The growth and knot property implications of a single stage thinning regime for *Pinus patula* saw log stands.

by

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Declaration

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ABSTRACT

The objective of the study was to analyse the growth and knot property implications of changing from the conventional two-stage thinning regime in *Pinus patula* saw log stands to a single stage mid-rotation thinning regime. (The investigation was done under conditions where no changes were made to the accompanying four-stage conventional pruning regime). The analysis of the growth ring widths showed that although individual trees in conventionally thinned stands, in both high and average site quality classes (hereafter SQ_1 SQ_3), yielded more individual mean DBH and more individual mean tree volume than conventionally pruned single thinned trees, single thinned stands yielded higher mean stand volume per hectare owing to a higher final stand density than the conventionally thinned stands. Single thinned stands on SQ_1 have on average 26.1 m^3/ha greater mean stand volume than conventionally thinned stands of the same site quality class. The difference between conventionally thinned stands and single thinned stands in SQ_3 was however not statistically significant.

The mean knot diameter for the log unit ranging in length from 0 -7.2 m in conventionally thinned stands was on average either 0.36 cm (SQ_1) or 0.30 cm (SQ_3) larger than the mean knot diameter for the corresponding treatment in single thinned stands. Higher up the merchantable stem, the mean knot diameter for log unit of length range 7.2 -16.8 m in conventionally thinned stands was on average 0.27 cm larger than the corresponding value in conventionally thinned stands of SQ_1. In SQ_3, the difference in the mean knot diameter for log unit 7.2 -16.8 m in both treatments was not statistically significant. The merchantable stems of trees conventionally thinned have a higher share of sound knots (76 % for SQ_1 and 74 % for SQ_3) compared to that of merchantable stems of trees conventionally pruned single thinned (68 % for SQ_1 and 69 % for SQ_3, respectively).

The study also contained two additional treatments where no thinning was carried out, either in the presence (P_4T_0) or in the absence (P_0T_0) of a conventional, four-stage pruning regime. In both site qualities, the pruning done in P_4T_0 led to an unexpectedly higher mean stand volume in P_4T_0 (194.2 m^3/ha for SQ_1 and 95.8 m^3/ha for SQ_3) compared to that of P_0T_0 (167.6 m^3/ha for SQ_1 and 86.1 m^3/ha for SQ_3, respectively). With a comparably higher percentage of sound knots, P_4T_0 also had a larger mean knot diameter compared to P_0T_0.

Keywords: *Pinus patula*, single stage thinning regime, knot related timber quality, growth, growth ring width, thinning-pruning interaction, relative knot diameter.

OPSOMMING

Die studie het ten doel gestel om die implikasies vir groei en houtkwaliteit te ondersoek wanneer die konvensionele twee-fase dunningsregime gewysig word na ꞌn enkele mid-rotasie dunning in saaghout opstande beplant met *Pinus patula*. (Die ondersoek is gedoen onder toestande waar die gepaardgaande vier-fase snoeiregime onveranderd gelaat is vir beide die getoetsde dunningsbehandelings). Analise van die jaarring wydte wys dat individuele bome in die konvensionele regime, in beide hoë en gemiddelde boniteitsklasse (hierna BK_1 en BK_3) meer deursnee groei en volume produseer het as die behandelings met enkel dunning. Enkel gedunde opstande het egter meer volume per hektaar produseer as die konvensionele regime met twee dunnings, en dit word toegeskryf aan die groter stamtal in opstande behandel met ꞌn enkel dunning regime. Konvensioneel gesnoeide opstande met enkel dunning op BK_1 het gemiddeld 26.1 m^3/ha meer finale volume produseer as konvensioneel gedunde opstande van dieselfde klas. Dieselfde tendens het gegeld met opstande in BK_3, maar hier was die effek nie statisties betekenisvol nie.

Die gemiddelde kwasdeursnee op die stam seksie tussen 0 en 7.2 m hoogte in konvensioneel gedunde opstande was 0.36 cm (BK_1) tot 0.30 cm (BK_3) groter as die ooreenstemmende kwaste in die enkel dunning opstande. Vir die benutbare stam seksie van 7.2 tot 16.8 m hoogte was die kwaste in BK_1 van konvensioneel gedunde opstande 0.27 cm groter as in die ooreenstemmende vakke onder ꞌn enkel dunningsregime. In BK_3 het die gemiddelde kwasgrootte op hoogte van 7.2 tot 16.8 m nie beduidend verskil tussen dunningsregimes nie. Die benutbare stamme van bome in konvensionele dunningsregimes het ’n groter fraksie van vaste, onbevlekte kwaste (76% vir BK_1 en 74% vir BK_3) vergeleke met ooreenstemmende behandelings in die enkel gedunde opstande (naamlik 68% vir BK_1 en 69% in BK_3).

Die studie bevat ook twee behandelings waar geen dunning uitgevoer is nie, 'of in die afwesigheid of teenwoordigheid van 'n vier-fasige konvensionele snoeiprogram. In beide bonniteitsklasse het die snoeiprogram in gelei tot hoër gemiddelde opstandsvolume vergeleke met die ongesnoeide bome (die opstandsvolume in BK_1 en BK_3 was 194.2 en 95.8 m^3/ha vergeleke met 167,6 en 86.1 m^3/ ha, onderskeidelik). Gesnoeide bome het 'n groter persentasie vleklose kwaste asook 'n groter gemiddelde kwasdeursneë as ongesnoeide bome gehad.

Sleutelwoorde: *Pinus patula*, enkelfase dunningsregime, konvensionele dunningsregime, kwasverwante houtkwaliteit, groeitempo, jaarringwydte, dunning-snoei interaksie, verhouding van bevlekte tot onbevlekte kwaste, relatiewe kwasdeursnee.

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CHAPTER 1 INTRODUCTION

Thinning regimes for South African grown softwood species are set based on a pre-determined initial planting density and are scheduled based on site quality and organisational working circles (Kotze and du Toit, 2012). A conventional thinning regime for a stand whose pre-determined planting density is 1111 trees per hectare is a two stage thinning regime, scheduled at approximately eight years (first thinning to a stand density of 650 trees per hectare) and at approximately twelve years (second thinning to a stand density of 450 stems per hectare). Such a conventional thinning regime is usually integrated with a four stage conventional pruning regime, scheduled at approximately four years (first pruning to a height of 1.5 m), six years (second pruning to a height of 3 m), eight years (third pruning to a height of 5 m) and lastly ten years (fourth pruning to a height of 7 m). Softwood species grown for saw log rotations in South Africa are generally established on a wide range of site quality classes ranging from the high site quality (SQ_1) to the average site quality (SQ_3). SQ_1 being the site class whose site index at base year twenty (SI_{20}) is greater than 27 m while SQ_3 is the site class whose SI_{20} ranges from 19 m to 22.9 m (Kotze and du Toit, 2012).

The need to prioritise the salvage of any salvageable timber following a major fire event is one of the major reasons for the change from the conventional thinning regime to a single stage mid rotation thinning regime. A single stage mid rotation thinning regime for a stand whose pre-determined planting density is 1111 stems per hectare is a single thinning, scheduled at approximately twelve years to a final stand density of approximately 500 stems per hectare. Due to the rampant fires in the South African forestry industry, the single stage thinning regime, is becoming increasingly common as a default thinning regime to the conventional thinning regime in the South African saw log industry. Although there has been an increase in the use of the single stage thinning regime in South Africa, there is minimal research investigating the impact of the single stage mid rotation thinning on final standing volume per hectare and knot properties of the final wood.

According to Pretzsch (2009), the longer the time that trees spent under intense competition for growing resources including space, the smaller the mean stem diameters of the trees would be and the more unsound knots their stems would carry.

Based on this finding by Pretzsch (2009), single stage thinned stands are thought to yield smaller diameter trees with more unsound knots at rotation end compared to stands that have been conventionally thinned. Exploring the effect of a single stage thinning on stem diameter growth development and on knot morphology is therefore important. Understanding the effect of the single stage regime on growth and knot properties would better inform the process of migrating from the conventional thinning regime to the single stage thinning regime with minimal effect on volume growth and knot properties. This study thus sought to investigate the growth and knot property implications of the single stage thinning regime.

In this study, the growth ring profile of the diameter at breast height (DBH) disc of each selected merchantable stem in the conventionally thinned stand were compared to that of the selected stem in the single thinned stand. Any statistically significant differences in growth were noted and described. Based on the projected stem volume model proposed by Perez *et al* (2003), the assessment of the differences in knot properties between the two thinning regimes was done on pre-divided sections of the merchantable stem (hereafter referred to as log units). The first log unit comprising of three successive 2.4 m log pieces (from the base to 7.2 m), represented largely the knottiness within the thinning era while the second log unit comprising of successive 2.4 m log pieces from 7.2 m onwards represented largely the knottiness post the thinning era. Within each log unit, the differences in knot diameters and ratios of sound to unsound knots between the conventional and single thinned stands were noted and described statistically. Aware of the possible existence of an interaction of site quality and pruning-thinning combination (P_4T_2[1], P_4T_1[2], P_4T_0[3] and P_0T_0[4]), the study sought to reach a conclusion whether or not there is a statistically significant difference in knot characteristics and final standing volume between a single stage thinning regime and a conventional thinning regime and between SQ_1 and SQ_3.

