, will results in the minimum NPV's of R 372 R/ha, R 410 R/ha and R 307 R/ha respectively. No economic study has been done on the Mpumalanga escarpment on the LEV based on different planting densities for *Pinus patula*. This is the first study that attempts to perform an economic evaluation of *Pinus patula* for different management regimes based on higher planting densities.

Chapter 3

3. Materials and methods

3.1 Experimental layout

This study was conducted using an 18-year-old *Pinus patula* experimental spacing trial located near Barberton on the Mpumalanga escarpment. The average annual rainfall for this compartment from 1 981 to 2015 was 948.91 mm. The experiment consisted of two replications of four planting densities (Figure 6). The planting densities used were 403, 1 097, 1 808, and 2 981. Each spacing treatment had been planted with 49 seedlings in a 7x7 layout but only the centre 25 trees (5x5 layout excluding the buffer/edge trees) were included in the study. Forked trees were not considered for examination due to the fact that the software used to determine the stem form could not take forking into account. Out of a possible 200 trees only 144 were still available for this study due to forking and mortality.

Figure 6: Experimental layout of spacing treatments

3.2 Lidar and Stemfit

A terrestrial Lidar scanner, Trimble FX (Figure 7) was used to scan each plot in each repetition. For this study (Figure 7 and 8) four stations were used in each plot (one in each corner of each plot). Once the data was uploaded, a software program called Trimble RealWorks® was then used to extract each individual tree from the point cloud and saved as separate files. Each tree could then be assessed individually later in the *Stemfit* software, a program developed in *RStudio* by Scientes Mondium UG. Stemfit (Scientes Mondium, 2017) was developed in 2017 to determine five stem form characteristics (straightness, taper, butt-flare, ovality and sinuosity) of trees from data gathered in field through Lidar scanners and to obtain three 3 m logs of the first 9 m of each tree stem from this data that can be used to calculate log values and log recoveries in the Simsaw software.

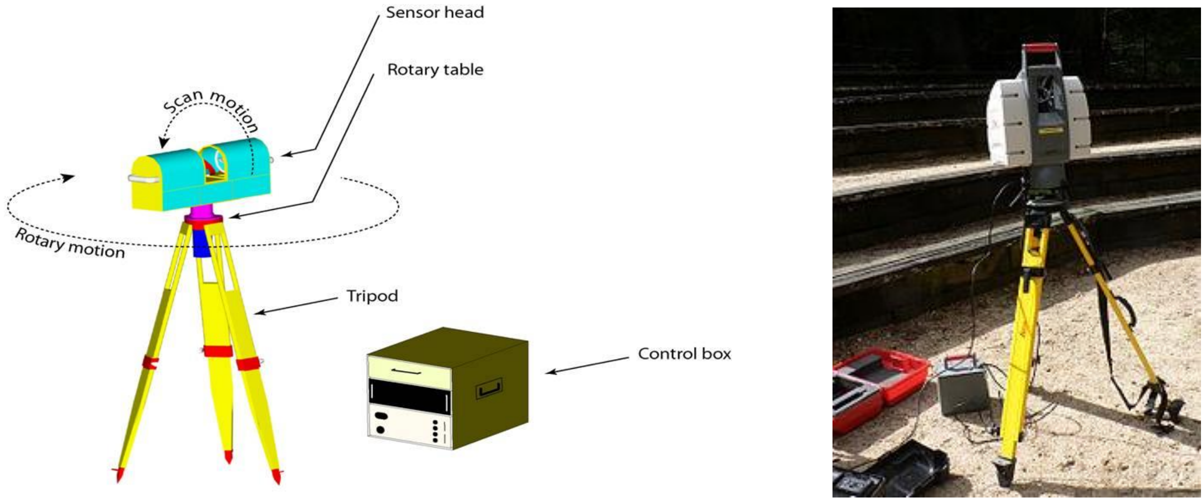


Figure 7: Image of Lidar scanner

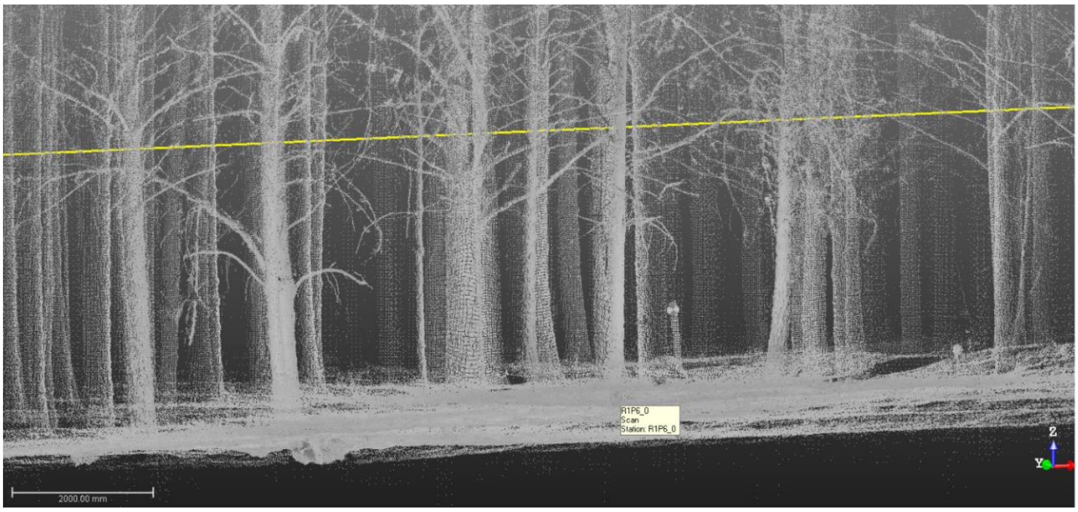


Figure 8: Lidar images of tree stems

Stemfit (Scientes Mondium, 2017) was used to determine the stem form characteristics of each tree from each spacing treatment. However, the program could not be used to determine stem form characteristics of trees that forked and any forked tree could not be considered for further evaluation. When *Stemfit* (Scientes Mondium, 2017) was run in *RStudio (*R Core Team, 2014), the programme opened up each individual tree file previously saved in point cloud form from Lidar data gathered of all trees in each plot. It then firstly put the tree into an upright position before determining the centre line through the stem

(Figure 9). It then predicted and fitted discs every 10 cm (similar to a cambium ring under bark) as best as possible and developed a stem profile (Figure 10 and Figure 11) before finally calculating the sinuosity, taper, straightness, butt-flare, and ovality of each tree log from 0.3 to 9.3 m along the stem. The 9 m log was then bucked into three by 3 m saw-logs and each stem form characteristic was then recalculated for each 3 m saw-log.

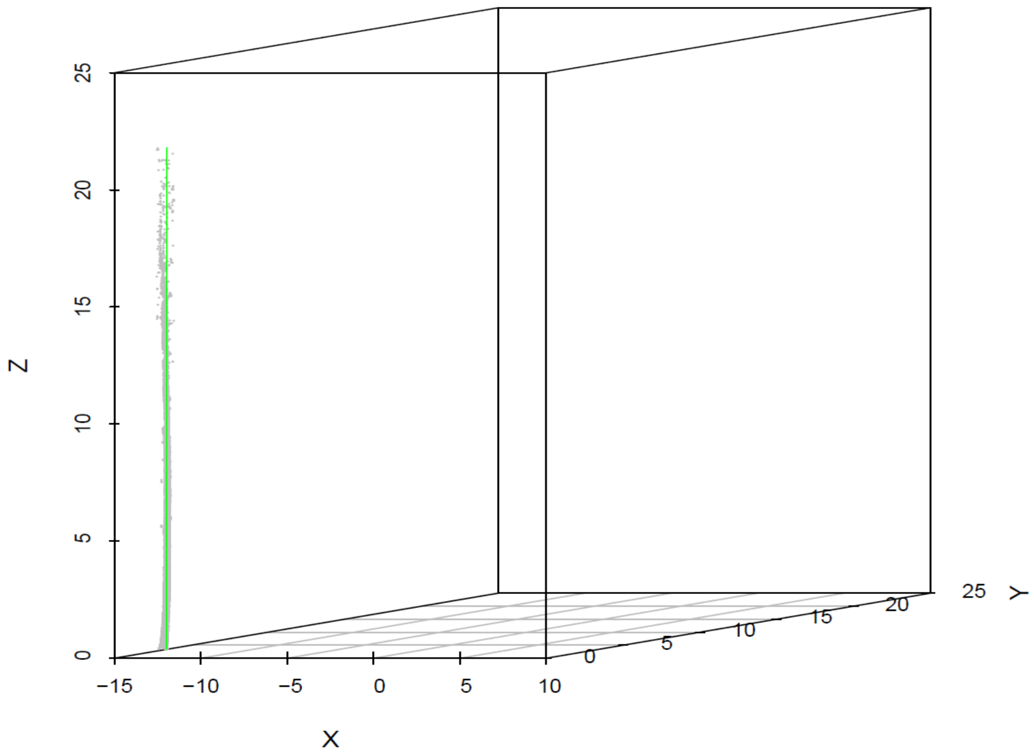


Figure 9:Upright positioning of tree stem in point cloud form (units in m). The graph is plotted using a coordinate system (x,y,z) in meters (m).

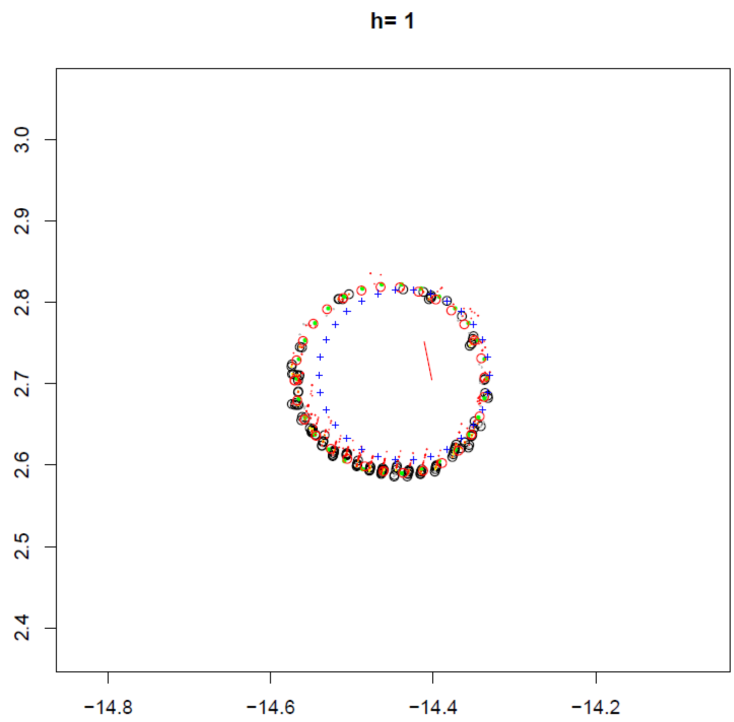


Figure 10: An example of the method of determining a disc at height = 1 m. The graph is plotted using a coordinate system (x,y) in meters (m).

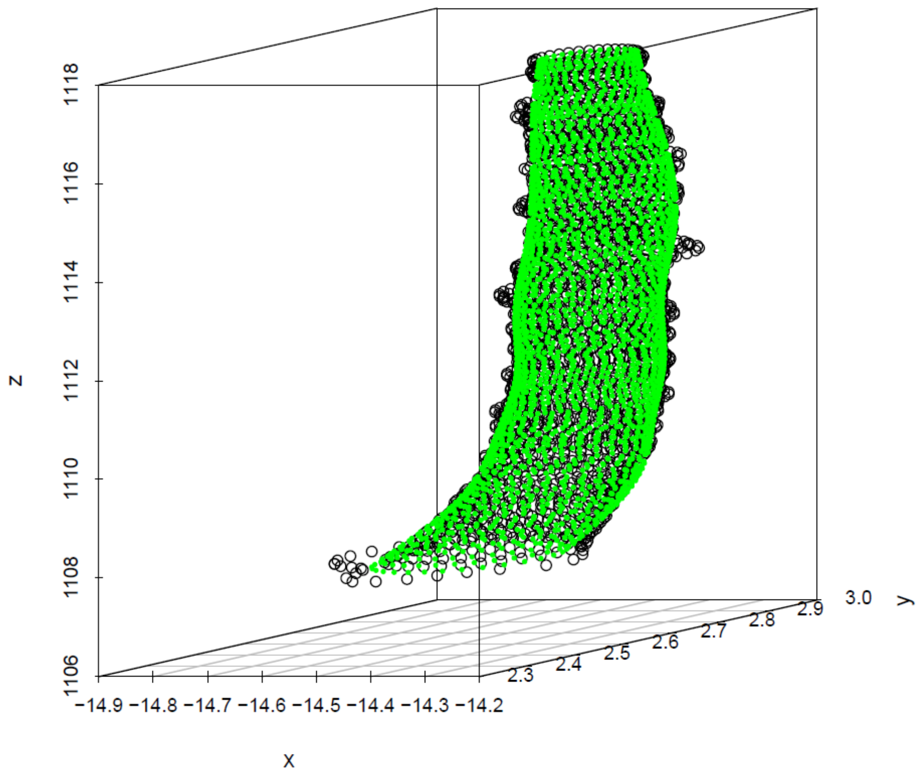


Figure 11: A stem profile of a randomly selected tree. The graph is plotted using a coordinate system (x,y,z) in meters (m).

Sinuosity (Figure 12) was calculated as the curved distance of a log divided by the straight line distance from the centre point at the bottom to the centre point at the top of each log. It is a ratio and therefore unit less (m/m).

$$Sinuosity = \frac{\mathrm{a}}{\mathrm{b}}$$

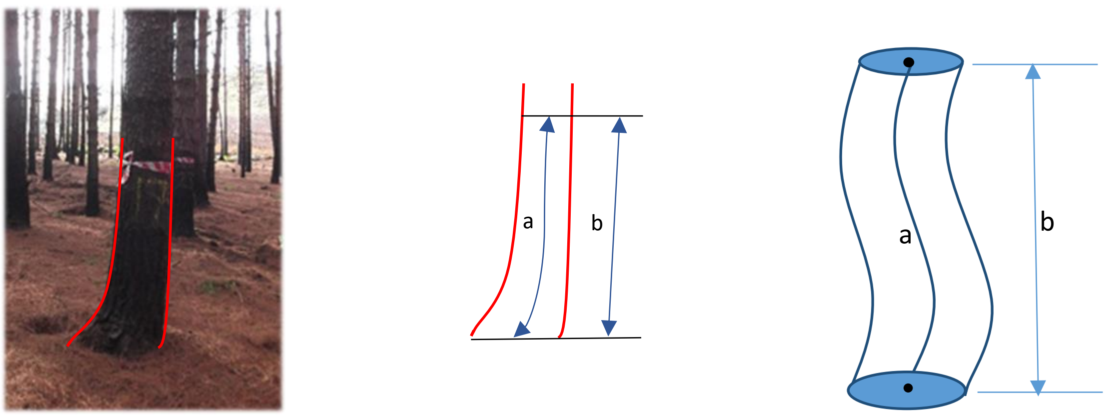


Figure 12: Drawings explaining sinuosity calculations

Straightness (Figure 13) was measured as the maximum deviation of the centre line of a log from the straight line distance fro the centre point at the bottom to the centre point at the top of each log. From here onwards straightness will be referred to as stem deviation.

$Straighness = t$ (m)

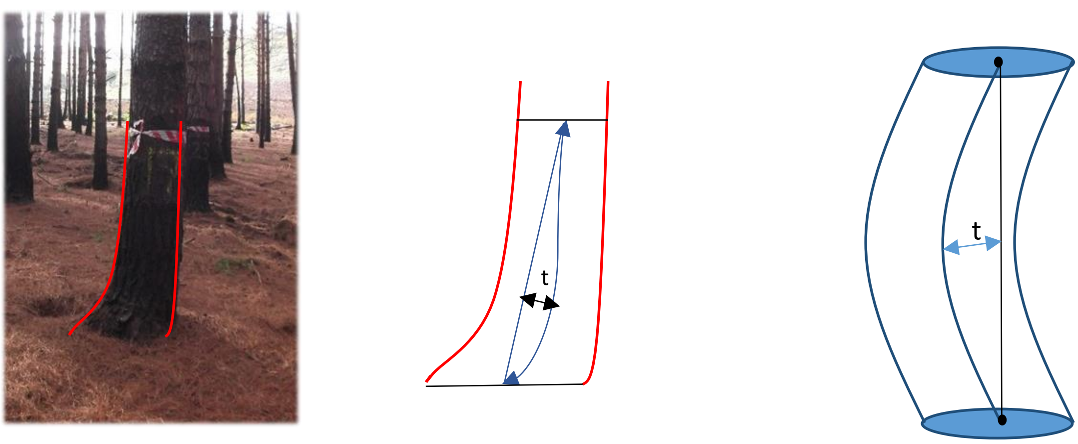
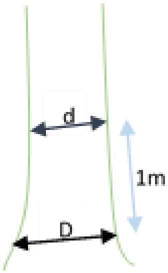


Figure 13: Drawings explaining straightness calculations

Butt-flare is the taper at the butt end of a log. Figure 14 shows an example of the method used to calculate butt-flare. It was calculated using the same formula as taper, however it was only measured over a 1 m distance from 0.3 to 1.3 m along the butt end of a log (Figure 14).

$$Buttflare = \frac{\mathrm{R} - \mathrm{r}}{1}$$



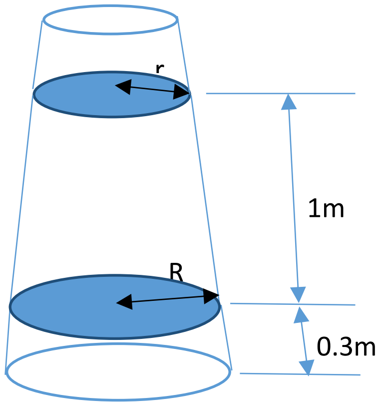


Figure 14: Drawings explaining butt-flare calculations

Figure 15 below shows an example of the method used to calculate ovality. Ovality was calculated as the maximum diameter divided by the maximum perpendicular diameter to the maximum diameter (Figure 15). For this study an average diameter was used for each 3 m saw log and the full 9 m log. The closer ovality is to 1, the closer it is to being a perfect circle. Ovality according to definition, cannot be less than 1.

$$Ovality = \frac{\text{maximum diameter (m)}}{\text{perpendicular diameter to maximun diameter (m)}}$$

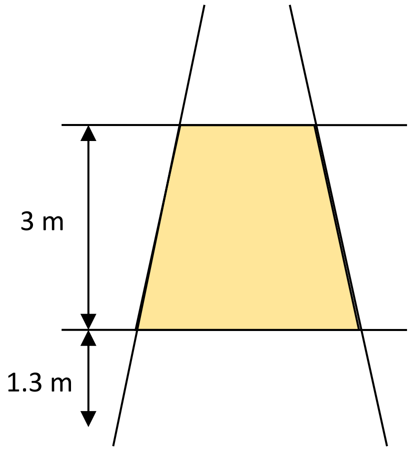
Figure 15: Drawings explaining ovality calculations

3.3 Statistical Analysis

The experiment consisted of two repetitions of six spacing treatments in a 3x2 design of which only four spacing treatment were considered for this study as seen in Figure 6. An Analysis of Variance (ANOVA) was performed on the data to test whether the population treatment means differed significantly. The errors (residuals from the linear model) were first tested for normality using Shapiro-Wilk test and homoscedasticity using Levene's test. The results from an ANOVA are only valid if the data is normal distributed and homoscedastic. If these two assumptions were rejected then a non-parametric test was performed using the Kruskal-Wallis test in conjunction with a box-cox transformation. Box-cox transformation is a tool that was used only in some instances to normalise data that was found to be not normally distributed when tested for normally using the Shapiro-Wilk test. Multiple comparison tests (Tukey's post hoc test) were also performed to determine exactly which spacing treatments differed from each other.