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[1] Conventional four pruning stages to 7 m, conventional two stage thinning

[2] Conventional four pruning stages to 7 m, single stage mid rotation thinning

[3] Conventional four pruning stages to 7 m, unthinned

[4] Unpruned and unthinned

1.1 OBJECTIVES

The objectives of this study were:

1. To determine if the standing volume at age 14 and the knot properties of *Pinus patula* trees in a stand subjected to a conventional thinning regime differed from that of *Pinus patula* trees in a stand subjected to a single stage thinning regime.
2. To determine if the standing volume at age 14 and the knot properties of *Pinus patula* trees established in SQ_1 differed from that of *Pinus patula* trees established in SQ_3.

1.2 RESEARCH HYPOTHESES

The growth related hypotheses for this study were the following:

H_1 *Pinus patula* stands subjected to a single stage thinning regime would not respond with a significant increase in standing volume (relative to a conventionally thinned regime stand), regardless of site quality.

H_{1alt} *Pinus patula* stands subjected to a single stage thinning would respond with a significant increase in standing volume (relative to a conventionally thinned regime stand), regardless of site quality.

Key questions

1) Is there a difference in standing volume between SQ_1 and SQ_3?
2) Is treatment P_4T_2 more productive than treatment P_4T_1?
3) Are there any significant interactions between site quality and thinning-pruning regime combinations P_4T_2 and P_4T_1?

The knot characteristics related hypotheses for this study were the following:

H_2: Log units at a specified height in *Pinus patula* stands subjected to a single stage thinning regime developed no differences in knot characteristics to log units at the same specified height in stands subjected to a conventional thinning regime, regardless of site quality.

H_{2alt} Log units at a specified height in *Pinus patula* stands subjected to a single stage thinning regime develop significant differences in knot characteristics to log units at the same specified height in stands subjected to a conventional thinning regime, regardless of site quality.

Key questions

1) Is there a difference in knot properties between the 0-7.2 m log unit and the 7.2-16.8 m log unit of the same merchantable stem, within the same pruning-thinning-site quality treatment ($P_4T_{2.}SQ_1$, $P_4T_{1.}SQ_1$, $P_4T_{2.}SQ_3$ and $P_4T_{1.}SQ_3$)?
2) Is there a difference in knot properties between the 0-7.2 m log units and the 7.2-16.8 m log units across different pruning-thinning-site quality treatments?
3) Are there any significant interactions between pruning-thinning-site quality treatment ($P_4T_{2.}SQ_1$, $P_4T_{1.}SQ_1$, $P_4T_{2.}SQ_3$ and $P_4T_{1.}SQ_3$) and log unit length (0-7.2 m and 7.2 -16.8 m)?

1.3 SCOPE AND LIMITATIONS OF THE RESEARCH

The oldest available sets of compartments that suited the $P_4T_{2.}SQ_3$ category were 14 years old while the rest of the treatments averaged 19 years. For an even comparability of standing volume and knot properties across all treatments, this study compared the standing volume and knot properties of the single stage thinning regime to that of the conventional two stage thinning regime only up to the age of 14 years. The scope of the study was to investigate the effect of changing from conventional to single stage thinning on final standing volume and on the knot properties in the final round wood product. The growth ring width progression at DBH (from pith to the cut off growth ring representing year number 14) was used to infer growth measured as final standing volume. The average knot diameter and the percentage of sound to unsound knots per log unit (0-7.2 m or 7.2 -16.8 m) were used to infer knot properties of the final round wood product.

Due to the study's focus on standing volume, the volume removed during thinning were excluded in the comparison of the conventional and single stage thinning regimes. Furthermore, due to the study's dependence on knot properties data collected through cross sectional stem analysis of discs from different heights, this study is limited in informing on the deeper analysis of other wood quality factors like bending strength, stiffness and stability. However while the findings from this study may not fully address overall stand productivity as well as other timber quality parameters of the single stage thinning, its findings would add to the body of knowledge aimed at better understanding the effect of a single mid-rotation thinning regime on final standing volume and knot properties on the final round wood product.

CHAPTER 2 LITERATURE REVIEW

This chapter deals with the analysis of available literature as it relates to the research questions of the study. The literature section is presented in a way that paints a picture of the methodological designs and how they relate to the response variables being measured in this study. In this chapter, the choice of the species *Pinus patula* and the choice of knot characteristics as the proxy for timber quality were put into the perspective of other studies.

2.1 THE SIGNIFICANCE OF *PINUS PATULA* IN SOUTH AFRICAN SAW TIMBER INDUSTRY

The pine genus constitutes the largest percentage of the South African forestry industry at 50.6 % of the commercial forestry area in South Africa followed closely by Eucalyptus at 41.8 % (Forestry South Africa, 2017). The percentage intake of the softwoods into South African sawmills is heavily skewed towards the species *Pinus patula* at approximately 50 % of the total percentage intake of softwood into sawmills (Southey, 2012). When this statistic is read together with the plantation area use by genus statistic, it makes *Pinus patula* a very important Pine species in South Africa whose silviculture need to be given as much attention to produce an end product of the market desired quality. To the benefit of the South African industry the species *Pinus patula* is very responsive to silviculture interventions when planted on most sites ranging from low to highly productive as long as it is not exposed to a lot of risk factors such as fire, drought and diseases (du Toit, 2012). When the correct site species is chosen, *Pinus patula* trees grown on high productivity sites under intensive silviculture are capable of giving maximum economic returns on investments (du Toit, 2012; Kotze and du Toit, 2012).

2.2 LOG CLASSIFICATION AND END USE PRODUCTS IN SOUTH AFRICAN SAW TIMBER INDUSTRY

The South African saw timber industry uses a saw log classification system that incorporates log length and thin-end diameter in its method of saw log classification (Southey, 2012). The South African saw log classes are shown in Table 2.1.

Table 2.1: Saw log 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 +

Source: Southey (2012)

While saw log class distribution within a stem is influenced by a number of site factors and silvicultural factors, the rotation length that a stand is subjected to becomes the final deciding factor. As rotation length in the South African forestry industry got shortened from as high as 35 years to as low as 23 years during the last two to three decades, the saw log class distribution percentage of “D” class logs also decreased while the smaller log class percentages increased (Southey, 2012).

The end use products shown in Figure 2.1 come mainly from rough sawn timber dimensions ranging in thickness from 16 mm to 76 mm and in width from 38 mm to 304 mm (Southey, 2012). Due to the fact that the main uses of timber in South Africa is for construction and roofing purposes at a combined 53 % as shown in Figure 2.1, the quality of the rough sawn timber is of paramount importance in fulfilling this end usage of the timber.

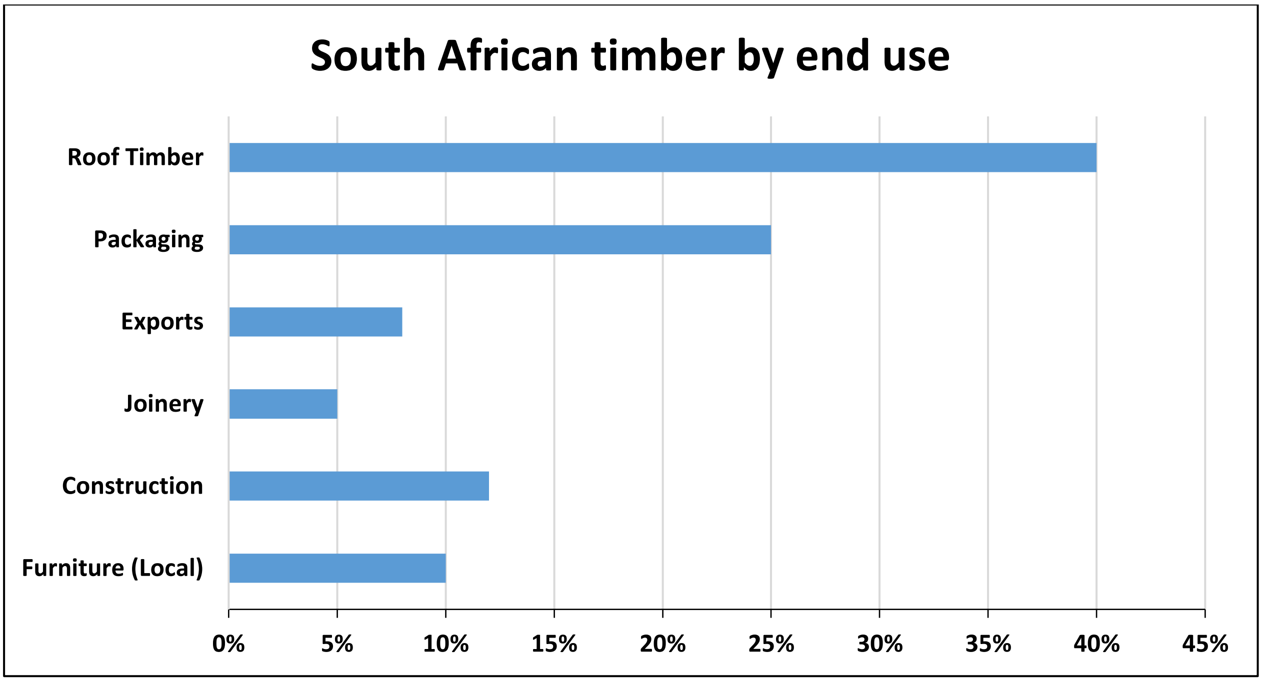


Figure 2.1: South African timber by end use: (Modified from Southey, 2012)

Knot characteristics in the context of the end use product is not only influenced by the species type but also the silviculture management through which the tree is exposed to. It follows that the silviculture regime, as dictated by planting density, pruning regime, thinning regime and rotation age is key in ensuring that the end use product meets the quality standards that will satisfy both local and export market.

2.3 SILVICULTURE REGIMES WITHIN THE SAW TIMBER CONTEXT

In plantation forestry stands where trees of the same species are grown for the same management objective, growing conditions are manipulated in a number of ways simulating natural conditions in order promote growth. Kotze and du Toit, (2012) term this manipulation at stand-level a silvicultural regime and further add that the design of such a silvicultural regime requires considerations such as species type, site quality and management objectives among other factors. The success of any silviculture regime to achieve the desired saw log product depends on correct timing and scheduling of the processes influencing growth and also matching the growth dynamics of the tree species to the site where the trees are planted (Shepherd, 1986; Kotze and du Toit 2012; du Toit, 2012). While the saw log value increase with an increase in thin-end diameter, length and pruning status, the full saw log value only materialise fully at clear-felling stage at which time the saw log quality need to comply with the end use saw timber specifications as dictated by the markets (Kotze and du Toit, 2012; Southey, 2012). According to Kotze and du Toit, (2012), these saw timber specifications are mainly mechanical strength, density and knottiness.

2.3.1 Site quality effect on silviculture regime

The ability of a site to supply growth resources to the trees growing on the site describes the quality of the site (Kotze and du Toit, 2012). Site quality is influenced by a number of factors namely topographic conditions, climate and soil conditions (Louw and Scholes, 2002; Kotze and du Toit, 2012). Since the quality of a site has an effect on the growth rate of trees, site quality is considered in determining the timing of the constituents of a silvicultural regime. Ultimately, in a properly managed silviculture regime a good quality site shows a positive correlation with growth and wood properties of trees in the stand (Malan, 2012; Kotze and du Toit, 2012).

According to Marsh, (1978) in order to apply a pruning-thinning regime and estimate yields, it is a necessary pre-requisite to assess the quality of the site. The site quality height tables used for *Pinus patula* in the South African forestry industry are shown in Table 2.2. Since dominant height is less affected by stand density compared to diameter, the dominant height attained by trees at a particular age is a good proxy for site quality (Marsh, 1978). Adding to what is shown in Table 2.2, in South Africa, the range of heights attained at 20 years is commonly divided into three site qualities labelled Site quality I (denoted SQ_1), Site quality II (denoted SQ_2) and Site quality III (denoted SQ_3).

Table 2.2: Site quality height tables for *Pinus patula*

Age (Years)	Mean height in metres		
	Site quality 1	**Site quality 2**	**Site quality 3**
5	7.0	6.0	4.5
10	16.5	14.0	11.5
15	23.0	19.5	16.0
20	27.0	23.0	19.0
25	30.0	25.5	21.0

Source: Marsh (1978).

2.3.2 Planting density as part of the silviculture regime

Kotze and du Toit, (2012) highlight the following initial stand densities: 816 stems per hectare (3.5 x 3.5 m), 1111 stems per hectare (3 x 3 m), 1333 stems per hectare (3 x 2.5 m), 1372 stems per hectare (2.7 x 2.7 m), 1667 stems per hectare (3 x 2 m) and 1736 stems per hectare (2.4 x 2.4 m) as the most common stand densities in South African pine plantations. For saw timber rotations, the common spacing however range between 816 and 1372 stems per hectare (Kotze and du Toit, 2012). With *Pinus patula* having the adaptability to establish across different sites, stands established with either the denser and wider spacing can display good growth depending on the silviculture management following after the establishment (du Toit, 2012).

2.3.3 Thinning schedules as part of the silviculture regime

Thinning, which is the selective removal of a predetermined number of trees per hectare to promote radial stem growth of remaining trees, forms a critical function in silviculture regimes whose aim is saw timber production. According to Kotze and du Toit, (2012), optimum gain is achieved when the design of a thinning regime takes into consideration the quality of a site, the end products, the species type and the rotation length. These factors would in turn influence the timing, intensity and kind of thinning that need to be done (Pretzsch, 2009). Furthermore, thinning regimes do not work in isolation to achieve the management objective of good quality timber. Where the objective is knot free saw timber production, thinning regimes are integrated with pruning regimes both in planning and in implementation to realise the objective (Hinze and van Laar, 1986; Lange *et al.,* 1987, Pretzsch, 2009 and Kotze and du Toit, 2012).

Thinning regimes used in the South African forestry industry are based on site qualities in terms of SI_{20} ranging from 15 to 35 m, planting densities ranging from 816 to 1372 stems per hectare and rotation ages ranging from 24 to 30 years (Kotze and du Toit, 2012). The regimes are presented in Table 2.3.

Table 2.3: Conventional thinning regimes for saw timber production in South Africa

Planting density and spacing					
1372 stems per hectare **2.7 m x 2.7 m**		**1111 stems per hectare** **3.0 m x 3.0 m**		**816 stems per hectare** **3.5 m x 3.5 m**	
Age (Years)	**Stems / Ha**	**Age (Years)**	**Stems / Ha**	**Age (Years)**	**Stems / Ha**
0	1372	0	1111	0	816
8-10	650-750	8-10	450 -750	8-10	450 -500
11-15	400-500	11-15	300-500	11-15	275-300
14-18	275-300	14-18	300	14-18	
24-30	0	24-30	0	24-30	0

Source: Kotze and du Toit, (2012)

2.3.4 Pruning schedules as part of the silviculture regime

Pruning, which is the scheduled removal of the branches in the lower sections of a crown to a predetermined height in fixed or variable prune heights, is done for access or to prevent the formation of dead knots or to produce clear wood (Kotze and du Toit, 2012). Pruning schedules are developed based on the working circle and are influenced by site quality. In the commonly used fixed-lift pruning scheduling system, the timing of pruning is based on age of the trees within a stand while readiness to take the pruning height is confirmed by means of a dominant height assessment, referenced to a set of researched dominant height growth curves for a range of site qualities (Kotze and du Toit, 2012). As shown in Table 2.4, the time a stand takes to be ready for pruning depends on the quality of the site. In good quality sites, the 3 m fixed-lift pruning may be achievable between three and four years while in average quality sites that may only be achievable after seven years.

Table 2.4: Conventional pruning regimes

Pruning lift (m)	**Dominant height (m)**	**Age of pruning (Years)**				
		SI_{20} class midpoint (m)				
		15	**20**	**25**	**30**	**35**
1.5	5.5	5.9	4.6	3.8	3.3	2.9
3.0	7.0	7.4	5.7	4.7	4.0	3.5
5.0	9.0	9.7	7.2	5.8	5.0	4.3
7.0	11.0	10.0	8.8	7.0	5.9	5.2

Source: Kotze and du Toit, (2012)

The other pruning approach which is based on target diameter over stub is the variable lift pruning scheduling system. As is shown in Figure 2.2 (an illustration adapted from Kotze, 2004), the target stem diameter over stub at the bottom of the pruned section is 15 cm, and is achievable by pruning the tree to a target stem diameter of approximately 10 cm (Kotze 2004, Kotze and du Toit, 2012). Doing the pruning on time, and consistently maintaining the 35% remaining crown height, would prevent the formation of dead knots and confines the defect core to less than 20 cm thereby maximising the clear wood radius (Kotze, 2004). In order to minimize growth loss, the timing of pruning lifts should be such that an average live crown of not less than 4 m is left at every pruning lift (Kotze and du Toit, 2012). To allow a pruned tree to add a considerable amount of clear wood around the defect core, at least 15 years of growth after pruning must be provided for, hence the pruning cut-off by many companies at 12 years (Kotze and du Toit, 2012). According to Neilsen and Pinkard (2003), an understanding of the effects of pruning severity on growth is critical to developing pruning regimes that will not reduce growth.