3.4 Board grading

Ten trees were randomly selected from each plot and felled. These trees were sent to a local saw mill where they were processed into boards of two different sizes. Boards were cut to 38 x 114 mm (wet dimension: 40 x 120 mm) and 38 x 152 mm (wet dimension: 40 x 160 mm) for the larger trees, then later re-sawn to 38 x 114 mm (Figures 16 and 17).



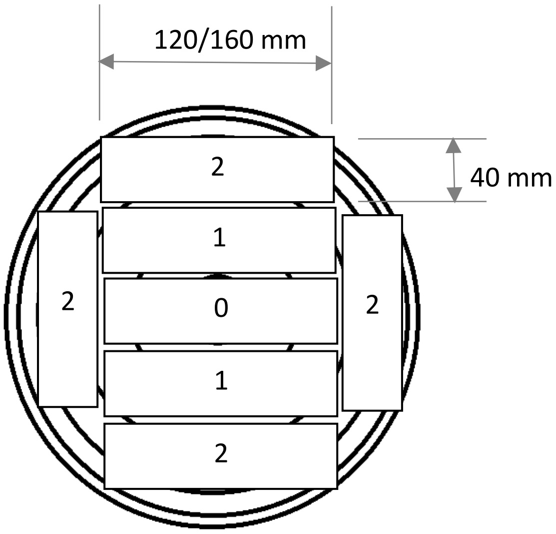
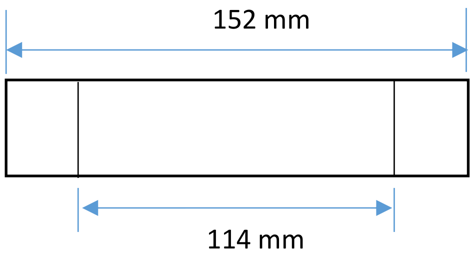


Figure 16: Sawlog position and numbering of board positions



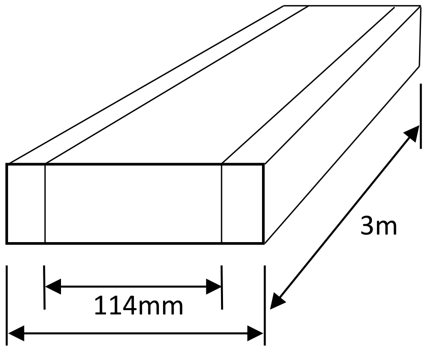


Figure 17: Re-saw process of kiln dried 152mm to 114mm wide boards

Each board was marked according to its position within the tree, starting with board "0" in the centre of the tree containing pith tissue moving outwards (Figure 16). A bending test was conducted according to SANS 6122 (2008). The mechanical properties were determined by calculating the MOE and MOR for each board. However, the MOR could not be calculated for board size 38 x 152mm because they still needed to be re-sawn to 38 x 114mm and MOR requires destructive testing (testing was done on the 38 x 114mm boards). The MOE was calculated according to the SANS 6122 method (Figure 18). The boards had to withstand a force between 400N and 2100N using an Instron universal testing machine. The universal Instron testing machine is commonly used to determine the compressive and tensile strengths of material as well as to perform bending tests to determine the modulus of elasticity (MOE) and modulus of rupture (MOR) of material. For this study the Instron machine was set with a cut out load of 2 100 N and recorded the displacement of the board up to the point where the cut-out load was reached or until we manually stopped it. During this process a graph was created with the displacement on the x-axis and force on the y-axis (Figure 19). The MOE was calculated using the initial linear part of the graph (Figure 19). MOE was determined as the stress (change in force in Newton) over strain (change in displacement in millimetre) between two points along the straight line (Figure 19).

The boards were then graded according to their MOE and MOR. According to SANS 10163-1 requirements, a group of boards must have a mean MOE of 7 800 MPa to pass for the lowest structural grade timber (S5). A study by Erasmus (2016) showed the position of each board in young *Pinus patula* trees had an influence on its mechanical properties.

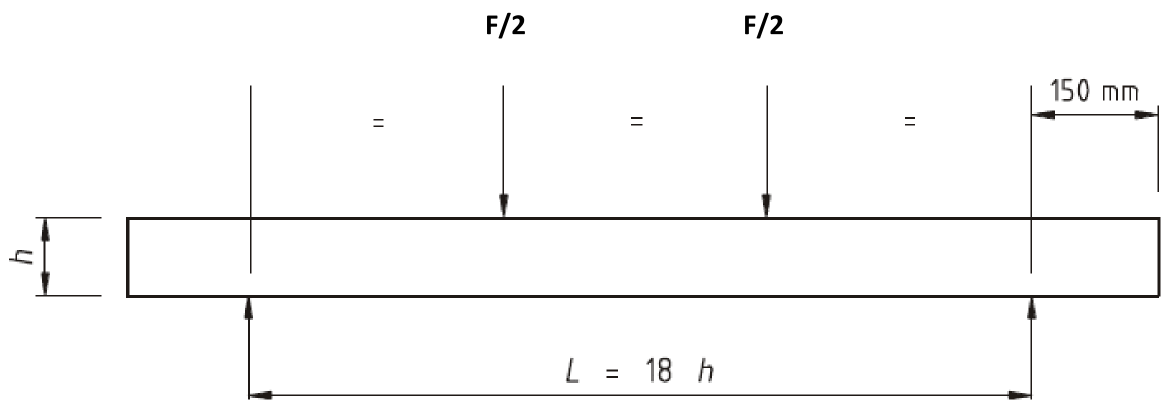


Figure 18: Bending test. Method for determining stiffness (F = Force in Newton, L = length, h = width of board)

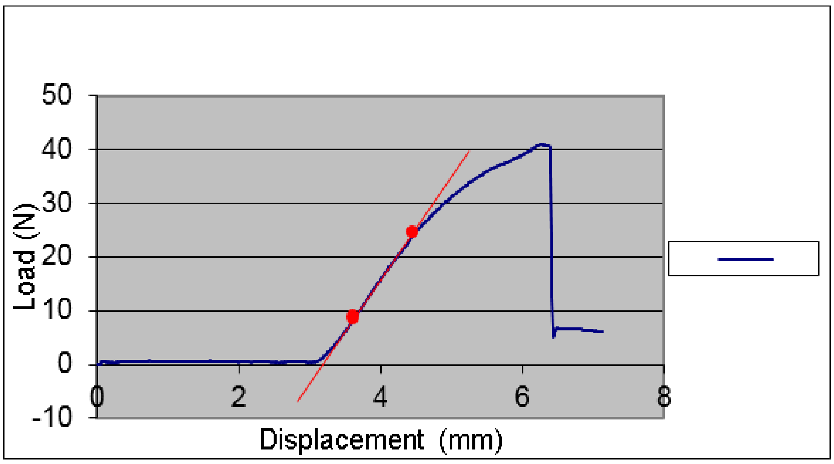


Figure 19: Example of an output graph from an Instron machine used to calculate MOE

3.5 Board value calculation

A board value was then calculated for each board position in each spacing treatment based only on the MOE requirements of grade S5. The reason for this is that MOE is the limiting property for our structural grades. The board value for this study was dependent on the initial planting density of the plot, the position in the tree that the board came from, as well as the ratio of black cross to S5 boards from each plot. The MOE from each board position of each spacing treatment was sorted in descending order (largest to smallest). The boards with the lowest stiffness (MOE) were eliminated one by one until the group of remaining boards achieved a mean MOE of 7 800 MPa required for S5. The percentage of boards remaining and the percentage of boards eliminated for each board position was then calculated. A board value was then calculated using the following formula:

$$Board\ value\ (R/m^3) = (A * S5price) + (B * XXXprice)$$

Where:

A = Percentage of boards that achieved the mean MOE of 7 800 MPa

B = Percentage of boards that did not achieve the mean MOE of 7 800 MPa

Table 1: Utility grade and S5 grade board prices

Board (mm):	XXX Price (R/m^3)	S5 Price (R/m^3)
38x114	R 2 351.00	R 2 680.00
38x152	R 2 386.56	R 2 712.00

The XXX and S5 saw timber board prices used to calculate board values were obtained from Crickmay and Associates (2015) (Table 1). These board values were later used in the sawmill simulation software Simsaw6 to calculate log values.

3.6 Simsaw6 simulations

The *Stemfit* software (Scientes Mondium, 2017) created three-3 m logs from each 9 m log and saved them in an MS Access Simsaw template. The exact stem shapes as determined from the Lidar scans were used and therefore the value influence of stem shape was included in this study. Simsaw takes ovality, sweep, diameter and taper into account. It was decided to use 3 m logs as it is a typical log length used by small-log sawmills. Six log classes were created in Simsaw6 that were used to group logs according to their small end diameters (SED). The board values calculated after grading were entered as part of the board product definitions in Simsaw6. An optimal sawing pattern for each log class was obtained by applying different sawing patterns to each log class and selecting the one that resulted in the best value and volume recovery for that log class. This ensured that the best volume and value recoveries were obtained for each log class. The input values for the Simsaw6 simulations were fairly standard (3 m sawlog lengths were used) for a short log saw mill and can be seen in Appendix A. It is important to note that no round-the-curve abilities were simulated which is standard for short log mills (where small short-log saws have curve sawing abilities it is very limited in terms of the curve it can handle). Also, take note that 25 mm boards were allowed in the sawing pattern but using only an average price with no quality influence (Figures 20-25).

The log volume recoveries were then plotted in a scatterplot and a line of best fit was applied. The equation for this line of best fit was then used to provide a volume recovery for the log classes that contained no logs. The value recovery obtained from Simsaw6 was adjusted by a ratio of the Simsaw6 volume recovery and the volume recovery according to the South African standard yields for softwood sawlog classes in in Appendix B (Table 8.7.5) as developed by the old Department of Forestry more than three decades ago (Southey, 2012). The reason for this was that different sawing patterns and log specifications for a specific sawmill setup can give fluctuating volume recoveries. The Department of Forestry values aimed to provide “general” volume recovery that could be obtained for a specific log class. Despite very old data it is still the best data available for normalisation. A log value for each log class of each spacing treatment was then calculated using the volume and value recoveries.

A scatterplot and line of best fit was also applied to obtain a value recovery for spacing treatment 1 097 spha. These small adjustments were necessary due to the small number of logs available for this study. A processing cost (cost of production) of R 484/m^3 was subtracted from the value recoveries of each log class from each spacing treatment to obtain a net value recovery. The net log values were later used in FORSAT to perform an economic analysis.

25/76/25 + 3*38/2*25

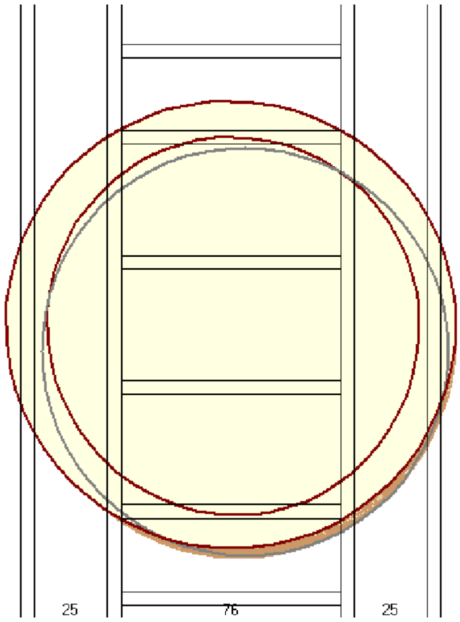


Figure 20: Sawing pattern for log class 13-17.9 SED

38/114/38 + 5*38

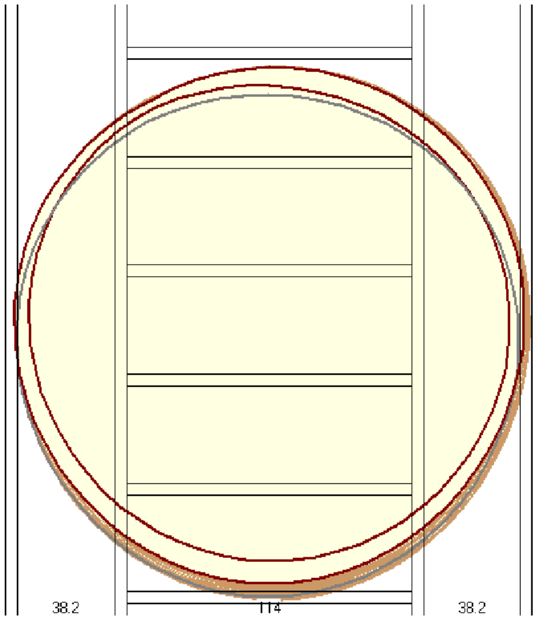


Figure 21: Sawing pattern for log class 18-21.9 SED

38/114/38 + 5*38

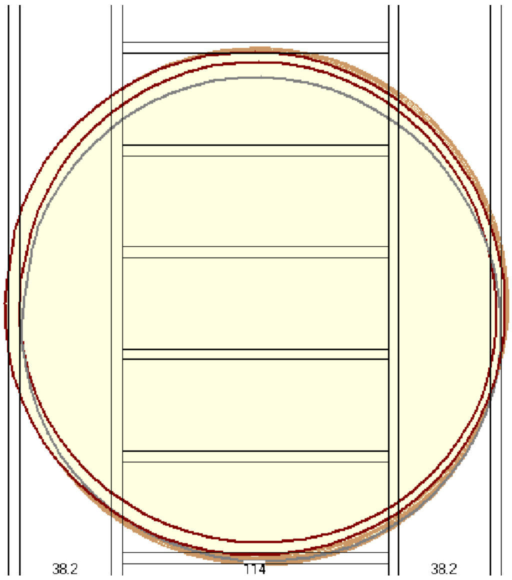


Figure 22: Sawing pattern for log class 22-25.9 SED

38/152/38 + 5*38/2*25

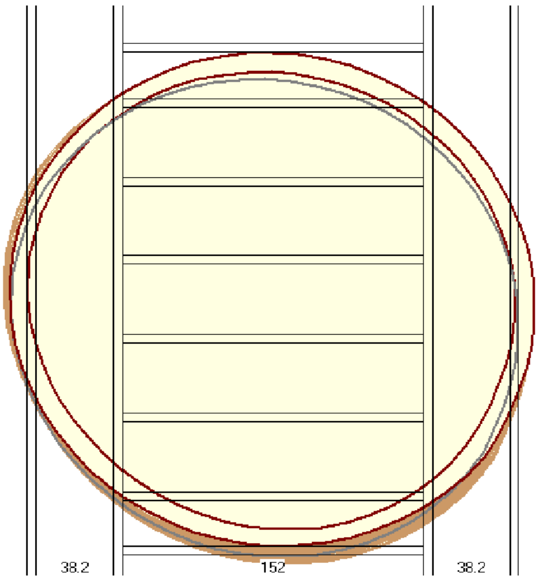


Figure 23: Sawing pattern for log class 26-29.9 SED

25/38/152/38/25 + 5*38/2*25

25/38/228/38/25 + 7*38/2*25

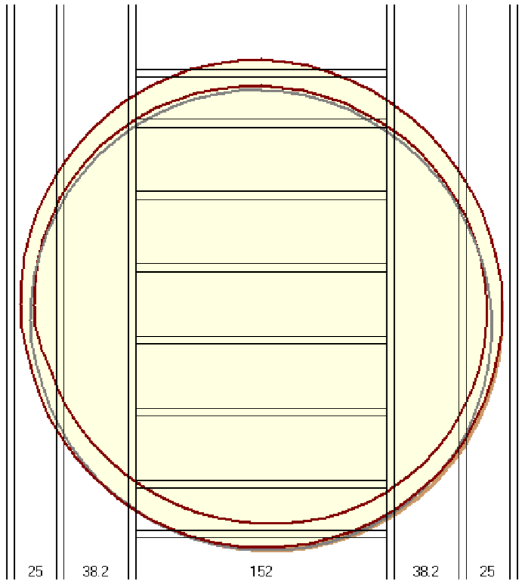


Figure 24: Sawing pattern for log class 30-33.9 SED

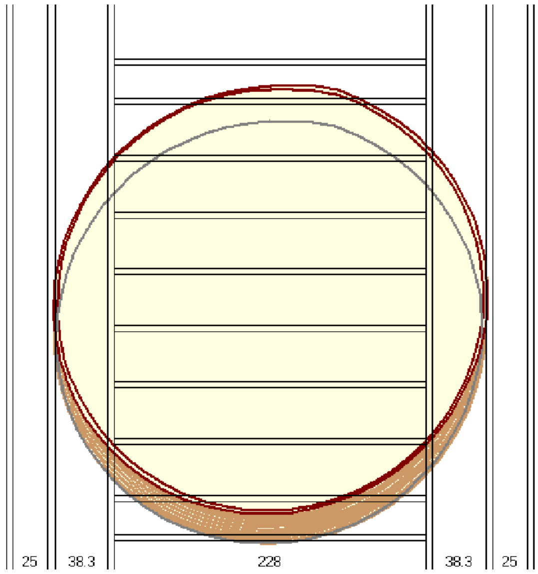


Figure 25: Sawing pattern for log class 34+ SED

The output from this part of the analysis was a set of log values for each log class of each spacing treatment. These log values essentially also captured the real quality-driven price from structural products. A 20 cm diameter log from spacing treatment 403 spha will therefore have a different value to a 20 cm diameter log from 2 981 spha treatment due to the difference in S5 recovery from the two treatments.