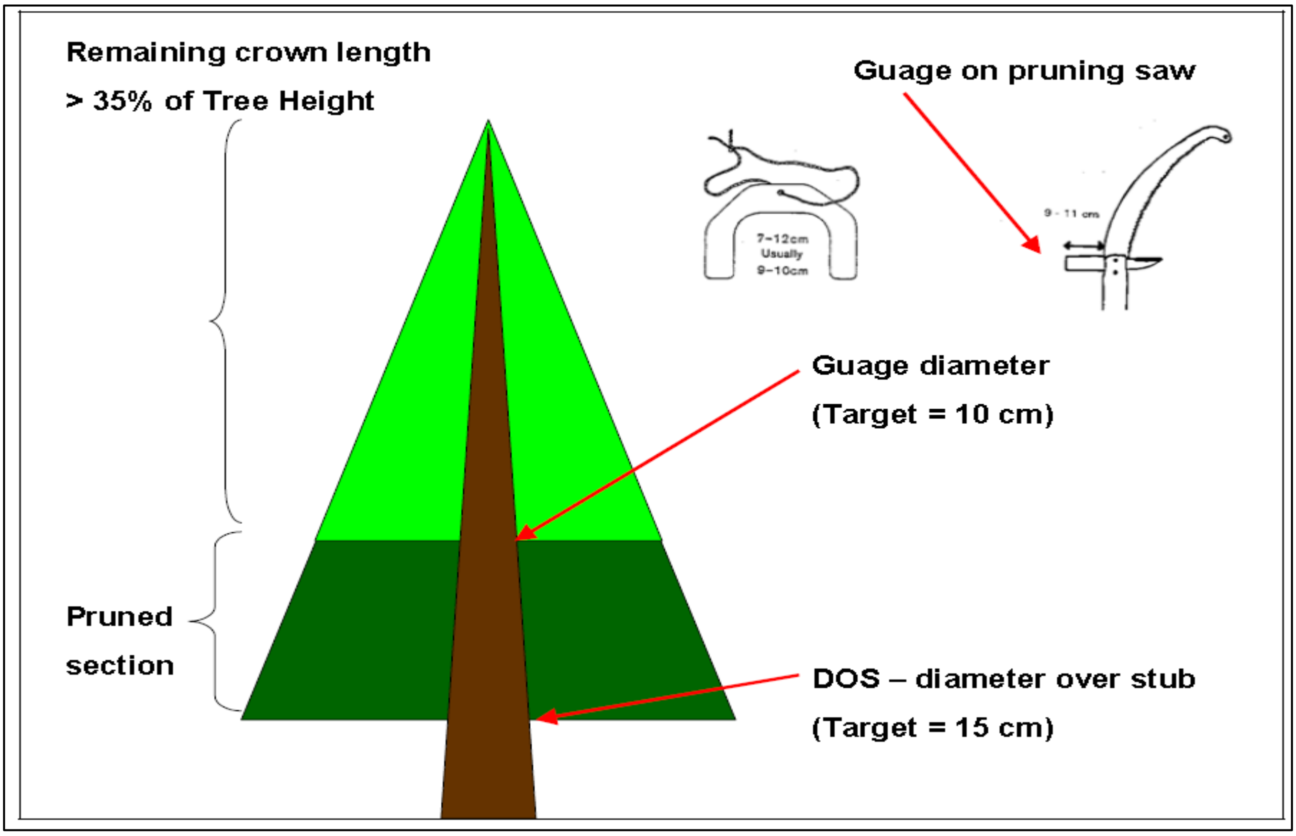


Figure 2.2: Parameters of a pruned tree (Kotze, 2004)

In multiple lift pruning regimes, early pruning of smaller diameters can be beneficial in reducing the diameter over stubs and the knotty core size (Neilsen and Pinkard, 2003). According to Neilsen and Pinkard, (2003), the size of the knotty core of *Pinus radiata* was significantly reduced by well-timed consecutive pruning lifts, with the more severe reduction in diameter over stub being experienced in the second lift pruning (Neilsen and Pinkard 2003). In their research, Neilsen and Pinkard (2003) found that an acceptable diameter over stub can be achieved by pruning to 60 % of the tree height at the second and third pruning lifts.

2.3.5 The pruning – thinning interaction

The combined effect of pruning and thinning on growth parameters in a planted stand, at a specific stand density is called a pruning-thinning interaction. This pruning-thinning interaction is site specific (Smith *et al* 1997; Pretzsch 2009; Amateis and Burkhart 2011). Pruning as a silviculture operation has its own individual effect on growth and knot characteristics of pine trees in a stand (Nielsen and Pinkard 2003). Likewise, thinning as a silviculture operation also has its own individual effect on growth and knot characteristics (Burton, 1981; Smith *et al* 1997; Kotze, 2004). However, the combined effect of the two operations produce an interaction that has a significant effect on growth and knot characteristics (Smith *et al* 1997; Pretzsch 2009; Wang *et al*., 2003; Amateis and Burkhart 2011). Based on the understanding of the dynamics of the pruning- thinning interaction, the saw timber industry prune trees to improve the quality of timber by restricting the knotty core to very minimal diameters (Amateis and Burkhart, 2011).

While timeous pruning narrows the knotty core, thinning boosts diameter growth thereby enhancing the production of large dimension saw logs with small defect cores and large clear wood radii that have a high market value. Pruning also alters crown structure by removing branches and leaves (Hinze and van Laar 1986, Kotze and du Toit 2012). The removal of leaves through pruning is however a problem because it alters the tree's photosynthetic capacity and depending on pruning intensity and frequency, pruning may significantly reduce growth in the process (Alcorn *et al* 2008, Kotze and du Toit 2012). It is therefore important that management objectives strike a balance between meeting the objective of producing timber of high quality and maintaining a good positive growth of the pruned trees (Amateis and Burkhart, 2011).

The pruning-thinning interaction is very important to the silviculture of softwoods. Thinning an already pruned stand in general has the potential to offset diameter growth loss brought about by pruning (Smith *et al.,* 1997). This is because research has shown that thinning reduce inter tree competition for light, water and nutrients thereby increasing the availability of growth resources to remaining trees (Pretzsch, 2009). Therefore even if the remaining trees have reduced photosynthetic capacity as a result of pruning, diameter growth of the trees may still be significantly high due to the abundance of growth resources necessitated by thinning (Smith *et al* 1997, Kotze and du Toit, 2012). A contradiction however still exists in literature as to what operation should be done first, between thinning and pruning to minimise the effects of diameter growth loss in regimes where pruning timing coincides with thinning timing. According to Neilsen and Pinkard (2003), the most appropriate time to thin is immediately after the pruning has been completed. Research has established that tree stems and branches respond profoundly in diameter growth after thinning and that such response in addition to being species specific is also site quality and stand density dependent (Pretzsch, 2009).

2.4 GROWTH DYNAMICS IN AN EVEN AGED STAND

Growth of a tree is the increase in height and diameter variables of that tree and how these variables jointly contribute to the increase in basal area, wood volume and biomass over time (Weiskittel *et al*., 2011; Kotze and du Toit, 2012; Bowman *et al*., 2013). Diameter is considered a representation for tree growth and is dependent on age. However, even though diameter is dependent on age and there is a strong correlation between tree diameter and age of the tree, trees of the same age could have differences in diameter due to the interaction of a number of factors (Worbes *et al*., 2003). Research has shown that height increases rapidly in the juvenile phase of growth, levels off and declines to lower levels of increase with age while diameter increases gradually over the lifetime of the tree (Hann and Larsen, 1991; Weiskittel *et al*., 2011; Bowman *et al*., 2013). According to Bowman *et al*, (2013), basal area and volume increase marginally in the juvenile phase and increase exponentially with age until senescence sets in.

According to Pretzsch (2009), resources needed for tree growth are not always adequate to the extent that trees in a stand have to compete for these growth resources for growth and in some case for survival. The competition in a stand is both between trees (inter tree competition) and within the tree itself among its own branches (intra tree competition). With inter tree competition the resultant effect is that some trees prevail over others and thereby receive a larger share of the available growth resources than their sub dominant counterparts (Mitchell, 1975; Nikinmaa and Hari, 1990). The same relationship exist with intra tree competition, where the branches advantageously positioned in terms of space and receiving more sunlight hours grow bigger and faster than those branches receiving less light and with less growing space (Pretzsch, 2009). This process result in the death of branches in the lower shaded sections of the canopy.

The upper sections of the canopies of the suppressed trees compete for resources with the lower sections of the canopies of dominant trees (Duchateau *et al.,* 2015). The suppressed trees' growing tips are able to withstand and survive the inter tree competition in the sub dominant region because they are competing for growth resources with the dead and dying branches of dominant trees which are already receiving less assimilates for growth compared to the upper branches on the upper crown chasing and maintaining dominance (Sprugel, 2002; Nikinmaa *et al.,* 2003). Yet for the suppressed trees, while more assimilates are still allocated to the upper section of their crowns, their upper crown is in the same crown height as the dying lower branches of the dominant trees. Supressed trees therefore adapt to the intense inter tree competition by maintaining their actively growing upper crowns in this zone of dying and dead branches where they thrive from light passing through the dominant trees' canopies. These dynamics of inter tree and intra tree competition determines the amount of time that branches remain alive within the canopy and the amount of diameter growth the live branches contribute to the stem in their lifetime (Kotze and du Toit, 2012). The amount of time a branch remains alive would in turn determine knot healthiness while the amount of diameter growth the live branches contribute to the stem before the branches die would determine the knot tightness with the stem as well as the relative knot diameter.

As is illustrated in the flow line diagram in Figure 2.3, genetics is one of the three factors affecting crown development and consequently knot characteristics. Therefore the significant inroads in genetics and tree improvement to reduce knottiness in forestry softwood species commercially grown for sawn timber need to be backed by sound site-specific silviculture in order to sustain production of knot free timber (Houllier *et al*., 1995). In structural timber, the size, location and structure of knots as determined by knot healthiness and knot degree of tightness with surrounding wood affect the overall quality of the timber (Barszcz and Gjerdrum, 2008).