3.7 FORSAT - LEV

FORSAT was used for economic analysis of different management regimes for each spacing treatment to determine the best LEV. According to the definition in the FORSAT user manual – "The LEV formula compounds all the items in the cash flow of a planned forestry project, excluding the cost of land, rotation age and discounts this net terminal value to the present time". The LEV was used rather than IRR (Internal rate of return) because IRR cannot be used to compare projects over different time periods (Ham and Jacobson, 2012). According to Uys (2000) IRR should not be used to compare or rank projects, even if the projects have equal lives.

FORSAT was calibrated using enumeration data (real data) that was recorded for each spacing treatment, of the same trial by Sappi, from year 0 to year 18. Calibration uses this "real data" (enumeration data) in the FORSAT model to accurately predict future results of the actual spacing treatments. Enumeration data consisted of the quadratic DBH (DBHq) and mean height for each spacing treatment at 8 y. Calibration also takes mortality into account and uses these values in a model to predict future tree growth.

The management regimes used were unthinned and one thinning per spacing treatment (Table 2). More thinnings were not considered simply because it would create too many options to model. There were 25 scenarios evaluated per spacing treatment except for spacing treatment 403 spha which only had one scenario (unthinned) (Table 2). For each plot a range of thinning ages and thinning densities was modelled. Thinning densities started at 150 spha up to 400 spha with increments of 50 spha for each scenario. This was repeated for four different thinning ages per plot (years 10, 11, 12, 13). The thinning ages considered for evaluation started at 10 y where it was guaranteed competition between trees would be evident and ended at age 13 (Table 2). Earlier thinning would possibly not result in the higher stiffness inner boards as found in several other studies (Dowse and Wessels, 2013) on *Pinus patula* planted at higher densities. This data, however, come from an unthinned trial. Late thinnings were allowed as the board quality in the juvenile section of the log start to stabilise after 10 y of age. Earlier thinnings will probably result in very low MOE values in the core sections as found in the study by Dowse and Wessels (2013).

All costs used in FORSAT were obtained from FES (Forest Economic Services) South Africa (Table 3). These costs included labour costs for each activity and were the benchmark costs for northern Mpumalanga in 2015 (Meyer and Rusk, 2015). Costs were adapted to get a "per tree" value where relevant i.e. planting, fertilising and prunning – in that case it was assumed that each operation would take the same amount of time per tree and thus the higher planting densities had higher costs associated with it. Other costs, such as harvesting and thinning cost, was calculated by plotting the FES harvesting cost for a particular tree size in a scatterplot (Figure 26) and applying an exponential fit to it. It was assumed that 1m^3 came from a tree with a DBH of approximately 69 cm. Therefore, spacing treatment 403 spha (DBH = 37cm) had a tree size of 0.54 m^3, 1097 spha (DBH = 26.5) had a tree size of 0.38 m^3, 1808 spha (DBH = 23) had a tree size of 0.33 m^3, 2981 spha (DBH = 20) had a tree size of 0.29m^3. FES calculated clearfell harvesting costs and thinning costs based on tree size using motor-manual felling for both operations which included the cost of extraction to road side.

Therefore, Figure 36 was used to determine thinning and harvesting costs based on tree sizes predicted using FORSAT. A transportation cost of R 100.23 per m^3 was obtained from FES and added to the thinning and harvesting costs.

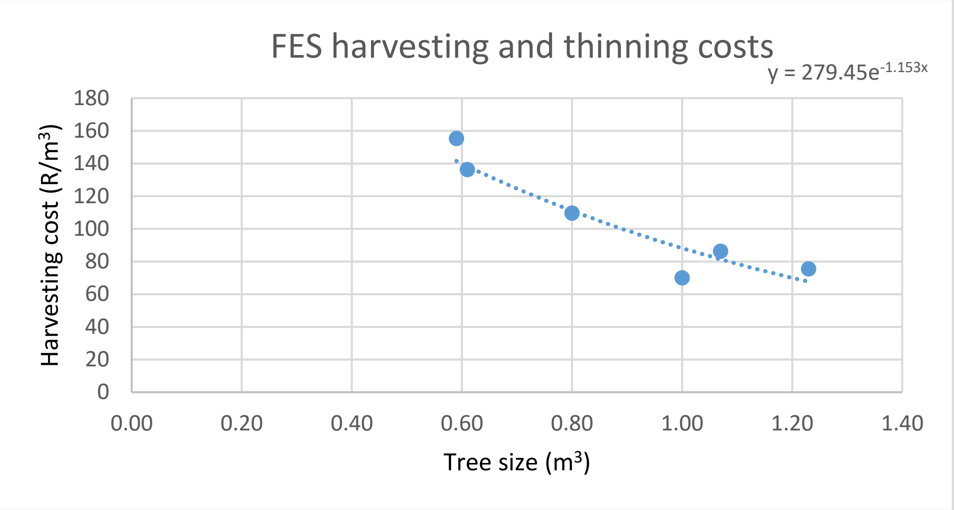


Figure 26: Scatterplot used for harvesting and thinnings calculations.

The economic evaluation was assessed by determining the best possible LEV for different scenarios simulated in FORSAT.

Table 2: Table 9: Management scenarios that were evaluated per spacing treatment in FORSAT

Spacing treatment (spha):	Thinning intensity (spha remaining)	Age of thinnings (years)
403, 1097, 1808, 2981	unthinned	-
1097, 1808, 2981	150	10,11,12,13
1097, 1808, 2981	200	10,11,12,13
1097, 1808, 2981	250	10,11,12,13
1097, 1808, 2981	300	10,11,12,13
1097, 1808, 2981	350	10,11,12,13
1097, 1808, 2981	400	10,11,12,13

Table 3: All activity costs used in FORSAT for each spacing treatment.

	Adjusted costs per spacing treatment				Units
Activity	2,981 spha	1,808 spha	1,097 spha	403 spha	
Pine Establishment:					
Land Prep	R 2,457.53	R 2,457.53	R 2,457.53	R 2,457.53	R/Ha
Planting	R 4,289.63	R 2,601.70	R 1,578.57	R 579.91	R/Ha
Blanking	R 1,500.99	R 910.36	R 552.36	R 202.92	R/Ha
Fertilising	R 2,325.98	R 1,410.72	R 855.95	R 314.45	R/Ha
Total	R 10,316.94	R 6,257.31	R 3,796.61	R 1,394.74	R/Ha
Tending:					
Weed control	R 536.79	R 536.79	R 536.79	R 536.79	R/Ha
Prun 2.5	R 1,775.29	R 1,076.73	R 653.30	R 240.00	R/Ha
Prun 3.5	R 1,809.42	R 1,097.43	R 665.86	R 244.61	R/Ha
Prun 5.5	R 1,888.95	R 1,145.66	R 695.13	R 255.37	R/Ha
Marking for Thin	R 860.02	R 521.61	R 316.49	R 116.27	R/Ha
Delayed Fertilising	-	-	-	-	R/Ha
Total	R 6,385.88	R 4,232.04	R 2,926.51	R 1,652.20	R/Ha
Capital Employed:					
Land	14000	14000	14000	14000	R/Ha
Trees	R 71,769.39	R 43,528.70	R 26,410.94	R 9,702.47	R/Ha
Movable Assets	196	196	196	196	R/Ha
Fixed improvements	1255	1255	1255	1255	R/Ha
Roads	2075	2075	2075	2075	R/Ha
Total	R 75,295.39	R 47,054.70	R 29,936.94	R 13,228.47	R/Ha
Harvesting costs:					
Total on road side (Clearfell thinned regime)	R 153.13	R 145.64	R 144.43	-	R/m3
Total on road side (Clearfell unthinned regime)	R 200.06	R 190.28	R 179.47	R 150.59	R/m3
Thinning:					
Total	R 206.86	R 193.49	R 182.49	-	R/m3
Transportation costs:					
Transport	R 100.23	R 100.23	R 100.23	R 100.23	R/m3

Forest protection and conservation:					
Control pest and noxious weeds	140.27	140.27	140.27	140.27	R/Ha
Fire protection and insurance	393.29	393.29	393.29	393.29	R/Ha
Fire fighing	53.17	53.17	53.17	53.17	R/Ha
Conservation and enviro management	63.14	63.14	63.14	63.14	R/Ha
Total	649.87	649.87	649.87	649.87	R/Ha
Forest Overheads:					
Hand tools	0.91	0.91	0.91	0.91	R/Ha
Building maintenance	99.07	99.07	99.07	99.07	R/Ha
Maintenance of other improvements	6.97	6.97	6.97	6.97	R/Ha
Administration	1330.36	1330.36	1330.36	1330.36	R/Ha
Total	1677.24	1677.24	1677.24	1677.24	R/Ha
Nominal cost of capital	11.8	11.8	11.8	11.8	%
Inflation index	5.5	5.5	5.5	5.5	%

Chapter 4

4. Results

The number of trees evaluated for stem form varied between treatments. The 1 097 spha treatment had a significantly lower number of trees for evaluation because there was only data available for one of the two repetitions due to the data for the second repetition being misplaced/lost. There was a total of 144 trees evaluated from four different spacing treatment. It consisted of 44 trees from 403 spha, 20 trees from 1 097,39 trees from 1 808 spha, and 41 trees from 2 981 spha,. Stem form was only evaluated on the bottom 9 m of each stem. The data for each stem form characteristic was not normally distributed and also not homoscedastic for stem deviation and stem sinuosity, therefore, the ANOVA results were not valid and non-parametric tests, post hoc multiple comparison tests and box cox transformations had to be performed to determine which spacing treatments differed from each other.

Table 4 indicates the average DBH (diameter at breast height) and average height (in m) for each spacing treatment. The decreasing trend in average DBH from 403 to 2981 spha was expected due to the fact that the trees in spacing treatment 403 spha have more room for growth, less competition and more growth resources per tree. Mortality is shown in Table 4 as a percentage of the initial planting density and calculated at age 18. Mortality increased with increasing planting density.

Table 4: General tree information for each spacing treatment.

Treatment	Average DBH	Average height	Average slenderness	Mortality (%)
403	34.98	23.53	0.69	2
1097	26.38	23.50	0.91	16
1808	23.18	22.44	1.00	34
2981	19.56	21.44	1.13	52

4.1 Stem deviation and Sinuosity

The stem form of 144 trees were evaluated and the results for stem deviation can be seen in Figure 27 and Table 5. The Shapiro-Wilk test was performed for normality and this test indicated that the data for stem deviation was not normally distributed ($p < 0.001$). Levene's test for homoscedasticity showed that there was a significant difference in variance between spacing treatments ($p < 0.001$). Tukey's post hoc test was performed to indicate any significant difference in mean stem deviation between spacing treatments. Results show that there was a significant difference in mean stem deviation between 403 spha and 2 981 spha ($p = 0.0113$), and 403 spha and 1 808 spha ($p = 0.0042$). There was a decreasing trend in stem deviation from 403 spha to 2 981 spha as seen in Figure 27. Spacing treatment 1 808 spha and 2 981 spha had similar mean deviations of 0.082m and 0.076m respectively (Table 5), however, there was a slight increase in mean deviation from 1 808 spha to 2 981 spha which contradicts the general decreasing trend.

Figure 28 represents the deviation (or straightness) of each 3 m saw log positions for different spacing treatments. There was a decreasing trend in deviation from 403 to 2981 spha for saw logs obtained at 0.3 to 3.3 m within trees. Saw logs obtained from 3.3 to 9.3 m within trees had fairly similar mean deviations from 403 to 2981 spha and therefore no obvious trend was visible. The 403 spha trial had a maximum stem deviation of 0.446 m which was more than double the maximum stem deviation from 1 808 spha of 0.208 m. The variance between treatments also differed significantly.

Results for sinuosity were very similar to the results for deviation. Spacing treatment also had a significant effect on mean stem sinuosity (Figure 29).

Table 5: Minimum, maximum, mean and standard deviation values for stem deviation from each spacing treatment.

Deviation (m)						
Spacing treatment	**No. of trees**	**Min**	**Max**	**Mean**	**Standard Dev.**	**Coef. of variance**
403 spha	44	0.026	0.446	0.132	0.100	0.759
1 097 spha	20	0.032	0.383	0.109	0.087	0.795
1 808 spha	39	0.015	0.208	0.076	0.042	0.545
2 981 spha	41	0.019	0.238	0.082	0.054	0.660

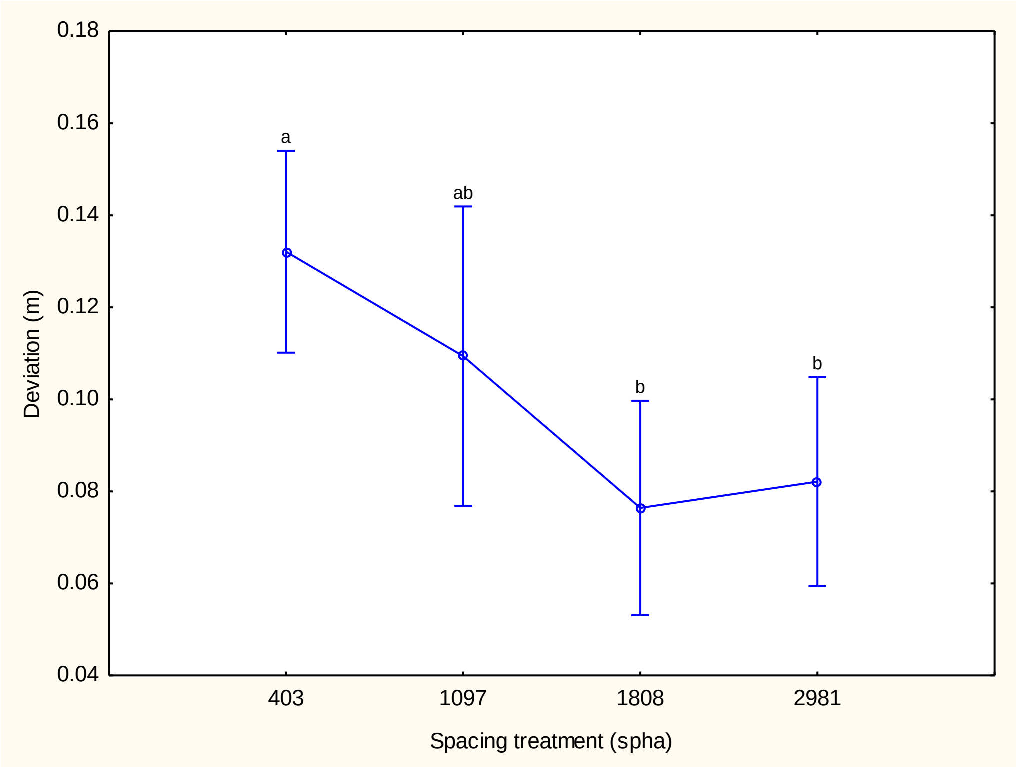


Figure 27: Means and 95% confidence intervals for stem deviation from 0 to 9m height for each spacing treatment

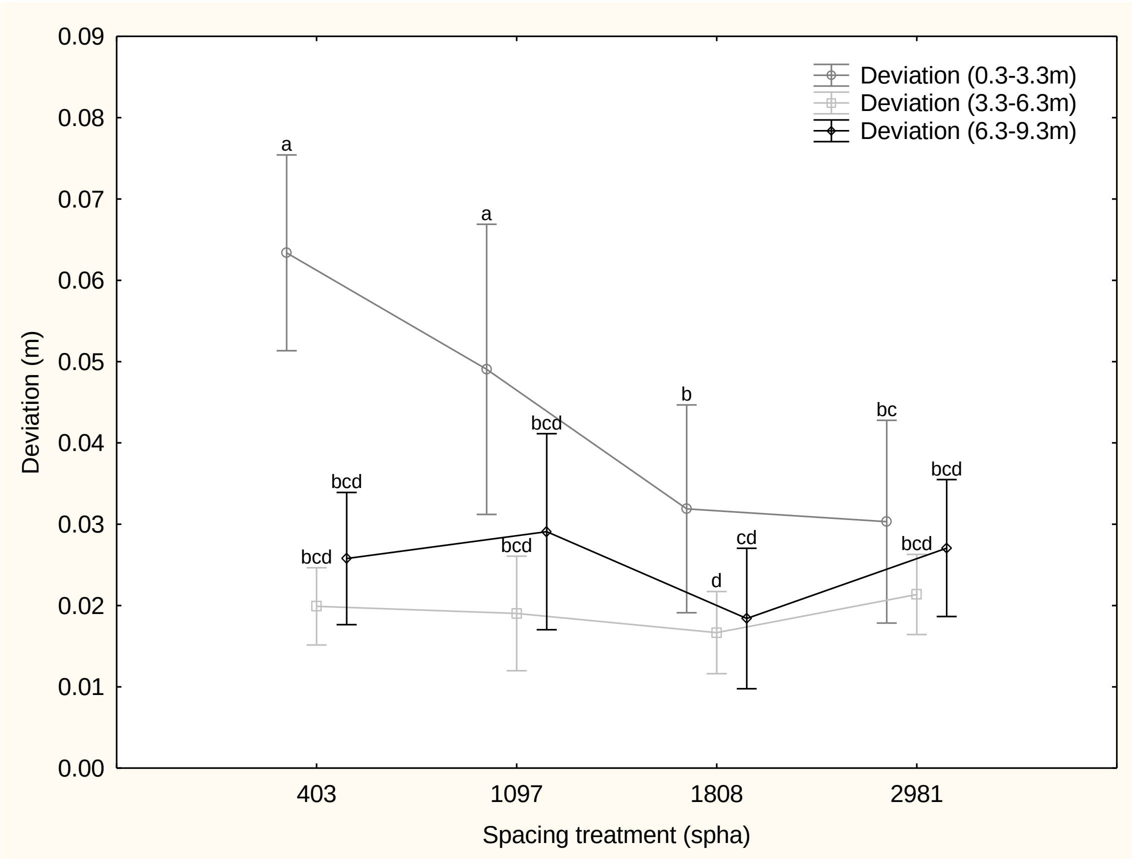


Figure 28: Means and 95% confidence intervals for stem deviation of each 3m saw log position for each spacing treatment.

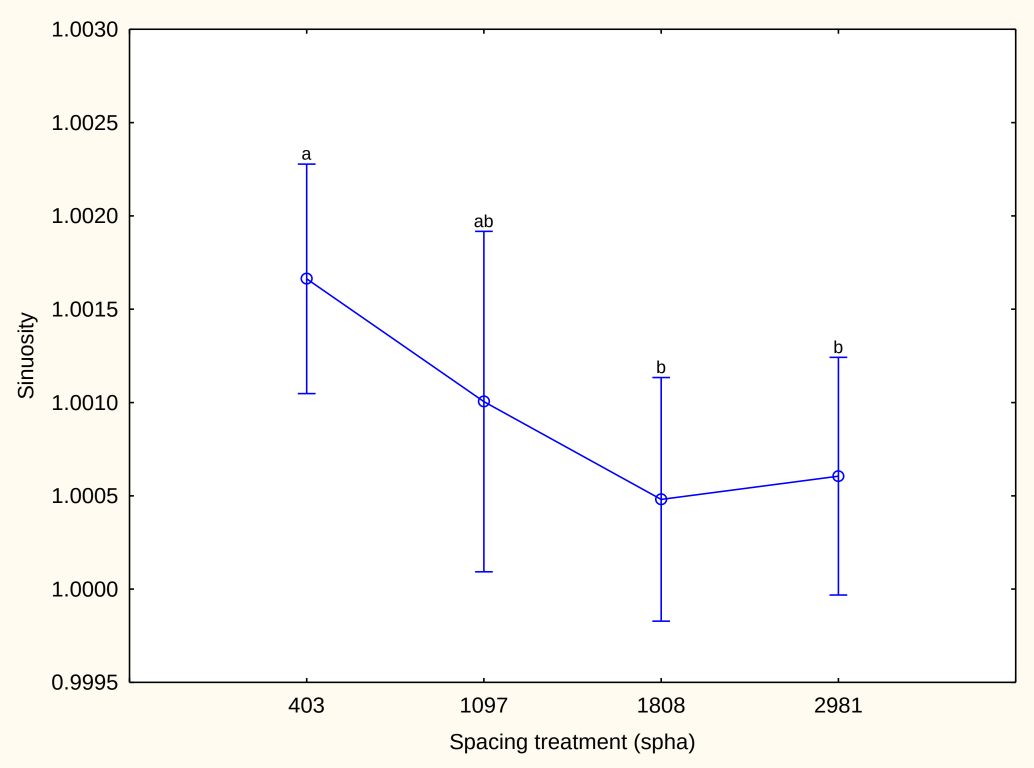


Figure 29: Means and 95% confidence intervals for stem sinuosity from 0 to 9m height for each spacing treatment.

4.2 Taper

The stem taper up to 9 m was tested for equal means among different spacing treatment. Results for stem taper can be seen in Table 6 below. The ANOVA results indicate that the mean stem taper up to 9 m differed between spacing treatments ($p < 0.0001$). Tukey's post hoc test indicated a significant difference in mean stem taper between 2 981 and 403 spha ($p < 0.0001$), 1 808 and 403 spha ($p < 0.0001$), and 1 097 and 403 spha ($p < 0.0001$). There was a decreasing trend in taper from 403 to 2 981 spha as seen in Figure 30.

Stem taper had a decreasing trend in saw logs positioned at 0.3-3.3 m within trees from 403 to 2 981 spha (Figure 31). There was a significant difference between mean stem taper from saw logs positioned at 0.3-3.3 m and saw logs positioned at 3.3-9.3 m within trees. The mean taper of saw logs positioned at 3.3-6.3 m from 403 to 2981 spha were similar. Saw logs positioned at 6.3-9.3 m within trees also had a similar mean taper from 403 to 2 981 spha. No obvious trend in mean taper was observed from 3.3-9.3 m.

Table 6: Table 3: Minimum, maximum, mean and standard deviation values for stem taper from each spacing treatment.

Taper (units in m/m)						
Spacing treatment	**No. of trees**	**Min**	**Max**	**Mean**	**Standard Dev.**	**Coef. of variance**
403 spha	41	0.009	0.020	0.015	0.003	0.184
1 097 spha	39	0.005	0.017	0.011	0.003	0.278
1 808 spha	20	0.003	0.017	0.010	0.003	0.278
2 981 spha	44	0.003	0.022	0.010	0.004	0.397

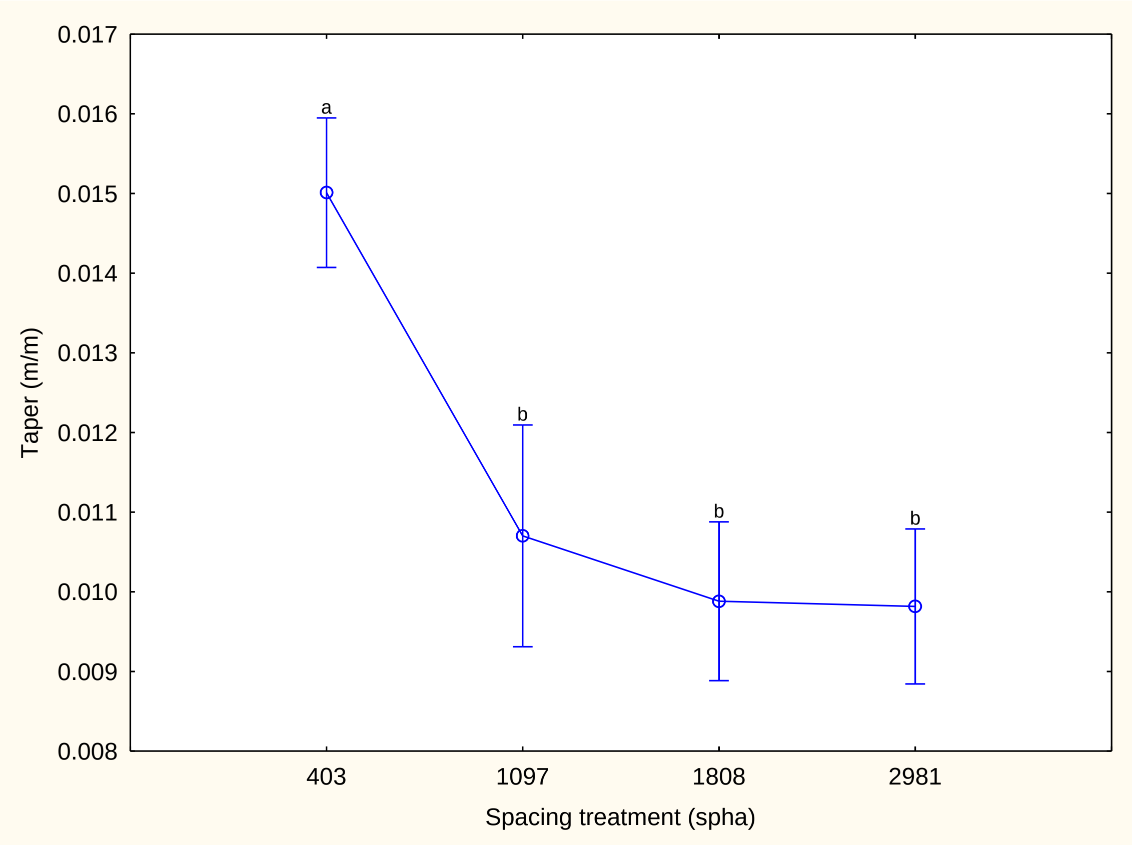


Figure 30: Means and 95% confidence intervals for stem taper from 0 to 9m height for each spacing treatment

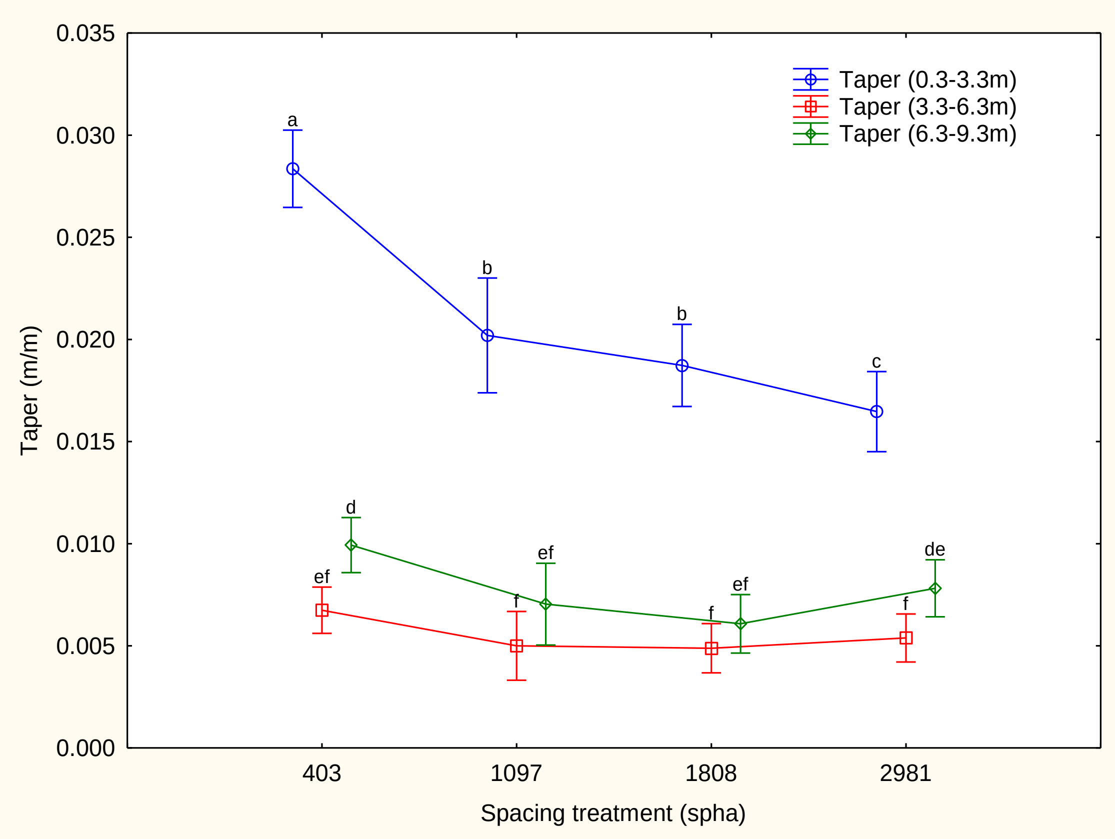


Figure 31: Means and 95% confidence intervals for stem taper of each 3m saw log position for each spacing treatment

4.3 Butt-flare

There was a decreasing trend in butt-flare from 403 to 2 981 spha as seen in Figure 32. The mean butt flare differed significantly between spacing treatments as indicated by the results from the ANOVA ($p < 0.0001$). Tukey's post hoc test indicated a significant difference in mean butt-flare between 403 and 2 981 spha ($p < 0.0001$), 403 and 1 808 spha ($p < 0.0001$), and 403 and 1 097 spha ($p = 0.0007$). Spacing treatments 2 981 s1 808, and 1 097 had similar means ranging from 0.027 to 0.032m/m (Table 7).

Table 7: Minimum, maximum, mean and standard deviation values for stem butt-flare from each spacing treatment.

Butt Flare (units in m/m)						
Spacing treatment	**No. of trees**	**Min**	**Max**	**Mean**	**Standard Dev.**	**Coef. of variance**
403 spha	41	0.002	0.079	0.046	0.015	0.327
1 097 spha	39	0.006	0.056	0.032	0.013	0.411
1 808 spha	20	0.009	0.074	0.029	0.011	0.373
2 981 spha	44	0.011	0.066	0.027	0.012	0.451

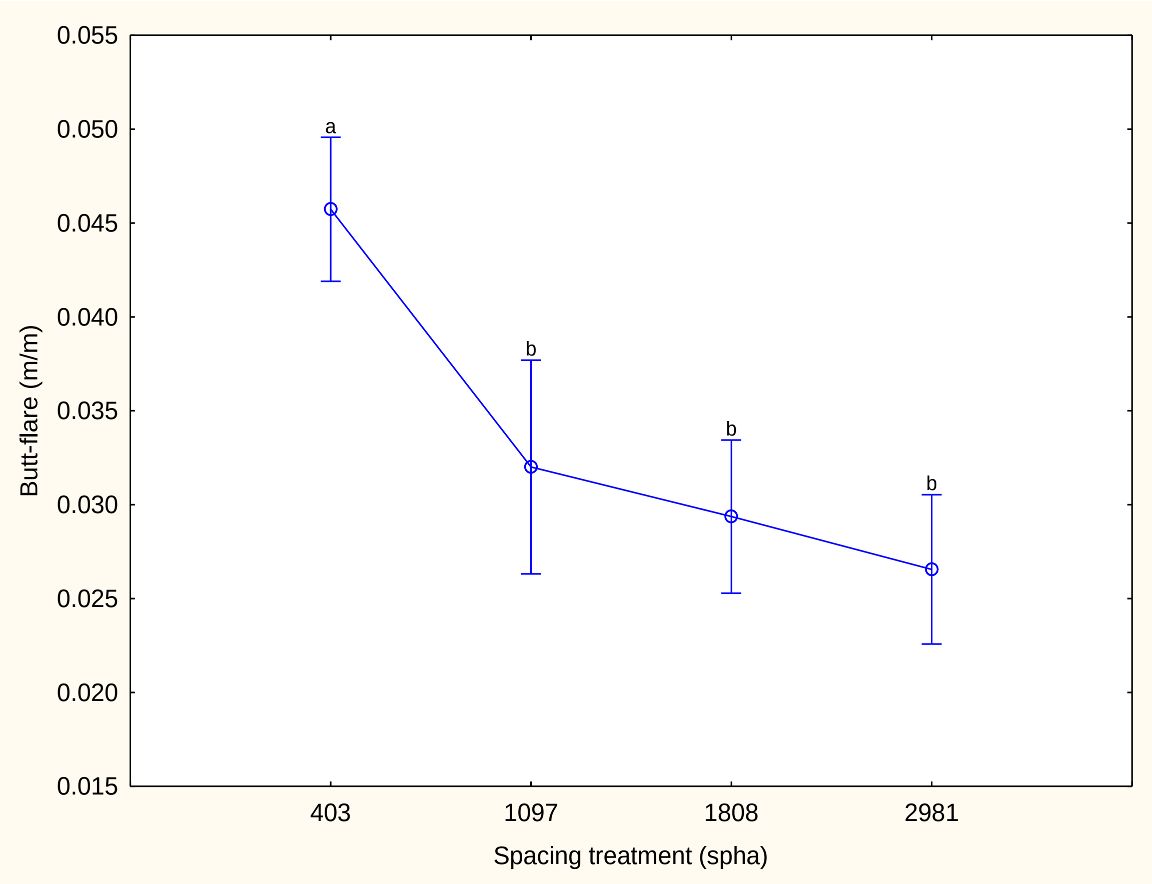


Figure 32: Means and 95% confidence intervals for stem butt-flare for the 0.3-1.3m height section for each plot.

4.4 Ovality

The ANOVA indicated that there was a difference in mean ovality in tree stems from different spacing treatments (p = 0.0077). There was an increasing trend in ovality from 403 to 2 981 spha (Figure 33). Tukey's post hoc test indicated a significant difference in mean stem ovality between 403 and 2 981 spha (p = 0.0176), and 403 and 1 808 spha (p = 0.0142). Tree stems from 1 808 and 2 981 spha had similar mean ovality of 1.0672 and 1.0666 respectively (Table 8).

An increasing trend of mean stem ovality from saw logs obtained from 3.3-9.3 m within trees from 403 to 2 981 spha can be observed in Figure 34. There was a decrease in mean stem ovality from 1 808 to 2981 spha of saw logs obtained from 6.3-9.3 m. Saw logs obtained from 0.3-3.3 m within trees have similar mean stem ovality from 403 to 2 981 spha. There was a significant difference between mean stem ovality from saw logs positioned at 0.3-3.3 meters and saw logs positioned at 3.3-9.3 meters within trees.

Table 8: Minimum, maximum, mean and standard deviation values for stem ovality from each spacing treatment.