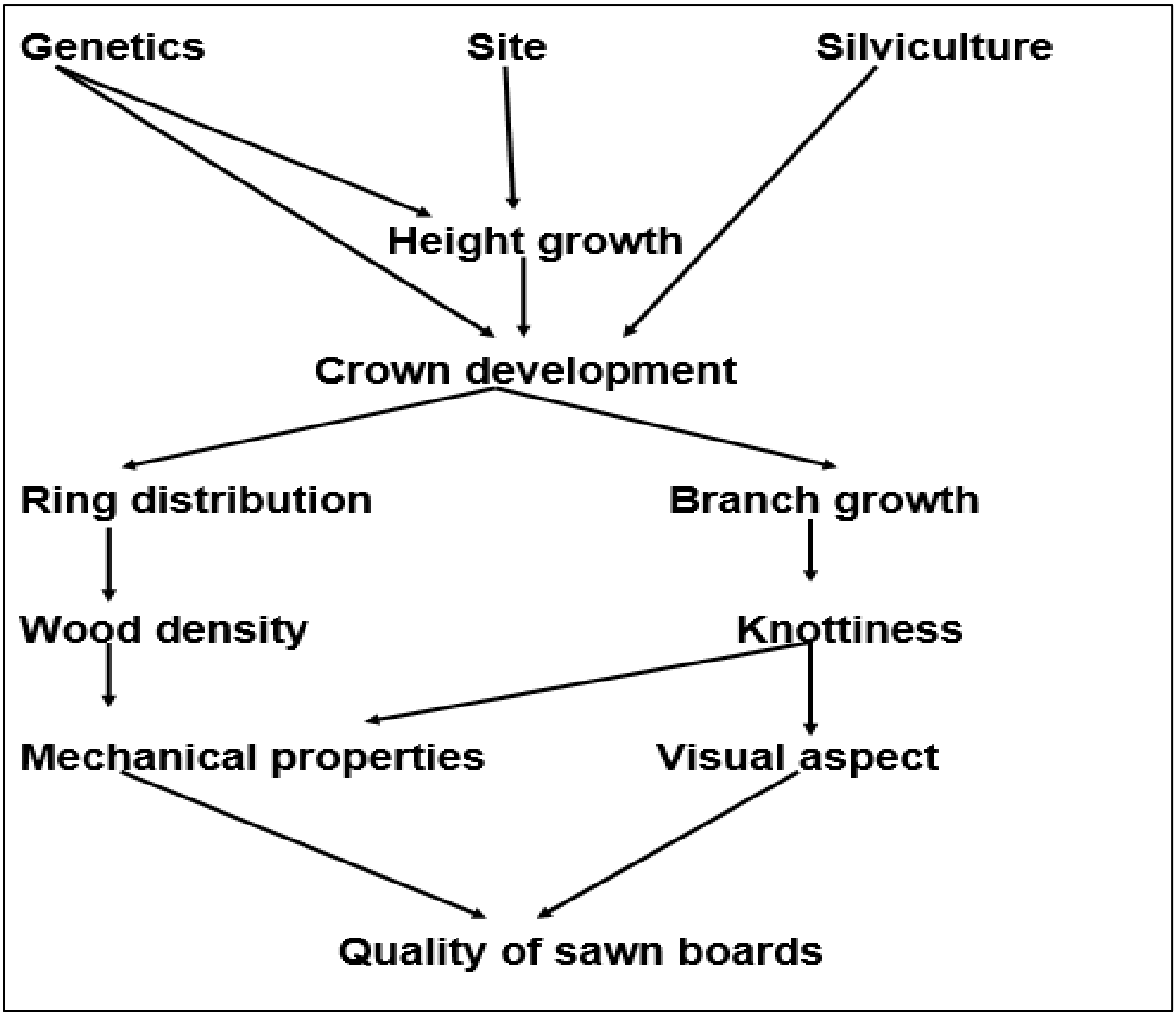


Figure 2.3: The framework of factors affecting the quality of sawn boards (Houllier *et al*., 1995)

The interaction effect of knottiness and ring distribution in influencing mechanical properties of wood is generally often overlooked in saw timber industry (Houllier *et al.,* 1995). In South Africa, this is evidenced by the absence of price incentives to the production of knot free timber.

2.5 SILVICULTURE MANAGEMENT AND RESULTANT EFFECT ON GROWTH

Kotze (2004) demonstrated in a *Pinus patula* spacing trial as shown in Figure 2.4 that at the age of 4 years the quadratic mean DBH (Dq) for 500 stems per hectare graphically diverges from the Dq for 1111 stems per hectare in response to thinning.

At age 6 the Dq of 250 stems per hectare also graphically diverges from Dq for 500 stems per hectare in response to thinning. This is translated to mean that in order to keep the stands free growing; thinning is required at the age of 4 and also at the age of 6 years (Kotze, 2004). It follows that delaying a thinning would lead to a loss of individual tree growth.

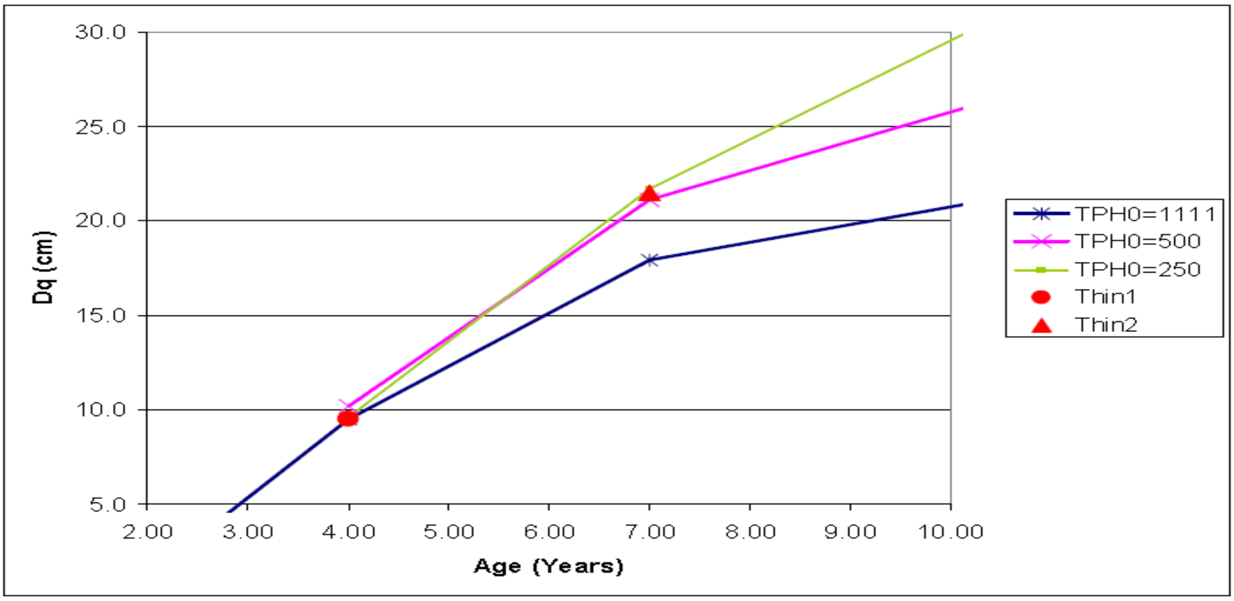
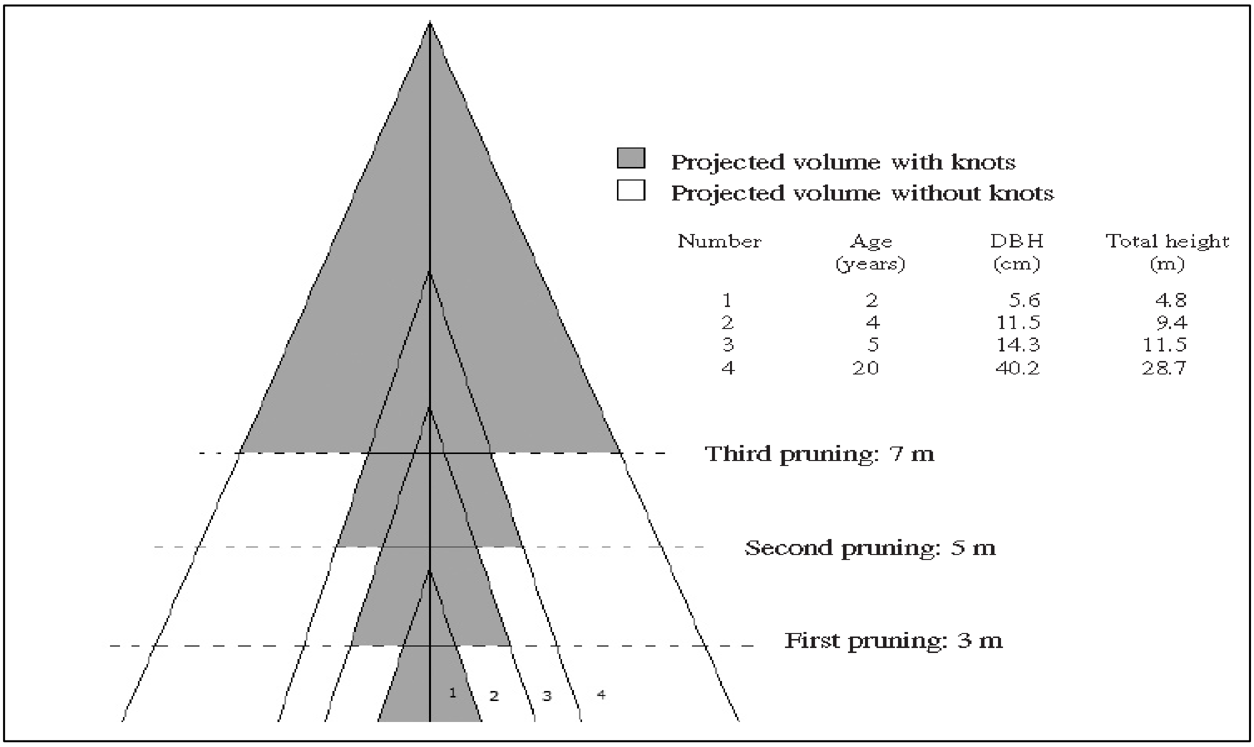