Ovality (unitless)						
Spacing treatment	**No. of trees**	**Min**	**Max**	**Mean**	**Standard Dev.**	**Coef. of variance**
403 spha	41	1.020	1.096	1.052	0.019	0.018
1 097 spha	39	1.042	1.094	1.061	0.015	0.014
1 808 spha	20	1.029	1.121	1.067	0.025	0.023
2981 spha	44	1.029	1.140	1.067	0.026	0.025

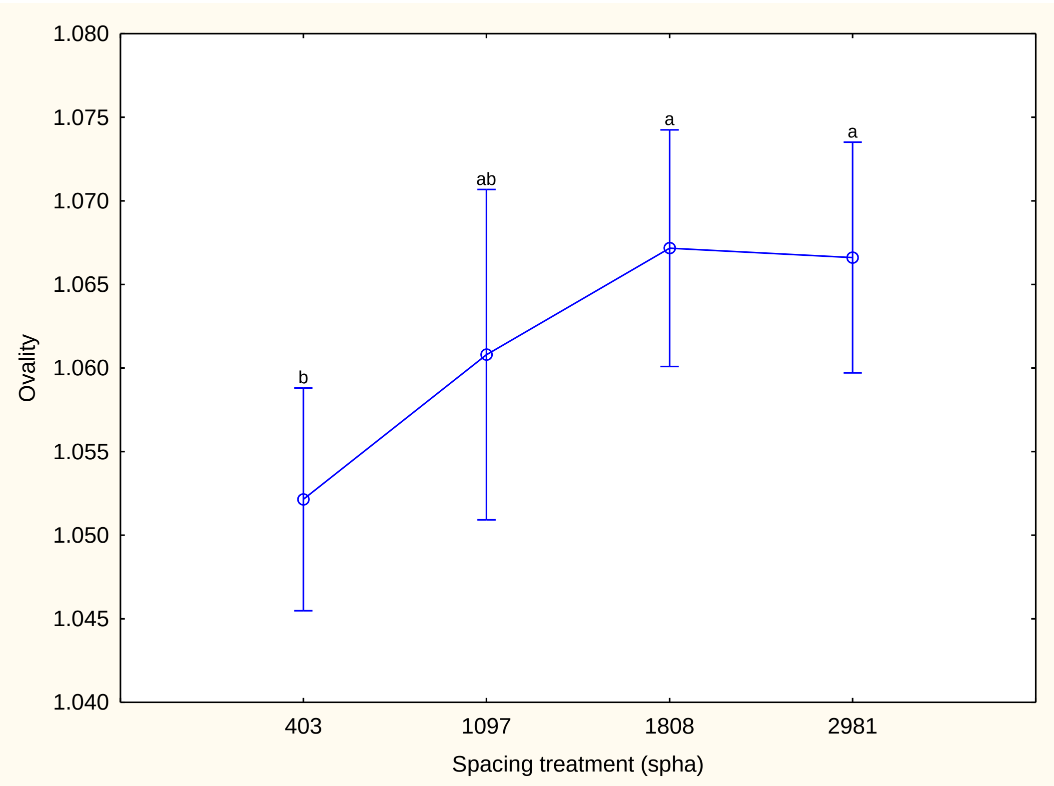


Figure 33: Means and 95% confidence intervals for stem ovality from 0 to 9m height for each plot

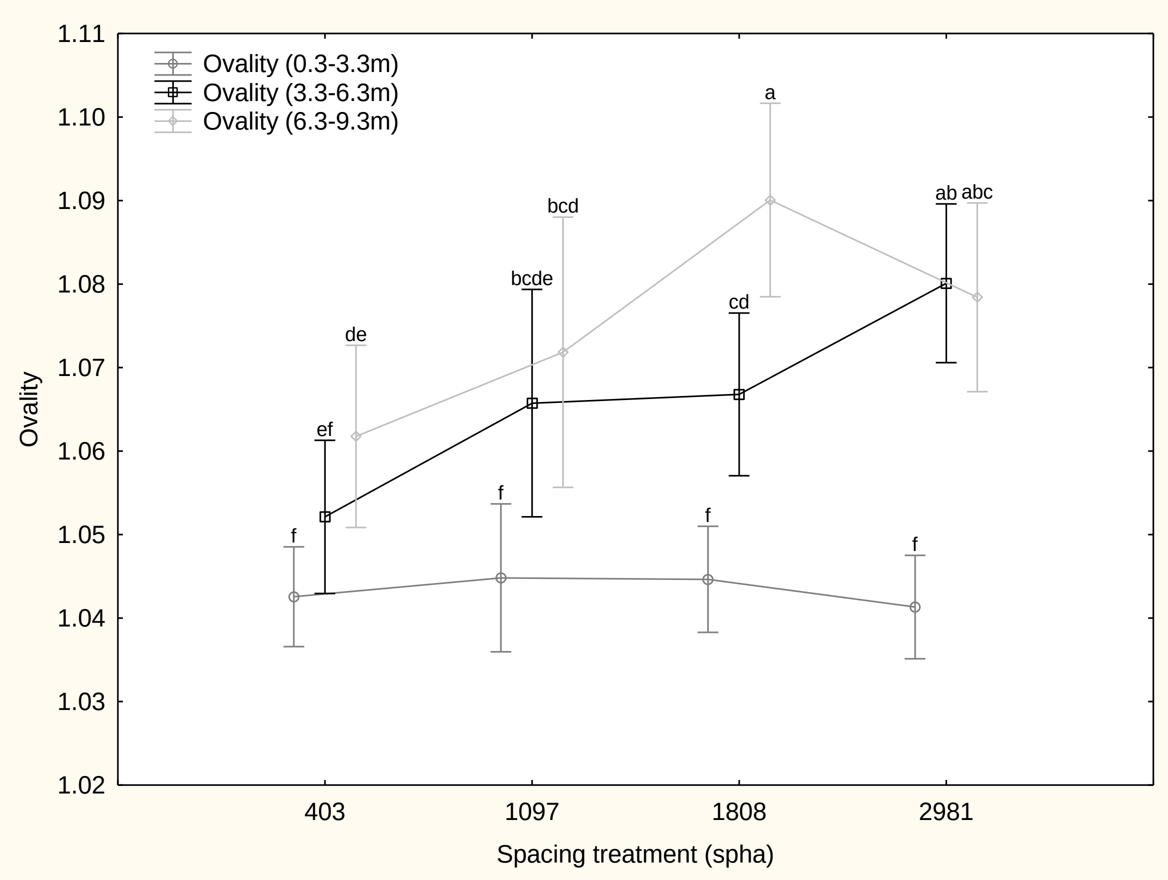


Figure 34: Means and 95% confidence intervals for stem ovality of each 3m saw log position for each spacing treatment

4.5 MOE:

The MOE of 39 boards from three different positions within trees from spacing treatment 2 981 spha were measured (Table 9). Board position 0 and 1 showed very similar results, while board position 2 had a much greater MOE with an increasing trend from board position 1 to 2 (Figure 36). Board 0 contains pith tissue, therefore it was juvenile wood with a lower density and probably higher MFA than board 2. Post hoc Tukey tests showed a significant difference between board position 0 and 2 ($p < 0.0001$) and board position 1 and 2 ($p < 0.0001$). Board position 2 had a much higher mean MOE (12 413.72 MPa) than board position 0 and 1 which had similar means of 7501.45 and 7 562.06 MPa respectively (Table 9). The mean MOE for board position 0 and 1 was lower than the required MOE for S5 grade timber of 7800 MPa. The unequal means between board positions was also indicated by the ANOVA ($p < 0.001$). The last column in Tables 9-12 showed the percentage of a group of boards from each board position that has a mean MOE greater than or equal to 7800 MPa.

Table 9: Mean MOE and percentage of boards with a mean MOE equal or greater than 7800 MPa making the S5 grade lumber in different board positions from trees in 2 981 spha

Plot 1 (2981 spha)				
Board Pos.	Mean MOE	No. of Boards	No. of boards with a mean MOE >= 7800 MPa	S5 grade recovery (%)
2	12413.72	8	8	100.0
1	7562.06	18	15	83.3
0	7501.45	13	11	84.6

The MOE of 39 boards from three different positions in trees from spacing treatment 1 808 spha were also measured (Table 10). Figure 36 showed an increasing trend from board position 0 to board position 2 for spacing treatment 1 808 spha. The ANOVA indicated that the mean MOE from different board positions in 1 808 spha do not have equal means ($p < 0.001$). Post hoc Tukey tests showed a significant difference between board position 0 and 2 ($p < 0.0001$) and board position 1 and 2 ($p = 0.0014$). The large whisker for the 95% confidence interval for board 2 may be a result of the low number of boards (only 4) available for testing. The mean MOE for board position 0 (6 277.6 MPa) and 1 (7 254.55 MPa) was lower than the required MOE for S5 grade timber of 7 800 MPa.

Table 10: Mean MOE and percentage of boards with a mean MOE equal or greater than 7800 MPa making the S5 grade lumber (>7800 MPa) in different board positions from trees in 1808 spha

Plot 2 (1808 spha)				
Board Pos.	Mean MOE	No. of Boards	No. of boards with a mean MOE >= 7800 MPa	S5 grade recovery (%)
2	9836.73	4	4	100.0
1	7254.55	19	13	68.4
0	6277.60	16	4	25.0

The 1 097 and 403 spha trials were planted at lower densities than 2 981 and 1808 spha, which meant larger trees with greater diameters were felled from 403 and 1097 spha which enabled a fourth board (board position 3) to be obtained for evaluation. The MOE of 56 boards from four different positions in trees from 1097 spha were measured (Table 11). Figure 36 showed an increasing trend from board position 0 to 2 and a slight decreasing trend from board position 2 to 3. However, results from board position 3 had very high confidence intervals due to low board numbers and should be viewed with caution. The mean MOE from these boards were not equal as indicated by the ANOVA. Post hoc Tukey tests showed a significant difference between board position 0 and 1 ($p = 0.0103$) and board position 1 and 3 ($p = 0.0357$) based on a 95% confidence interval. There was also a significant difference between board position 0 and 2 ($p < 0.0001$), board position 0 and 3 ($p = 0.0006$) and board position 1 and 2 ($p < 0.0001$). The mean MOE for board position 0 (5826.91 MPa) and 1 (7043.80 MPa) was lower than the required MOE for S5 grade timber of 7800 MPa.

Table 11: Mean MOE and percentage of boards with a mean MOE equal or greater than 7800 MPa making the S5 grade lumber (>7800 MPa) in different board positions from trees in 1097 spha

Plot 3 (1097 Stems/ha)				
Board Pos.	Mean MOE	No. of Boards	No. of boards with a mean MOE >= 7800 MPa	S5 grade recovery (%)
3	9428.12	2	2	100.0
2	10228.35	15	15	100.0
1	7043.80	22	13	59.1
0	5826.91	17	2	11.8

The MOE of 74 boards from four different positions in trees from 403 spha were measured (Table 12). Figure 36 showed an increasing trend from board position 0 to board position 3. Post hoc Tukey tests showed a significant difference between board position 0 and 2 ($p < 0.0001$), board position 0 and 3 ($p < 0.0001$), board position 1 and 2 ($p < 0.0001$) and board position 1 and 3 ($p < 0.0001$). Board position 0 and 1 and board position 2 and 3 have a strong correlation with MOE and each had similar means (Table 12) with p values of 0.973 and 0.9784 respectively. The ANOVA showed that all boards from this plot do not have equal means ($p < 0.001$). The mean MOE for all board positions from 403 spha was lower than the requirement for S5 grade timber.

Table 12: Mean MOE and percentage of boards with a mean MOE equal or greater than 7800 MPa making the S5 grade lumber (>7800 MPa) in different board positions from trees in 403 spha

Plot 5 (403 spha)				
Board Pos.	Mean MOE	No. of Boards	No. of boards with a mean MOE >= 7800 MPa	S5 grade recovery (%)
3	7805.98	11	11	100.0
2	7618.65	29	28	96.6
1	5081.01	21	0	0.0
0	4879.27	13	0	0.0

The mean MOE from boards of each spacing treatment can be seen in Figure 35. There was an increasing trend in mean board stiffness from 403 spha to 1 097 spha slightly decreasing from 1 097 spha to 1 808 spha (although not significantly different) then increasing again from 1 808 spha to 2 981 spha. There was a general increase in lumber stiffness from 403 spha to 2 981 spha, however the mean MOE decreased slightly from 1097 to 1808 spha although they still had similar mean MOE. There was a significant difference in MOE between 403 and 2 981 spha ($p < 0.001$), 403 and 1 097 spha ($p = 0.0019$), and 1 808 and 2 981 spha ($p = 0.0101$). Spacing treatment 2 981 spha was the only planting density out of the four that had a mean MOE of all its boards greater than 7 800 MPa.

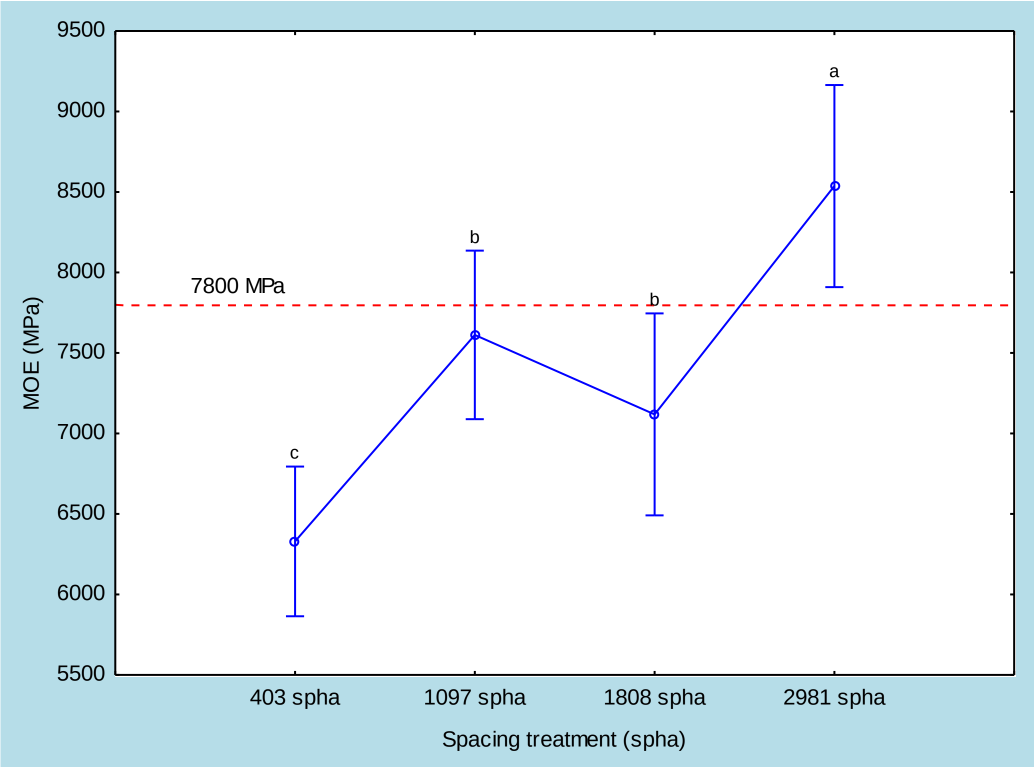


Figure 35: Means and 95% confidence intervals for MOE for different spacing treatments. Different letters denote significant differences between treatments.

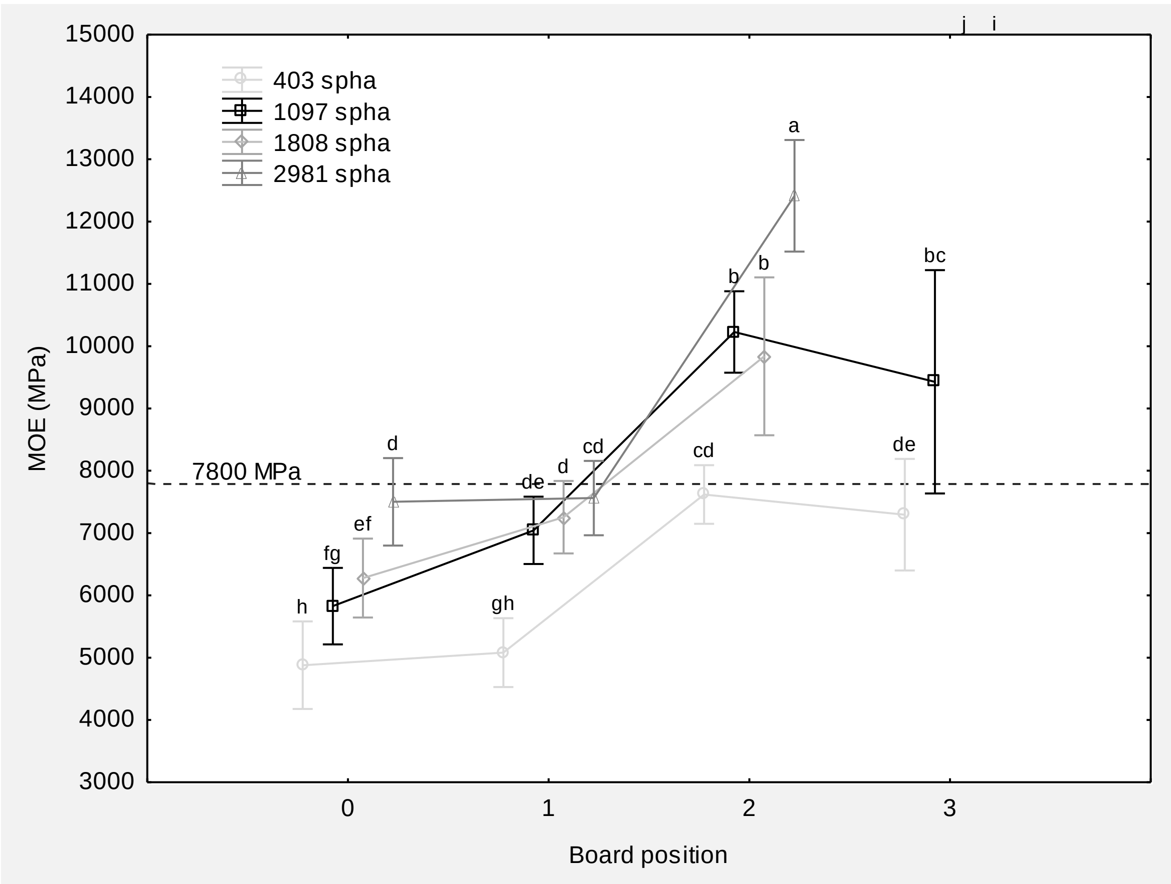


Figure 36: Means and 95% confidence intervals for MOE on board position for each spacing treatment. Different letters denote significant differences between board positions.