Figure 2.4: The effect of competition on DBH growth (Adapted from Kotze 2004)

Assuming a site index of 25, a tree with a DBH of at least 35 cm pruned to 7 m would produce a pruned class C1 log of 6.6 m with a tip end diameter of 26 cm (Kotze and du Toit, 2012). The response of a stand to thinning fluctuates with age and the response reaches a maximum value beyond which there is no further response until the density on the same site has been changed again. According to Kotze and du Toit (2012), although delaying thinning allows for useful log dimensions to be achieved, this happens at the expense of individual tree diameter growth. However, research has also shown that diameter growth increase dramatically in response to increased growing space, the degree of diameter increase varying with the intensity of the thinning (Kotze and du Toit, 2012). While the absolute loss in individual tree volume as a result of delayed thinning may not be fully recovered by the dramatic increase in diameter after the thinning, the relative loss in individual tree volume become less and less towards rotation end. According to Kotze and du Toit, (2012), an aggressive thinning regime invokes a useful growth response that enable the trees within the stand to reach a target diameter at clear-felling in a short period thereby giving room for shortening the rotation (paraphrased from Kotze and du Toit, 2012).

2.6 SILVICULTURE MANAGEMENT AND RESULTANT EFFECT ON KNOT CHARACTERISTICS

While silviculture management can influence the type and size of knots in logs, as is shown in Figure 2.5, research has proven that since both live and dead branches form knots on the stem, there is an inner section of the stem that is always with knots either sound or unsound knots for the whole stem length (Viquez and Perez, 2005). However, Figure 2.5 also shows that the earlier a stem is pruned to remove either the live or dead branches, the earlier surface wood without knots begin to form around the knotty core from the lower stem part upwards (Kellomaki *et al* 1999). Silvicultural pruning intervention timing is therefore critical.



Number	Age (years)	DBH (cm)	Total height (m)
1	2	5.6	4.8
2	4	11.5	9.4
3	5	14.3	11.5
4	20	40.2	28.7

Figure 2.5: Projected stem volume with and without knots according to the pruning system suggested by Perez *et al* (2003), cited in Viquez and Perez (2005)

The growth habit and distribution of shoots greatly determine the form a tree crown takes and consequently the type and size of knots its branches form in the tree's stem

(Bandara *et al.,* 1999). The availability of light from the crown top to the lowest level of the canopy regulates the rate and extent of branch survival and growth (Smith *et al.,* 1997; Sprugel, 2002). It is for this reason that trees in lower planting densities develop large branches that form large knots after pruning compared to trees in higher planting densities. When pruning is done, a sheath of new growth is formed following a series of cambial divisions until the stub is eventually occluded with wood (Kotze, 2004). According to Smith *et al* (1997), the wood that is produced after the stubs are covered is knot free timber of more superior strength, superior quality and of a higher market value based on end use, compared to the wood within the stub inclusion.

2.6.1 Branch live to dead ratio and the transition to knot sound to unsound ratio

According to Wang *et al.,* (2015), occluded knots may include two parts: live knot (tight portion) and dead knot (loose portion) which has no physical connection to the surrounding wood and interrupts the wood grain. Research has shown that knot-related defects are mostly caused by the dead knot. Whenever a branch dies, an occlusion is formed over the dead stub of the branch, and the dead stub end becomes a dead knot (O’Hara, 2007; Wang *et al.,* 2015). As a tree grows, branches also grow from the pith outwards resulting in the formation of live knots. The resultant live knot is intrinsically embedded into surrounding wood, which according to Wang *et al.,* (2015) makes live knots have less negative influence on the mechanical strength of timber compared to a dead knot.

O’Hara (2007) defines branch occlusion as the process whereby trees form a callus and thereafter some sheath of clear wood over the dead branch stubs. The smaller the dead branch diameter, the earlier the branch wound occludes and consequently, the earlier the production of clear wood can start (Smith *et al.,* 1997; O’Hara, 2007). It therefore follows that forest management practices need to be focused on keeping the branch diameters small while at the same time avoiding the natural death of branches on the stem prior to pruning. To produce high-quality timber, a balanced pruning-thinning interaction is thus essential. In the absence of the thinning intervention at eight years, the pruning frequency need to be increased more than the often prescribed conventional four stage pruning.

According to Kotze and du Toit (2012), since commercial pine species are not self-pruning the bases of their live crowns die in response to stand competition dynamics as stand height and crown height increases. It therefore follows that stand density also affects the rate of growth of the tree branches as well as the ratio of live to dead branches within the crown of a tree. In the presence of light, tree branches will keep on growing for as long as the holding tree is alive and also growing, within the confines of tree to tree stand competition (Smith *et al,.* 1997). As the intensity of the competition increases, supply of growth resources and light become limiting to lower canopy branches and naturally the lower branches of the tree begin to die (Kotze and du Toit, 2012). This phenomenon leads to the development of dead knots which are not desirable for the production of clear structural timber. The moment just before competition induced branch mortality set in, pruning has to be introduced in order to remove the branches before the development of dead unsound knots in the stem profile (Pretzsch, 2009). Silviculture management has to time this pruning intervention correctly by taking site quality and stand density (as influenced by planting stems per hectare or thinning induced stems per hectare) into consideration (Pretzsch, 2009).

Barszcz and Gjerdrum (2008), working in spruce forests of Norway, presented in their research that knot sound to unsound ratio is correlated to the location of the knot on the stem. The largest percentage of sound knots, which also were the biggest sized knots occurred within 60 percent to 90 percent of the merchantable stem length from the base (Barszcz and Gjerdrum, 2008). Relative diameters of sound knots (i.e. knot diameter relative to stem diameter where the knot is located) followed an increasing trend from base to tip end, with stem taper contributing to this trend. On the other hand the greatest percentage of unsound knots occurred within 20 percent to 30 percent of the merchantable stem from the base (Barszcz and Gjerdrum, 2008). The relative diameters of unsound knots showed an up and down trend from base towards the tip. According to Barszcz and Gjerdrum, (2008), the relative diameter of tight knots decrease with increasing height. Loose knots decreased in number up the stem with their relative diameter however increasing with the stem height.

2.6.2 Branching habits and the translation to timber knot tightness

Knot tightness in timber is closely linked to how branch morphology relates to stem morphology when a tree is still alive and growing (Kellomaki *et al.,* 1999). According to Kellomaki *et al.,* (1999), live branches penetrate the annual wood layers formed by the radial growth around the stem and form a green sound knot which is tight with the stem while a dead branch gives rise to a dead unsound knots whose dead cells cannot bond with the surrounding live stem cells. According to Trincado *et al., (*2006), working on *Pinus taeda* stands in the USA, in each growing tree, branch tissue formation is prioritized more than stem tissues at the beginning of each growing season. The growth of branches always originate at the stem pith and grow outwards (Trincado *et al.,* 2006). In the same manner stem growth depends on the availability of growth resources, the rate of growth of branches also depends on the amount of light, the amount of nutrients and water allocated to the branches (Trincado *et al.,* 2006). Towards the end of the growth season, stem diameter growth gets more growth priority compared to branch diameter growth which then considerably slows down to near static levels towards the end of the growing season (Trincado *et al.,* 2006). When insufficient solar radiation reaches the foliage of lower branches, production of new needles ceases, mature needles drop, and branches die shortly thereafter (Schutz, 1997; Trincado *et al.,* 2006).

2.6.3 Branch death and resultant persistent grain distortion in timber

According to Trincado *et al., (*2006), after branches die, they continue holding on to the stem for a period of time. This persistent retention of dead branches with acute angles is not good from the wood quality perspective because the resulting knots are relatively large and pass through a large volume of stem wood (Trincado *et al.,* 2006). According to Trincado *et al., (*2006) dead branches for *Pinus taeda* trees persist for an average of 8 years irrespective of the branch diameter nor the age of the branch. Research has shown that the average persistence time for branches of most pines range between 4 years and 11 years (Trincado *et al.,* 2006). Trincado *et al.,* 2006 further assets that after self-pruning, the time required for the branch stub to become occluded and to form clear wood depended on the length and diameter of the stub and on the rate of growth of the tree. Trincado *et al., (*2006) estimated that the time required for a band of clear wood to grow over the spot formerly occupied by the branch varied from 9 to 13 years, averaging 10.2 years.