Figure 37 represented the MOE of the 38x152 mm boards and the MOE of the resawn boards (38x114 mm) from spacing treatments 403 spha and 1 097 spha. This Figure showed that MOE was significantly affected by board position and an increasing trend in MOE from board position 0 to board position 2 was observed for both the 152mm and 114 mm boards. An interesting observation was made at board position 2 where the mean MOE for the 114 mm boards was higher than the MOE from the 152 mm boards. The MOE for the 152 mm boards was expected to be higher due to the fact that better quality wood was removed at the edges (where older year rings were situated) during the resaw process for the 114 mm boards.

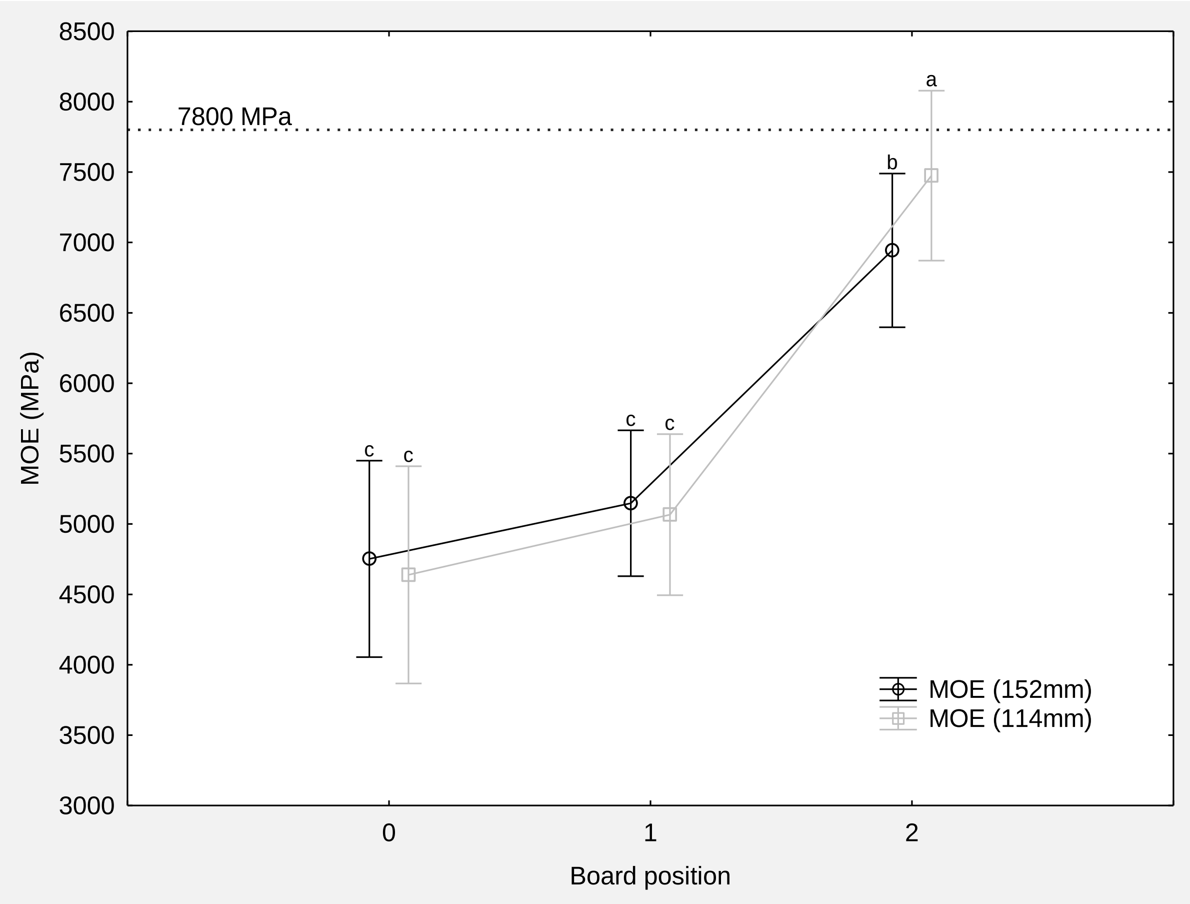


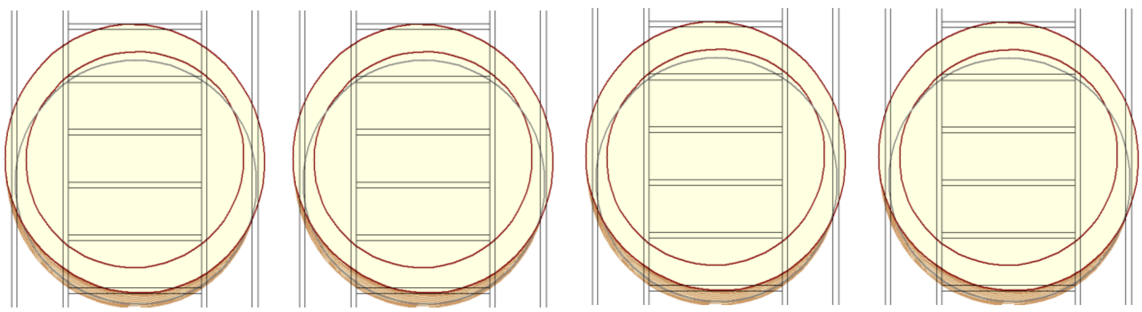
Figure 37: Means and 95% confidence intervals for MOE on board position for 152mm and 114mm re-sawn boards. Take not that it was the same boards measured – the 114 mm boards were resawn out of 152 mm boards.

4.6 Value recovery:

The number of logs obtained for each log class of each spacing treatment can be seen in Table 13. Table 14 shows how the value recovery for calculated for log class 13-17.9 mm. As seen in Table 14 there were no logs obtained for spacing treatment 403 in the 13-17.9 mm log class. Figure 38 show how a scatterplot was used to determine a volume recovery for 403 spha. Figure 39 was then used to determine a value recovery for 1 097 spha. This was necessary due to the small number of logs available for that spacing treatment. Table 15 showed the value and volume recoveries for each log class of each spacing treatment that was calculated in Simsaw6. The value recoveries increased with increasing log classes and also increased from spacing treatment 403 spha to 2 981 spha. The net value recovery was multiplied by the harvested volume per hectare to obtain the income used in the LEV calculations.

<u>An example of the actual value recovery calculations for the 22-25.9cm log class:</u>

403 spha treatment	1 097 spha treatment	1 808 spha treatment	2 981 spha treatment



38/114/38 + 5*38	38/114/38 + 5*38	38/114/38 + 5*38	38/114/38 + 5*38
(10 logs)	(10 logs)	(10 logs)	(10 logs)
Simsaw6 volume recovery = 40.03%	Simsaw6 volume recovery = 44.4%	Simsaw6 volume recovery = 43.92%	Simsaw6 volume recovery = 41.8%
DWAF volume recovery = 46 %	DWAF volume recovery = 46 %	DWAF volume recovery = 46 %	DWAF volume recovery = 46 %

Grade recovery (Bending tests) Board 3: S5 = 100% Board 2: S5 = 96.6% Board 1: S5 = 0% Board 0: S5 = 0%	Grade recovery (Bending tests) Board 3: S5 = 100% Board 2: S5 = 100% Board 1: S5 = 59.1% Board 0: S5 = 11.8%	Grade recovery (Bending tests) Board 2: S5 = 100% Board 1: S5 = 68.4% Board 0: S5 = 25%	Grade recovery (Bending tests) Board 2: S5 = 100% Board 1: S5 = 83.3% Board 0: S5 = 84.6%
Board 3 value = 1*2680 + 0*2351 = R2680/m^3 Board 2 value = 0.96*2680 + 0.034*2351 = R2652.73/ m^3 Board 1 value = 0*2680 + 1*2351 = R2351 /m^3 Board 0 value = 0*2680 + 1*2351 = R2351/ m^3	Board 3 value = 1*2680 + 0*2351 = R2680/m^3 Board 2 value = 1*2680 + 0*2351 = R2680/ m^3 Board 1 value = 0.591*2680 + 0.409*2351 = R2531.33 /m^3 Board 0 value = 0.118*2680 + 0.882*2351 = R2389.82/ m^3	Board 2 value = 1*2680 + 0*2351 = R2680/ m^3 Board 1 value = 0.684*2680 + 0.316*2351 = R2576.04 /m^3 Board 0 value = 0.25*2680 + 0.75*2351 = R2433.25/ m^3	Board 2 value = 1*2680 + 0*2351 = R2680/ m^3 Board 1 value = 0.833*2680 + 0.167*2351 = R2625.06/m^3 Board 0 value = 0.846*2680 + 0.154*2351 = R2629.33/ m^3
Log value recovery = R1142.56/ m^3	Log value recovery = R1175.67/ m^3	Log value recovery = R1208.78 /m^3	Log value recovery = R1241.89/ m^3
Net value recovery = R1142.56 – R484 (processing cost) = **R658.56/ m^3**	Net value recovery = R1175.67 – R484 (processing cost) = **R691.67/ m^3**	Net value recovery = R1208.78 – R484 (processing cost) = **R724.78/ m^3**	Net value recovery = R1241.89 – R484 (processing cost) = **R757.89/ m^3**

Table 13: Log classes and number of logs in each log class per spacing treatment

Plot 5 (403 spha)	Log class (mm)	Number of logs
	14-17.9	0
	18-21.9	3
	22-25.9	10
	26-29.9	17
	30-33.9	16
	34+	11
Plot 3 (1 097 spha)	Log class (mm)	Number of logs
	14-17.9	8
	18-21.9	13
	22-25.9	10
	26-29.9	4
	30-33.9	2
	34+	0
Plot 2 (1 808 spha)	Log class (mm)	Number of logs
	14-17.9	17
	18-21.9	26
	22-25.9	11
	26-29.9	4
	30-33.9	1
	34+	0
Plot 1 (2 981 spha)	Log class (mm)	Number of logs
	14-17.9	38
	18-21.9	10
	22-25.9	4
	26-29.9	6
	30-33.9	0
	34+	0

Table 14: The adjusted volume and value recoveries for log class 13-17.9mm.

Spacing treatment	Volume recovery	Adjusted volume recovery	No. Of logs	Value recovery	Adjusted value recovery
2 981	30.00	29.25	38	518.52	521.35
1 808	31.00	32.59	17	507.19	502.89
1 097	38.00	37.37	8	-	484.44
403	-	32.59	-	464.59	465.99

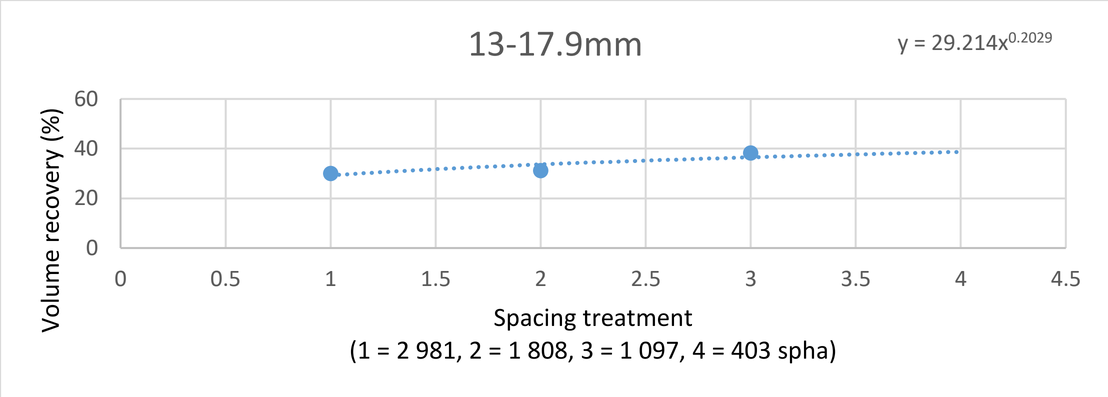


Figure 38: Example of a scatterplot for volume recovery with line of best fit for log class 13-17.9mm.

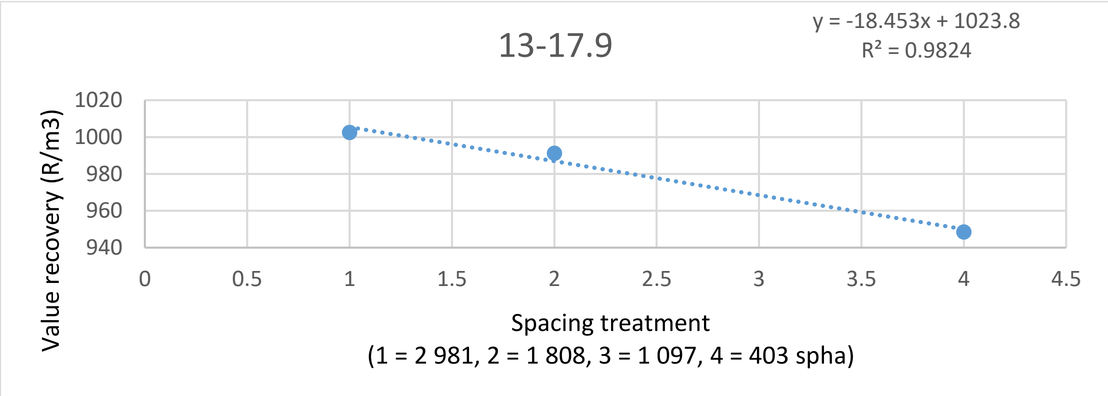


Figure 39: Example of a scatterplot for value recovery with line of best fit for log class 13-17.9mm.

Table 15: Volume and value recoveries for each log class from each spacing treatment

Spacing treatment 403 spha						
Log class SED (cm)	13-17.9	18-21.9	22-25.9	26-29.9	30-33.9	34+
Log class	A	B1	B1	C1	C1	D1
Volume recovery – standard SA (%)	38	46	46	52	52	57
Volume recovery – Simsaw6 (%)	-	34.19	40.03	48.29	47.67	52.36
Value recovery (R/m^3)	949.99	1046.28	1142.56	1238.84	1335.13	1431.32
Processing costs (R/m^3)	484.00	484.00	484.00	484.00	484.00	484.00
Net Value recovery (R/m^3)	465.988	562.276	658.56	754.844	851.132	947.316
Spacing treatment 1097 spha						
Log class SED (cm)	13-17.9	18-21.9	22-25.9	26-29.9	30-33.9	34+
Log class	A	B1	B1	C1	C1	D1
Volume recovery– standard SA (%)	38	46	46	52	52	57
Volume recovery - Simsaw6 (%)	38.29	42.69	44.4	44.9	49.73	-
Value recovery (R/m^3)	968.44	1072.06	1175.67	1279.28	1382.9	1486.41
Processing costs (R/m^3)	484.00	484.00	484.00	484.00	484.00	484.00
Net Value recovery (R/m^3)	484.441	588.057	691.67	795.283	898.899	1002.412
Spacing treatment 1808 spha						
Log class SED (cm)	13-17.9	18-21.9	22-25.9	26-29.9	30-33.9	34+
Log class	A	B1	B1	C1	C1	D1
Volume recovery– standard SA (%)	38	46	46	52	52	57
Volume recovery - Simsaw6 (%)	31.18	40.23	43.92	49.01	51.67	-
Value recovery (R/m^3)	986.89	1097.84	1208.78	1319.72	1430.67	1541.51
Processing costs (R/m^3)	484.00	484.00	484.00	484.00	484.00	484.00
Net Value recovery (R/m^3)	502.894	613.838	724.78	835.722	946.666	1057.508
Spacing treatment 2981 spha						
Log class SED (cm)	13-17.9	18-21.9	22-25.9	26-29.9	30-33.9	34+
Log class	A	B1	B1	C1	C1	D1
Volume recovery – standard SA (%)	38	46	46	52	52	57
Volume recovery – Simsaw6 (%)	30.04	36.35	41.8	50.69	-	-
Value recovery (R/m^3)	1005.35	1123.62	1241.89	1360.16	1478.43	1596.6
Processing costs (R/m^3)	484.00	484.00	484.00	484.00	484.00	484.00
Net Value recovery (R/m^3)	521.347	639.619	757.89	876.161	994.433	1112.604

4.7 LEV:

The best land expectation value was calculated for each spacing treatment based on different management regimes. The best land expectation value for 2 981 spha was -R 15 424.57/ha (Table 17). This value would be obtained if a stand of 2 981 spha was thinned at age 11 to 350 spha and clearfelled at 19 y (Figure 40). 56.7% of the total volume available for 2 981 spha at 19 y can be utilised for saw timber (Table 16). The best land expectation value for 1 808 spha was R5 47 693.02/ha (Table 17). This value would be obtained if a stand of 1 808 spha was thinned at age 12 to 300 spha and clearfelled at age 19 (Figure 41). 56.5% of the total volume available for 1 808 spha at age 19 can be utilised for saw timber (Table 16). 1 097 spha obtained a best land expectation value of R 46 677.59/ha (Table 17). This value would be obtained if a stand of 1 097 spha was thinned at age 13 to 250 spha and clearfelled at age 18 (Figure 42). 61.85% of the total volume available for 1 097 spha at age 18 can be utilised for saw timber (Table 16). 403 spha was unthinned and a land expectation value of R 41 930.36/ha could be expected if clearfell took place at age 15 (Table 17). 64.98% of the total volume available for 403 spha at age 15 can be utilised for saw timber (Table 16). The cash flows for each spacing treatment can be seen in Table 18 – 21. The cash flow tables indicate the income or expenditure for different activities from establishment (year 0) to clearfell for each spacing treatment.