2.7 GROWTH AND KNOT CHARACTERISTICS EXPERIMENTAL DESIGNS

The research question determines the design the experiment takes, which may be testing the effect of a single or multiple factors on growth (Pretzsch, 2009). The design of the experiment need to take site conditions (homogeneity or heterogeneity) into consideration to correctly contextualise the validity of the results (Pretzsch, 2009). Experiments to determine growth and knot characteristics are usually long term oriented and they generally assume a two-factor or multifactor experimental design approach. These experimental designs are common in growth and knot properties research because they allow for the testing of both main effects and interaction effects in one experiment (Pretzsch, 2009). Silviculture is evolving fast with foresters combining a variety of prescriptions to improve yields and knot characteristics. Multifactor designs make it possible to test the interaction effects of the factors being tested and their associated variables because according to Pretzsch, (2009), the main effects are easily understood while interactions are rarely known.

2.7.1 Stand parameters relating to growth and knot characteristics

In growth and knot characteristics experiments, the stand represents the environmental and forest conditions that would put the results of the research in context of applicability to other areas and conditions (Pretzsch, 2009). It is common in research to select plots in each stand to represent the stand. After the plot has been selected, the next stage is to measure the height and diameter of all trees in the plot. Based on the height and diameters, the trees for destructive sampling is then selected. Barszcz and Gjerdrum, (2008), in their study used breast height diameter as a selection criteria, by allocating a diameter over the bark that the selected tree must have to qualify for selection.

To commence the process of extracting response variables, selected trees are felled, debranched and measured for merchantable length to a selected tip end diameter. Although Barszcz and Gjerdrum, (2008) measured merchantability to a tip end diameter of 7 cm, in South African saw timber industry, A class saw log merchantability is up to tip end diameter of 13 cm (Southey, 2012). While some researchers treat the stem as one entity from base to tip end, Barszcz and Gjerdrum, (2008) split the stem into 1 m lengths for analysis. At these log segments, Barszcz and Gjerdrum, 2008 only assessed knots sizes greater or equal to 1 cm according to their healthiness (sound, unsound and rotten knots) and also according to their tightness with the surrounding wood (tight, partially intergrown and not tight knots).

The use of a merchantable section of the stem to calculate tree volume and escalate it to stand volume by means of interpolation is done in growth research (Barszcz and Gjerdrum, 2008). Determining growth rates from tree ring analysis yields more accurate values than extrapolations based on data from repeated diameter measurements (Brienen and Zuidema, 2006; Buruh *et al*., 2016). Establishing the relationship between the stem diameter and the diameter of the knot on that diameter is valuable in assessing the effect of knots in timber. Barszcz and Gjerdrum, (2008) used concepts such as relative knot height (relation of the distance of the knot from the lower end of the stem to the merchantable stem length) and relative knot diameter (relation of the knot diameter to the stem diameter at the point where the knot is located) to minimise the effect of age differences in analysing knottiness.

2.7.2 Stem analysis to assess growth and knot characteristics

Cross sectional and longitudinal analysis of stem discs cut at selected stem intervals show a balanced indication of stem growth rates over time as well as the quality of timber with respect to knot size and distribution along the stem sections chosen for analysis (Wang *et al.,* 2015). Literature identifies knot size and knot distribution on the selected merchantable stem sections as some of the stem parameters having an immense influence on overall knot characteristics (Wang *et al.,* 2003; Trincado *et al.,* 2006; Wang *et al.,* 2015). *Pinus patula* stands are likely to have a very unique stem cross section, given the branching pattern that *Pinus patula* trees have. The stem of the species *Pinus patula* contains a lot of branch whorls within a few meters of each other making timeous pruning intervention in *Pinus patula* important in managing knottiness in the final round wood product.

2.7.3 Growth ring width analysis methods for determining growth

Growth ring analysis on a cut stem cross section is done in horizontal sequence from the first ring after the pith to the last ring towards the bark end (Akachuku, 1991). The most common method to identify, mark and measure growth rings is through a digital measuring or scanning device which in most cases would be linked to a computer program for processing and analysing the data (Buruh *et al*., 2016). Macroscopic marking, identification and measuring of ring widths may also be done on large discs. The use of photographs to macroscopically or microscopically identify, mark and measure growth rings is also common in research (Akachuku, 1991; Lerm *et al.,* 2013). To increase accuracy, the marking and measuring process for growth ring boundaries must be done on four radii passing through the pith at right angles to each other and thereafter adopting the averages as the accepted measurement at each growth ring width (Buruh *et al*., 2016).

Growth and wood quality are linked to the eco-physiological processes that happen in a tree. According to Houllier *et al*., (1995), the growth ring width and ring age give a good prediction of some basic properties of wood like juvenile wood, wood density, grain angle and machinability, which when combined with wood defects like knots have a very strong influence on the end products in terms of shrinkage, mechanical strength and visual aspect (Houllier *et al*., 1995). Growth rings are annual and therefore they represent mean annual diameter increments in sampled trees (Buruh *et al*., 2016). While stem analysis of trees generally show a declining ring-width trend with increasing age, radial growth increase exponentially in the early juvenile years, followed by lagging growth when competition sets in and another surge in growth at the last phase when dominance in the canopy structure has been defined (Buruh *et al*., 2016). While radial growth trends are inherently controlled by the genetic make-up in trees, the silviculture management practices and the quality of a site can either enhance or trivialise the genetic effect.

2.7.4 Knot analysis methods

Research has shown that information on branch growth and crown dynamics can be accurately recovered from destructive sampling of branches (Trincado *et al.,* 2006). The collection of knot data can either be done using non-destructive or using destructive techniques. According to Trincado *et al.,* (2006), the most effective non-destructive techniques involve the use of ultrasound, electromagnetic and nuclear magnetic resonance using computer tomography as was reported by Oja (1997); Moberg, (2000; 2001). The only set back of these techniques is that they require the use of sophisticated and expensive instruments that are not easily available, hence their uncommon use (Trincado *et al.,* 2006). In research literature there are many documented methods of disc dissection techniques with the most common being: (*i*) the flitch method, (*ii*) the disk method and (*iii*) the peeling method (Trincado *et al.,* 2006).

2.7.5 The disc method of knot analysis

The disc method involves making of transverse sectional cuts throughout the length of the log. According to Trincado *et al.,* (2006), this method has a lot of shortcomings with its difficulty to maintain perpendicularity to pith and inconsistence in maintaining disc thickness being the method's criticism (Trincado *et al.,* 2006). However, these shortcomings are greatly reduced by sampling more discs on the stem section (Lerm *et al.,* 2013). Each disc cut needs to be referenced to an external axis to maintain a common reference among the discs (Trincado *et al* 2006; Lerm *et al.,* 2013).

CHAPTER 3 METHODOLOGY

This chapter explains in detail the steps taken to collect the data that was used in deriving the findings of this study. The chapter starts with the background that led to the use of the methodology adopted and goes on to detail the actual methodology used in data collection as well as in data analysis. The chapter is split into two sections to reflect the two response variables that were measured in the study; namely growth and knot characteristics in *Pinus patula* trees subjected to a single stage thinning regime and how these variables varied statistically with *Pinus patula* trees subjected to a conventional thinning regime.

3.1 BACKGROUND TO THE STUDY METHODOLOGY

The methodology used in this study was developed based on the methodology used in various studies conducted on knots and growth rings: (Wang *et al*., 2003; Trincado *et al.*, 2006; Barszcz and Gjerdrum, 2008; Barszcz *et al*., 2010; Lerm *et al.,* 2010). After the methodology was developed, a feasibility study was conducted to test the developed methodology by analysing the growth ring widths and knot characteristics of *Pinus patula* trees in Weza's compartment D25. The results of this feasibility study motivated the need to use the same but refined methodology for this study.

3.1.1 Feasibility study: Site description

The feasibility study was conducted in compartment D25 at Weza which was planted at 3 m x 3 m (1111 stems per hectare) and had received a thinning to 650 stems per hectare at 8 years and again to 450 stems per hectare at 12 years (conventional thinning regime). Some sections of the compartment D25 had however not received the conventional thinning for unknown reasons. The thinned section of D25 was thus treated as a separate block from the unthinned section of D25. Two plots of 400 m^2 each (radius 11.28 m) were set out in the thinned polygon of compartment D25 while the other two plots 400 m^2 each (radius 11.28 m) were set out in the unthinned sections of D25. The two plots in D25 that had received conventional thinning treatments at 8 years and at 12 years were named Plot D25T while the other two plots that had not been thinned were named Plot D25NT.

3.1.2 Feasibility study: Plot setting

Besides the visual confirmation that Plot D25T and Plot D25NT had received different thinning treatments (thinned and unthinned respectively), it was also important to confirm that Plot D25T and Plot D25NT belonged to the same site quality class. D25 site classification maps containing soil class data as provided by the Merensky planning department at Weza were used to identify sections of Plot D25 T and Plot D25 NT that belonged to the same site class and then to position them on the ground using Geographical Positioning Systems (GPS) coordinates obtained from the map. This follows studies of Louw (1995) and Louw and Scholes (2002) that found that sites of relative homogeneity regarding soils, climate and topography would be able to support similar growth rates and productivities such as indicated by their site indices (confirmed through height measurements).