Table 16: Summary of important data from each spacing treatment

Spacing treatment:	Clearfell age (years)	DBHq (cm)	Mean height (m)	Utilisable saw timber volume (% of total)
403 spha	15	36.89	23.33	61.77
1 097 spha	18	37.31	26.88	56.02
1 808 spha	19	38.62	27.63	54.87
2 981 spha	19	35.46	27.52	54.2

Table 17: Best expected LEV per plot and unthinned LEV per plot.

Plot:	Best LEV:	Thinning to:	Thinning age:	Clearfell age:
Plot 1 (2981)	-R 15 424.57	350	11	19
Plot 2 (1808)	R 47 693.02	300	12	19
Plot 3 (1097)	R 46 677.59	250	13	18
Plot 1 (2981)	-R 62 610.04	Unthinned	-	16
Plot 2 (1808)	-R 286.12	Unthinned	-	15
Plot 3 (1097)	R 15 905.28	Unthinned	-	15
Plot 5 (403)	R 41 930.36	Unthinned	-	15

Table 18: Cash flow for spacing treatment 2 981 spha

Cash flow (2 981 spha)		
Activity	Year	Total Amount (R/Ha)
Establishment	0	-R 10,574.13
Annual Admin	1-19	-R 25,276.84
Annual Maintenance	1-19	-R 18,938.25
Thinning	11	R 63,027.96
Tending	2,7,9	-R 1,933.60
Pruning	5,7,9	-R 5,473.66
Clearfelling	19	R 146,476.85
	Total =	R 147,308.33

Table 19: Cash flow for spacing treatment 1 808 spha

Cash flow (2 981 spha)		
Activity	Year	Total Amount (R/Ha)
Establishment	0	-R 7,380.31
Annual Admin	1-19	-R 25,276.84
Annual Maintenance	1-19	-R 18,938.25
Thinning	12	R 98,700.02
Tending	2,7,9	-R 1,595.19
Pruning	5,7,9	-R 3,319.82
Clearfelling	19	R 154,559.72
	Total =	R 196,749.33

Table 20: Cash flow for spacing treatment 1 097 spha

Cash flow (2 981 spha)		
Activity	Year	Total Amount (R/Ha)
Establishment	0	-R 5,444.41
Annual Admin	1-18	-R 23,946.48
Annual Maintenance	1-18	-R 17,941.50
Thinning	13	R 96,059.11
Tending	2,7,9	-R 1,390.07
Pruning	5,7,9	-R 2,014.29
Clearfelling	18	R 107,730.79
	Total =	R 153,053.15

Table 21: Cash flow for spacing treatment 403 spha

Cash flow (2 981 spha)		
Activity	Year	Total Amount (R/Ha)
Establishment	0	-R 3,554.81
Annual Admin	1-15	-R 19,955.40
Annual Maintenance	1-15	-R 14,951.25
Tending	2,7,9	-R 1,610.37
Pruning	5,7,9	-R 739.98
Clearfelling	15	R 143,468.99
	Total =	R 102,657.18

Table 22 shows the site index (SI_{15}) with a base age of 15 years old as well as the relative stand density (RD) and stability factor (SF) at clearfell for each spacing treatment. Spacing treatments 1 097, 1 808 and 2 981 spha had relative stand densities ranging from 4 to 6 which indicates that these stands are at low risk of tree mortality due to competition. 403 spha had a RD of 7 indicating a moderate risk of tree mortality due to competition. Spacing treatments 403, 1 097 and 1 808 spha had stability factors ranging from 1.39 to 1.58 that indicates that these stands were at low risk if planted in exposed areas that experience high winds. 2 981 spha was at moderate risk (SF = 1.28) if planted in exposed areas that experience high winds considering that a high risk is a SF less than one.

Table 22: Site index, relative stand density and stability factor for each spacing treatment.

Spacing treatment:	Site index (SI_{15}):	Relative stand density (RD) at clearfell:	Stability factor (SF) at clearfell:
403	19.8	7	1.58
1 097	24.8	4	1.38
1 808	28.3	5.5	1.39
2 981	28.9	6	1.28

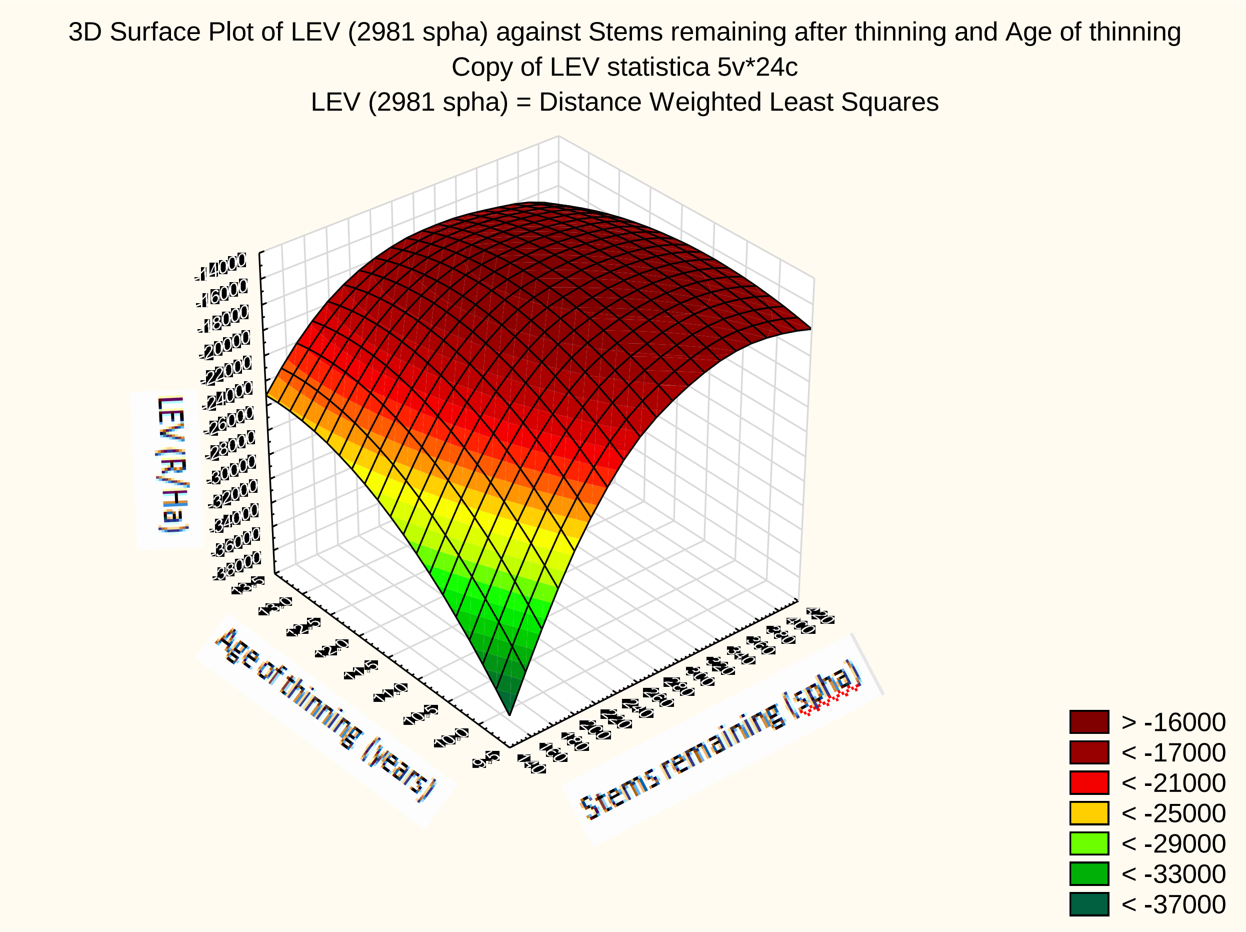


Figure 40: Expected LEV for 2981 spha plot as a function of thinning age and thinning intensity

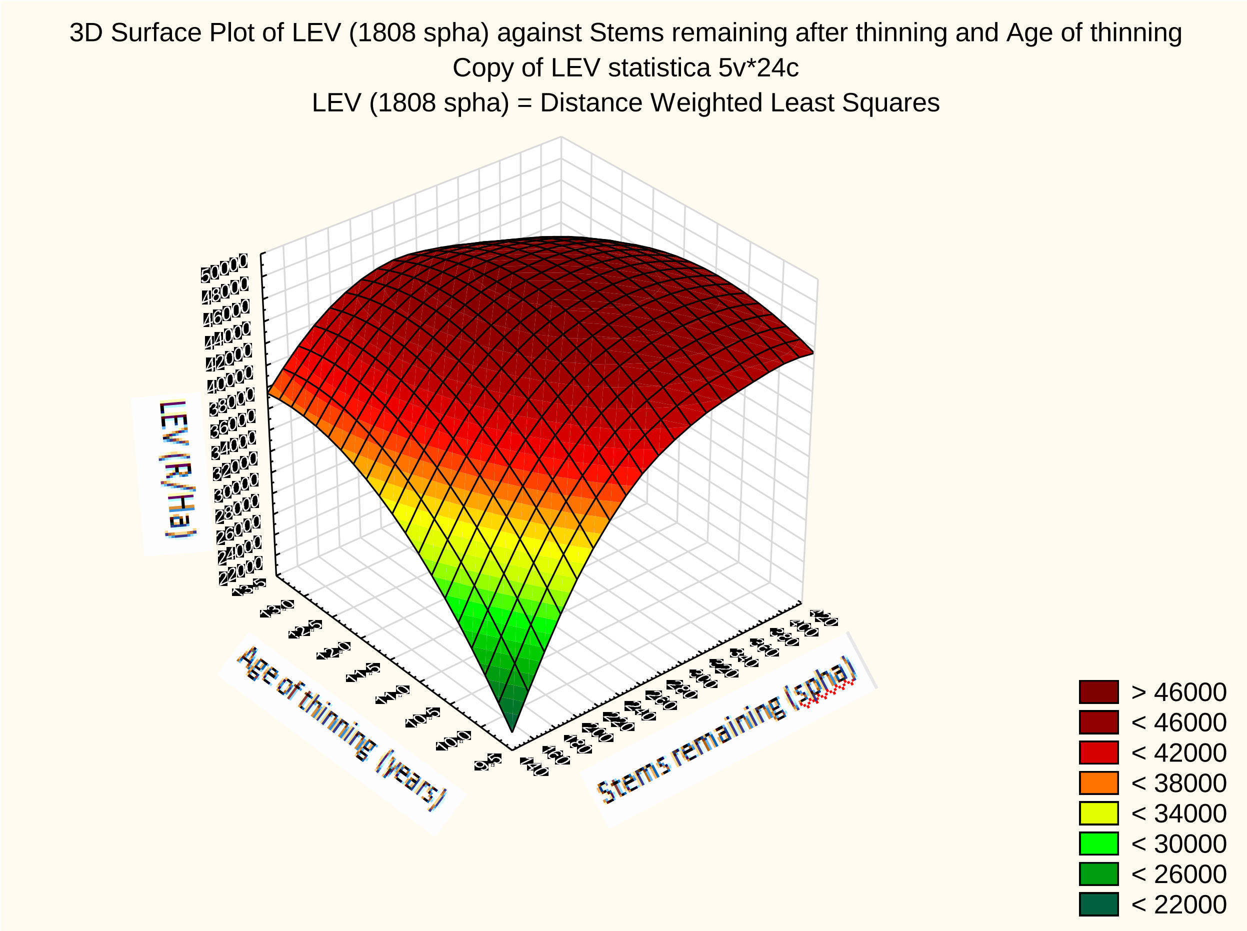


Figure 41: Expected LEV for 1808 spha plot as a function of thinning age and thinning intensity

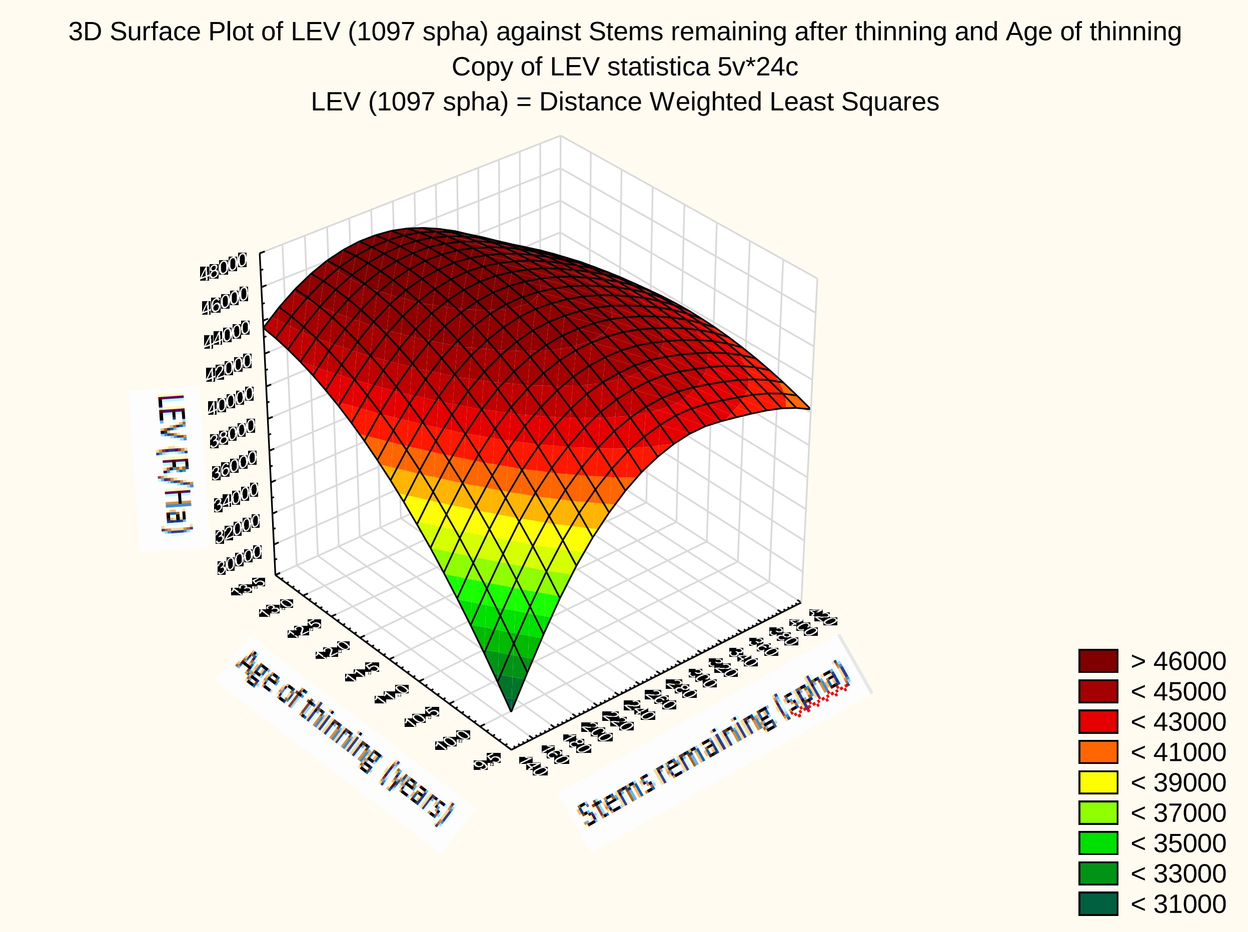


Figure 42: Expected LEV for 1097 spha plot as a function of thinning age and thinning intensity

Chapter 5

5. Discussion

5.1 Stem form

Results from this study showed that spacing treatment had a significant effect on average stem deviation and stem sinuosity. The lower planting densities (403 and 1 097 spha) had mean stem deviations in the bottom 9 m part of the stem of 132.1 mm and 109.3 mm respectively while the higher planting densities (1 808 and 2 981 spha) had mean stem deviations of 76.4 mm and 82.1 mm respectively (Figure 27). There was a statistically significant difference between the mean stem deviation of the 403 spha treatment and the deviation of the two highest planting densities. The mean deviations of the 1 097, 1 808 and 2 981 spha treatments were not statistically different. Erasmus (2016) found that spacing treatment also had a significant effect on the average stem deviation up to 6 m. He also added that no obvious trend was observed across spacing treatments since, in his study, the 403 spha had the highest stem deviation and the 1 808 spha treatment the second highest. This was not in agreement with results from this study where there was a decreasing trend in mean stem deviation from 403 spha to 1 808 spha. The 2 981 spha treatment had a similar stem deviation to the 1 808 spha. Previous studies have proven that trees in more densely planted compartments tend to be narrower but straighter than trees in less dense compartments (Erasmus, 2016). This is believed to be a result based on competition for resources from other trees. Trees in more dense compartments focus on growing taller rather than wider to obtain sufficient sunlight for growth. A lack of sunlight suppresses growth which eventually results in mortality. Results from this study proved similar to that of previous studies (Erasmus, 2016).

Spacing treatment from this study had a significant effect on average stem deviation and stem sinuosity for each 3 m sawlog section. The bottom section (0.3-3.3 m) of the 403 spha treatment had a much higher mean stem deviation than any of the other stem sections of any other treatment. The stem deviation of the bottom section of the 1 097 spha treatment was also relatively high. For the other two planting density treatments (1 808 and 2 981 spha) there were relatively small differences in stem deviation between the three log sections. There was a decreasing trend for stem deviation and stem sinuosity up to 3.3 m with increasing planting density. This could be a result from trees focusing on height growth rather than diameter growth in higher planting densities due to competition from other trees in high density stands which could possibly have had an influence on stem straightness and stem sinuosity up to 3.3 m. Spicer et al. (2000) did a study on sinuous stem growth on Douglas-fir and they suggested that sinuosity could be caused from intrinsic factors, such as elongation relative to radial growth rates. It was found in this study that the trees with the maximum stem deviation and stem sinuosity from each spacing treatment had more space for growth due to mortality of trees surrounding them causing open spaces. Individual competitive circumstances influenced the stem form of each tree which was probably why there was also relatively high variation in results for instance, spacing treatment 1 097 spha had a tree with the maximum stem deviation of 0.383 m. It was found that this was caused by a neighbouring tree that forked, therefore forcing the high stem deviation of that specific tree. The results from this study in general supported the hypothesis that denser spacing will result in trees growing straighter towards the light opening in the canopy. Where there was relatively large growing space, trees tend to have larger stem deviation. The reason for the much higher stem deviation in the 0.3-3.3 m stem sections (especially in the 403 and 1 097 spha treatments) was probably related to the relative higher availability of growth space when trees were young and still small. Once they get taller (i.e. above 3.3 m) branches of neighbouring trees will limit growth space and force a straighter growth path towards light opening. An issue that has not been addressed and will be very relevant in plantation trees is the effect that thinning will have on stem form. It is likely that thinning might result in stem deviations higher in the trees due to uneven canopy openings.

Competition in stands could also be the reason that planting density had a significant effect on stem taper and butt-flare from this study. Taper and butt-flare had a decreasing trend from 403 spha to 2 981 spha. The mean taper for 403 spha was 1.5 cm per meter which was slightly higher than the taper of 1cm/m considered average for saw logs. The trees planted at 403 spha had little competition for growth resources and therefore these trees focused on diameter growth rather than height growth. Spacing treatment also had a significant effect on stem taper and butt-flare for each 3 m sawlog. The taper up to 3.3 m was exceptionally high between 2.5 and 3cm/m for 403 spha and between 1.5 and 2cm/m for 1 097, 1 808 and 2 981 spha. Stem taper remained constant between 0.5 and 1 cm/m between 3.3 and 9.3 m height for each spacing treatment.

Results from this study indicated that ovality increased with increasing planting density from 403 spha to 2 981 spha. Spacing treatment had a significant effect on ovality up to 9m and for each 3m sawlog. Ovality also increased with increasing height along the tree stem, which seemed unusual. The maximum ovality was 1.14 from a tree in spacing treatment 2981 spha. This tree had sufficient space around it from mortality of three of its neighbours which meant it was more exposed to wind than other trees. Other studies concluded that prevailing winds have a greater effect on the ovality of stems compared to the effect of rectangular planting patterns on stem ovality (Salminen and Varmola, 1993). Wind as a causal factor for ovality would also explain the relatively lower ovality in the low planting density treatments. The lower planting densities had higher diameter, and higher taper and would therefore be more stable with less development of bending stresses in the stem. Presumably ovality will be directed in the direction of prevailing winds to withstand the higher bending stresses developed in this direction (this aspect was not tested in our study).

5.2 Economic evaluation

MOE results from this study showed that spacing treatment had a significant effect on the mean stiffness of boards from different planting densities and different positions in the log. There was a general increase in board stiffness with increasing planting density from 403 to 2 981 spha. Results were similar to other studies on pines (Erasmus, 2016; Froneman, 2014; Wessels et al, 2014). The earlier development of mature wood from earlier competition in more dense plantations could explain the increase in tree stiffness. Erasmus (2016) reported on the effect of spacing treatment on wood density, MFA and year rings and he found that there was generally higher density wood and lower MFA in higher spacing treatments. Malan et al. (1997) found that that the annual ring density and radial gradient increases with increasing intensity of suppression. They also stated that ring number, effect of spacing densities and their interaction accounted for most of the variation in annual ring density. Tree form is another factor that has an influence on MOE. Research from New Zealand has shown that air temperature and stem slenderness together are responsible for 75% of the variation in green MOE (Watt et al. 2006). Board position within the sawlogs also had a significant effect on the mean stiffness. The stiffness increased from the inner boards to the outer boards (from pith to bark). The MOE or stiffness results prove similar to studies done by Erasmus (2016) and Wessels et al. (2014).

Results from this study showed that board value was greatly influenced by MOE. Board value increased with increasing spacing treatment and also increased from the inner board position to the outer board position. Comparing the different planting treatments, one can see for instance, that 84.6% of the pith boards (board position 0) of the 2 981 spha treatment could be recovered as S5 grade lumber (Table 9). In contrast, no S5 grade lumber could be recovered from the pith boards of the 403 spha treatment or from the position 1 boards (Table 12). That effectively means that for small logs from the 403 spha treatment it will not be possible to recover structural grade lumber, whereas for the 2 981 spha treatment more that 80% of lumber from small logs could potentially be structural grade lumber. That also translated into value differences of logs from these treatments: An A-grade log (13-17.9 cm) from the 403 spha spacing treatment created net product value of R 465.99/m^3 whereas an A-grade log from the 2 981 spha created net product value of R 521.35/m^3 (Table 15). The value differences could also be seen for larger logs i.e. D1 logs from the 403 spha treatment had a net product value of R 947.32/m^3 whereas a D1 from the 2 981 spha treatment had a net product value of R 1 112.60/m^3.

The log net value recovery results (Table 15) also need to be seen in the context of the input values. For instance, processing costs were considered constant for all log sizes at an SA average of R 484/m^3 in 2015 (Table 15). For some sawmills that will not be true (especially framesaw mills) as smaller log sizes will have much higher processing costs due to smaller volume throughputs possible the same goes for harvesting costs. On the other hand, modern small log mills can process small logs at a very low cost – and the lowest cost producer in SA is apparently a mill processing log sizes from 13- 30 cm diameter. We considered a flat processing cost rate more realistic for the future, but one needs to be aware of this cost assumption as LEV values were of course also dependent on the processing cost inputs. Product pricing also need to be considered – although it is difficult to forecast what price behaviour will be in the future. There was a relatively small price difference between XXX and S5 timber in 2015 (R 2 351/m^3 vs. R 2 680/m^3). If that difference increase it will also result in wider value differences for logs from denser planting spacing and less dense spacings. Another cost that can vary quite a lot dependent on the technology used is that of harvesting. It is thus important to view the log value recoveries in the context of input values as it will also help one to understand the factors with a relatively high influence on the full value chain operation – in this case measured in terms of LEV.

Tree form also has an influence on log value. Poorly shaped trees will result in poor volume recoveries from sawmills and therefore lower value recoveries.

Although the highest log values were obtained from spacing treatment 2 981 spha, this did not mean that it would necessarily have had the best LEV. In fact, results from this study showed that 2 981 spha had the poorest LEV out of the four spacing treatments at an LEV of –R 15 424.57/ha (Table 17). This LEV would have realised if thinning occurred at 11 y to a final density of 350 spha and clearfelling at 19 years (Table 17). Considering the land value stated by FES (R14 000), this management regime is not economically feasible. The clearfelling ages of the best management regimes for each planting density decreased from 2981 and 1 808 spha (19 years) to 1 097 spha (18 years) and 403 spha (15 years). This was probably due to the faster diameter growth of low planting densities which allow harvesting at a younger age. It is interesting to note that the preferred thinning age, where the maximum LEV was calculated, increased with decreasing planting densities from 2 981 spha (11 years) to 1 097 (13 years) – which was the maximum thinning age considered in our models. From the LEV surface graphs (Figure 40-42) it seems as if that was close to an optimal in any event and would not have increased much if more than 13 years was an option. The best land expectation value (LEV) of R 47 693.02/ha would come from a spacing treatment of 1 808 spha if it was thinned at age 12 to 300 spha and clearfelled at 19 y. This planting density is currently higher than the industry standard and the thinning age is just much later than the norm. It must be noted that the log value recoveries obtained if an earlier thinning age is selected will probably be lower since there would be less competition and wood properties would not be as favourable.

The best management regime for the 1 097 spha sites had an LEV very close to that of the 1 808 spha treatment of R46 677.59/ha while the unthinned 403 spha treatment had an LEV of R41 930.36/ha. Except for the LEV of the management regime of the 2 981 spha treatment (-R 15 424.57/ha), the other three planting densities all returned LEV values relatively close to each other. Since these values are so close to each other, other considerations might also be taken into account for selecting a regime. The log diameter mix and subsequent product size mix, the product grade mix (structural vs. utility) and the rotation age might play a role in decisions.

Chapter 6

6. Conclusion and recommendations

6.1 Conclusion

The following conclusions can be drawn from the stem form study:

1. The initial planting density had a significant effect on each of the five stem form characteristics (stem deviation, sinuosity, butt flare, taper, ovality);
2. The results for stem deviation, stem sinuosity, and butt flare had similar trends, decreasing with increasing planting density up to the 1808 and 2981 spha treatments which had similar values;
3. Stem deviation of the bottom 0.3-3.3m section of the 403 spha and 1097 spha treatments were much higher than any other stem section of any other treatment;
4. Taper was very high up to 3.3m for all spacing treatments. Taper for the 403 spha treatment was much higher than the others;
5. Ovality showed completely different behaviour to the other stem form characteristics – it increased with higher planting densities and with tree height.
6. The stem form investigation confirmed that planting density did indeed influence stem form (deviation, butt flare, taper, ovality) of trees.

The following conclusions can be drawn from the study on the effect of management regimes on LEV:

1. There was an increase in mean board stiffness with increasing planting density from 403 to 2 981 spha. The two mid-level spacings (1 097 and 1 808 spha) had similar mean board stiffness;
2. Similarly, the structural grade recoveries (S5) of similar board positions increased with planting density. For example, the S5 grade recovery for pith boards for the 403

spha treatment was 0%, for the 1 097 spha it was 11.8%, for the 1 808 spha it was 25%, and for the 2 981 spha treatment it was 84.6%;

3. Net product value recovery, for the same log sizes, also increased with planting density. For instance, an A-grade log (13-17.9cm) from the 403 spha spacing treatment created net product value of R 465.99/m^3 whereas an A-grade log from the 2 981 spha created net product value of R 521.35/m^3;
4. The best land expectation value (LEV) of all the management scenarios was R 47 693.02/ha from 1 808 spha planting density with a thinning to 300 spha at age 12 and clearfelling at age 19. The best management regime for the 1 097 spha sites had an LEV very close to that of the 1 808 spha treatment of R 46 677.59/ha while the unthinned 403 spha treatment had an LEV of R 41 930.36/ha. Except for the LEV of the management regime of the 2 981 spha treatment (-R 15 424.57/ha), the other three planting densities all returned LEV values relatively close to each other.

6.2 Recommendations

Stemfit is a new program that was only developed in 2017. This is the first study that attempted to use Stemfit to determine stem form characteristics. Results obtained appear reasonably accurate, however, the sample size of trees used for this study could potentially have been much larger. Stemfit, at the moment, cannot determine stem form of trees that fork and also return errors when trees have too little detail from LiDar scans. This can be improved by performing more scans per plot to ensure enough data of each tree is obtained. Only four scans per plot were used for this study for 25 trees in a 5x5 layout. It is recommended that at least 5 or more scans for a sample plot of this size should be used for more accurate results. It would also be beneficial to obtain data from a sample plot that is a full hectare and not just in a 5x5 sample layout. Enumeration data might not be so accurate using the 5x5 layout sample plot because it is only based on a very small percentage of the full planting density. For example, consider a planting density of 2981 spha, 25 trees in a 5x5 layout is less than 1% of the number of trees available in a full hectare of 2981 spha. Poor enumeration data could also lead to inaccurate prediction models. The prediction models used in FORSAT also need to be improved for stand densities that are much higher (2981 spha) and much lower (403 spha) than the norm of 1000-1300 spha. It was evident that the prediction models used in FORSAT were inaccurate for higher and lower planting densities because FORSAT indicated that each sample plot of 2981, 1808, 1097 and 403 spha had completely different site indices although these sample plots were planted on the same site. The sample plots used for this study were also unthinned. It could be beneficial adding management regimes to sample plots of one hectare that include at least 1 thinning. This will be interesting to see if the board stiffness from different positions within trees are improved. These values could then be used to obtain log values that can then be used in FORSAT for different management regimes.

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Appendix A

Simsaw Simulation Report : Summary

(Real Logs)

CSIR

Log class specifications

Log class no.	Diameter (cm) Min	Max	Length (m) Min	Max	Incr	Taper (mm/m) Min	Max	Sweep (mm/m) Min	Max	Ovality Min	Max	Defect core (%) Min	Max	Grade description	Log price ($/m³)	No. of logs
1	14.0	17.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100	All log grades	120.00	35
2	18.0	21.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100	All log grades	120.00	27
3	22.0	23.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100	All log grades	120.00	7
4	24.0	27.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100	All log grades	120.00	12
5	28.0	31.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100	All log grades	120.00	3
6	32.0	45.0	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100	All log grades	120.00	4

Grade Outputs

Log grade	Thickness (mm)	Width (mm)	Board grade	Precentage defect core 0 %	1-50%	51-99%	100%
	25.0	76.0	All board grades	100	100	100	100
		114.0	All board grades	100	100	100	100
		152.0	All board grades	100	100	100	100
		228.0	All board grades	100	100	100	100
	38.0	76.0	All board grades	100	100	100	100
		114.0	All board grades	100	100	100	100
		152.0	All board grades	100	100	100	100
		228.0	All board grades	100	100	100	100
	38.1	76.0	All board grades	100	100	100	100
		114.0	All board grades	100	100	100	100
		152.0	All board grades	100	100	100	100
		228.0	All board grades	100	100	100	100
	38.2	76.0	All board grades	100	100	100	100
		114.0	All board grades	100	100	100	100
		152.0	All board grades	100	100	100	100
		228.0	All board grades	100	100	100	100
	38.3	76.0	All board grades	100	100	100	100

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		114.0	All board grades	100	100	100	100
		152.0	All board grades	100	100	100	100
		228.0	All board grades	100	100	100	100
	50.0	76.0	All board grades	100	100	100	100
		114.0	All board grades	100	100	100	100
		152.0	All board grades	100	100	100	100
		228.0	All board grades	100	100	100	100
	76.0	76.0	All board grades	100	100	100	100
		114.0	All board grades	100	100	100	100
		152.0	All board grades	100	100	100	100
		228.0	All board grades	100	100	100	100

Machine settings

1 Line 1

Primary Breakdown Machine		Secondary Breakdown Machine		Edging		Resaw	
Kerf sizes (mm) :	5.0	Kerf sizes (mm) :	5.0	Edging for max :	Volume	Primary :	On
Log rotation (deg) :	0	Cant guiding :	None	No of blades :	2	Kerf size (mm) :	5.0
Log misalignment (mm) :	0	Cant misalignment (mm) :	0	Kerf size (mm) :	5.0	Secondary :	On
Saw offset (mm) :	0	Saw offset (mm) :	0			Kerf size (mm) :	5.0
		Min radius for RTC machine (m):	0.0 (0mm)				

Product specifications

Thicknesses (mm) Dry	Wet	Widths (mm) Dry	Wet	Lengths (m) Description	Min	Max	Incr	Combinations Thickness (mm)	Width (mm)	Length	Grade	Price ($/m³)
25.0	27.0	76.0	81.0	All	0.9	6.6	0.3	25.0	114.0	All	All board grades	2546.00
38.0	41.0	114.0	120.0					38.0	114.0	All	All board grades	2629.38
38.1	41.0	152.0	160.0					38.1	114.0	All	All board grades	2625.17
38.2	41.0	228.0	240.0					38.2	114.0	All	All board grades	2680.00
38.3	41.0											
50.0	54.0											
76.0	81.0											

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	%
38.1	76.0	0.0	0.0	0.0	%
38.1	114.0	0.0	0.0	0.0	%
38.1	152.0	0.0	0.0	0.0	%
38.1	228.0	0.0	0.0	0.0	%
38.2	76.0	0.0	0.0	0.0	%
38.2	114.0	0.0	0.0	0.0	%
38.2	152.0	0.0	0.0	0.0	%
38.2	228.0	0.0	0.0	0.0	%
38.3	76.0	0.0	0.0	0.0	%
38.3	114.0	0.0	0.0	0.0	%
38.3	152.0	0.0	0.0	0.0	%
38.3	228.0	0.0	0.0	0.0	%
50.0	76.0	0.0	0.0	0.0	%
50.0	114.0	0.0	0.0	0.0	%
50.0	152.0	0.0	0.0	0.0	%
50.0	228.0	0.0	0.0	0.0	%
76.0	76.0	0.0	0.0	0.0	%
76.0	114.0	0.0	0.0	0.0	%
76.0	152.0	0.0	0.0	0.0	%
76.0	228.0	0.0	0.0	0.0	%

Summary results

	Lengths	
Cross-section	All	Total
25.0 x 114.0	72	**72**
38.0 x 114.0	71	**71**
38.1 x 114.0	73	**73**
38.2 x 114.0	49	**49**
	265	**265**

Appendix B

Table 8.7.3 Sawlog class classification.

Log Class	Length	Thin-end diameter
A	1.8 m to under 3.6 m	130 – 179 mm
B1	1.8 m to under 3.6 m	180 – 259 mm
B2	3.6 m and longer	180 – 259 mm
C1	1.8 m to under 3.6 m	260 – 339 mm
C2	3.6 m and longer	260 – 339 mm
D1	1.8 m to under 3.6 m	340 + mm
D2	3.6 m and longer	340 + mm

Table 8.7.5 Standard yields for softwood sawlog classes.

Log class	Recovery (%)	%Structural	%Other
A	38	0	100
B1	46	20	80
B2	44	60	40
C1	52	70	30
C2	49	70	30
D1	57	80	20
D2	55	80	20