3.1.3 Feasibility study: Site index and stems per hectare verification per plot

From each of the four plots (D25T replicated twice and Plot D25NT replicated twice), height and diameter measurements were taken using a Haglöf Vertex IV Ultrasonic Hypsometer and diameter tape respectively and recorded. All live trees with broken tops were marked and excluded from mean height calculations but were included in mean diameter and stand density calculations. The mean height of the 20 dominant trees per plot was calculated and recorded as the plot's dominant height. The plot dominant height together with the age of the stand extracted from the Merensky data base were used in conjunction with the Site index curves for *Pinus patula* recorded in Marsh (1978) to extrapolate the plots' site index to base year 20 (hereafter SI_{20}).

According to Marsh (1978), based on dominant height at 20 years: an SQ_1 supports site index values equal or greater than 27 m. Since the selected plots (Plot D25T and Plot D25NT) all had a site index value of 27 m, they were all on similar site quality and by direct implication were considered in this study to be of similar productivity (based on Louw (1995) and Louw and Scholes (2002)). To verify the difference in thinning treatments between the thinned plots (Plot D25T) and the unthinned plots (Plot D25NT), the total number of trees per plot were counted and divided by the plot area of 0.04 Ha (400 m^2) to give the stems per hectare in each plot. The stem count confirmed that thinned plots (Plot D25T) were both at 450 stems per hectare while the unthinned plots (Plot D25NT) were both still at 1100 stems per hectare[5].

3.1.4 Feasibility study: Stem analysis methodology

From each of the four plots of D25 the live tree with the largest diameter and with no broken top, was selected for destructive sampling. The largest DBH tree in the plot was selected because according to Marquis (1991), in an even aged stand of the same age, large DBH trees represent inherent competitive dominance of a tree over its neighbours. It follows that large DBH trees are therefore better representatives of the site productivity and treatment effect than their suppressed counterparts. After the selected tree per plot was felled with a chainsaw at 10 cm above ground, the stem was de-branched and measured with a measuring tape from its base to its tip end to obtain its total tree length. The merchantable length of the stem (from base of the tree to a tip diameter end of 13 cm) was measured and recorded. The butt end of the cut tree was then squared off and the first 2 cm thick disc was removed off the squared base end for ring width analysis. The second 2 cm thick disc was cut at 1.3 m from the base end and it represented the diameter at breast height. The base disc was used for stem radial growth analysis while the 1.3 m disc was used for volume growth analysis. The subsequent discs (3, 5, 7, 9, 11, 13 and 15 m) were consistently cut within 2 cm of the point where whorls of branches or where scars of branch whorls protruded from the stem. These subsequent discs (after 1.3 m) were cut this way so that they would be useful in the knot analysis (knot size, knot frequency, knot sound to unsound ratio and relative knot diameter). Before each disc was cut off the stem, a photograph of the base end of the disc was taken to show ring width projection, and where applicable knot size, knot frequency, knot sound to unsound ratio and relative knot diameter in cross sectional view at each known height where the disc was taken from. As was done by Lerm *et al.,* (2013), the photographs were used for growth and knot analysis by extracting the relevant information using ImageJ-1.45 software. Growth knots were characterised as sound or unsound according to the knot categorisation used in the studies done by Barszcz *et al.,* (2010), and Wang *et al.,* (2015).

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[5] Since 1100 stems per hectare is closer to the planting stocking of 1111 stems per hectare than the first thinning stocking of 650 stems per hectare, 1100 stems per hectare was accepted as the planting stocking.

3.1.5 Feasibility study: Findings that influenced the new study methodology

After analysis of the data collected through Imagej-1.45 software on knot characteristics and growth ring widths, the following observations and conclusions were made;

1. The number of growth rings decreased from the base of the tree stem to the tip of the stem. The full number of growth rings were found to be located as close to the base of the stem as was possible. The base disc was therefore recommended as the better proxy for showing long term diameter growth patterns of the tree in its full life than the 1.3 m disc- where some growth rings would not be present.
2. While the base disc showed the long term diameter growth trend better than the 1.3 m disc, the base disc did not give an accurate representation of the overall volume growth of the tree due to the butt swell at the base of the tree and the huge taper from base to diameter at breast height both of which exaggerated the diameter measured at the base disc. The 1.3 m disc was therefore recommended for use in depicting the diameter that was used in calculating mean individual tree volume in line with conventional forestry standards in which diameter at breast height is used to calculate tree standing volume (Pretzsch, 2009; Bowman *et al.,* 2012).
3. The feasibility study revealed that the differences in knot properties between the thinned and unthinned plot began to show from year number nine onwards. The recommendation based on this finding was that for analysis of variances of knot properties to reflect the pruning-thinning treatment effect correctly, the analysis needed to be done on a merchantable stem split into two sections (log units). The first log unit (from the base to 7.2 m) representing knot characteristics within the pruning-thinning era and the second log unit (from 7.2 upwards) representing knot characteristics largely post the pruning-thinning era.

3.2 EXPERIMENTAL DESIGN

The approach to planning forest growth and yield experiments outlined by Pretzsch (2009), formed the backbone of the experimental design, the sampling strategy and the data collection mechanisms adopted in this study. The methodology of this study was designed to investigate both the quantitative and qualitative aspects of growth (annual growth ring width increment and mean volume yield) and knot properties (knot size, knot frequency, knot sound to unsound ratio and relative knot diameter) in *Pinus patula* trees grown under different site qualities and subjected to different pruning-thinning combinations (Section 3.2.1).

3.2.1 Treatments description

In this study, a 2 X 4 factorial design with 9 replications which resulted in 72 experimental plots (2 site qualities X 4 pruning-thinning combinations X 9 replications) was used. The experimental design comprised 2 experimental factors namely:

1. Site quality class at base age 20 years and
2. Pruning-thinning combinations.

The site quality class was divided into two treatment levels as described in Marsh (1978) as follows:

- i. Site quality class I (denoted SQ_1): SI_{20} greater or equal to 27 m.
- ii. Site quality class III (denoted SQ_3): SI_{20} between 19 and 22.9 m.

The pruning-thinning combination was divided into four treatment levels as shown in Table 3.1.

Table 3.1: Experimental treatments

	Thinning regime			**Pruning regime**			
Pruning-thinning treatment	**TPHa (planting)**	**TPHa @ age 8**	**TPHa @ age 12**	**1.5 m prune age**	**3 m prune age**	**5 m prune age**	**7m prune age**
Conventional thinning-**(P_4T_2)**	1111	650	450	4	6	8	10
Single stage thinning-(**P_4T_1**)	1111	1111	500	4	6	8	10
Unthinned-**(P_4T_0)**	1111	1111	1111	4	6	8	10
Unthinned-**(P_0T_0)**	1111	1111	1111	None done	None done	None done	None done

There were therefore 8 treatments (2 site qualities X 4 pruning-thinning combinations) as summarised in Table 3.2. Each of these 8 treatments were replicated 9 times (3 compartments X 3 plots in each of the 3 compartments) to a total of 72 experimental plots (8 treatments X 3 compartments per treatment X 3 replications per compartment).

Table 3.2: Experimental treatments

Treatment number	**Treatment name**	**Treatment Description**
1	$P_4T_{2.}SQ_1$	Site class I:Conventional thinning regime- First thinning at approximately 8 years (from 1111 to 650 stems per hectare), second thinning at approximately 12 years (from 650 to 450 stems per hectare) with conventional pruning done from 1.5 m to 7 m
2	$P_4T_{1.}\ SQ_1$	Site class I: Single stage thinning regime - Single thinning done at approximately 12 years (from 1111 to 500 stems per hectare) with conventional pruning done from 1.5 m to 7 m
3	$P_4T_{0.}\ SQ_1$	Site class I: Control 1- No thinning done but conventional pruning done from 1.5 m to 7 m.
4	$P_0T_{0.}\ SQ_1$	Site class I: Control 2 – No thinning done, no pruning done
5	$P_4T_{2.}\ SQ_3$	Site class III: Conventional thinning regime- First thinning at approximately 8 years (from 1111 to 650 stems per hectare), second thinning at approximately 12 years (from 650 to 450 stems per hectare) with conventional pruning done from 1.5 m up to 7 m.
6	$P_4T_{1.}\ SQ_3$	Site class III: Single stage thinning regime- Single thinning done at approximately 12 years (from 1111 to 500 stems per hectare) with conventional pruning done from 1.5 m to 7 m.
7	$P_4T_{0.}\ SQ_3$	Site class III: Control 1- No thinning done but conventional pruning regimes done from 1.5 m to 7 m
8	$P_0T_{0.}\ SQ_3$	Site class III: Control 2 – No thinning done, no pruning done

3.3 THE STUDY AREA AND SAMPLED COMPARTMENTS

The study was carried out at Merensky's East Griqualand Forests (Mpur and Langgewacht plantations) in Kwa Zulu Natal. The East Griqualand management unit is situated 50 km east of Kokstad and extends from Harding in the south to Franklin in the north. The extent of the area is shown in the map of the area in relation to the province of Kwa Zulu Natal (Figure 3.1).

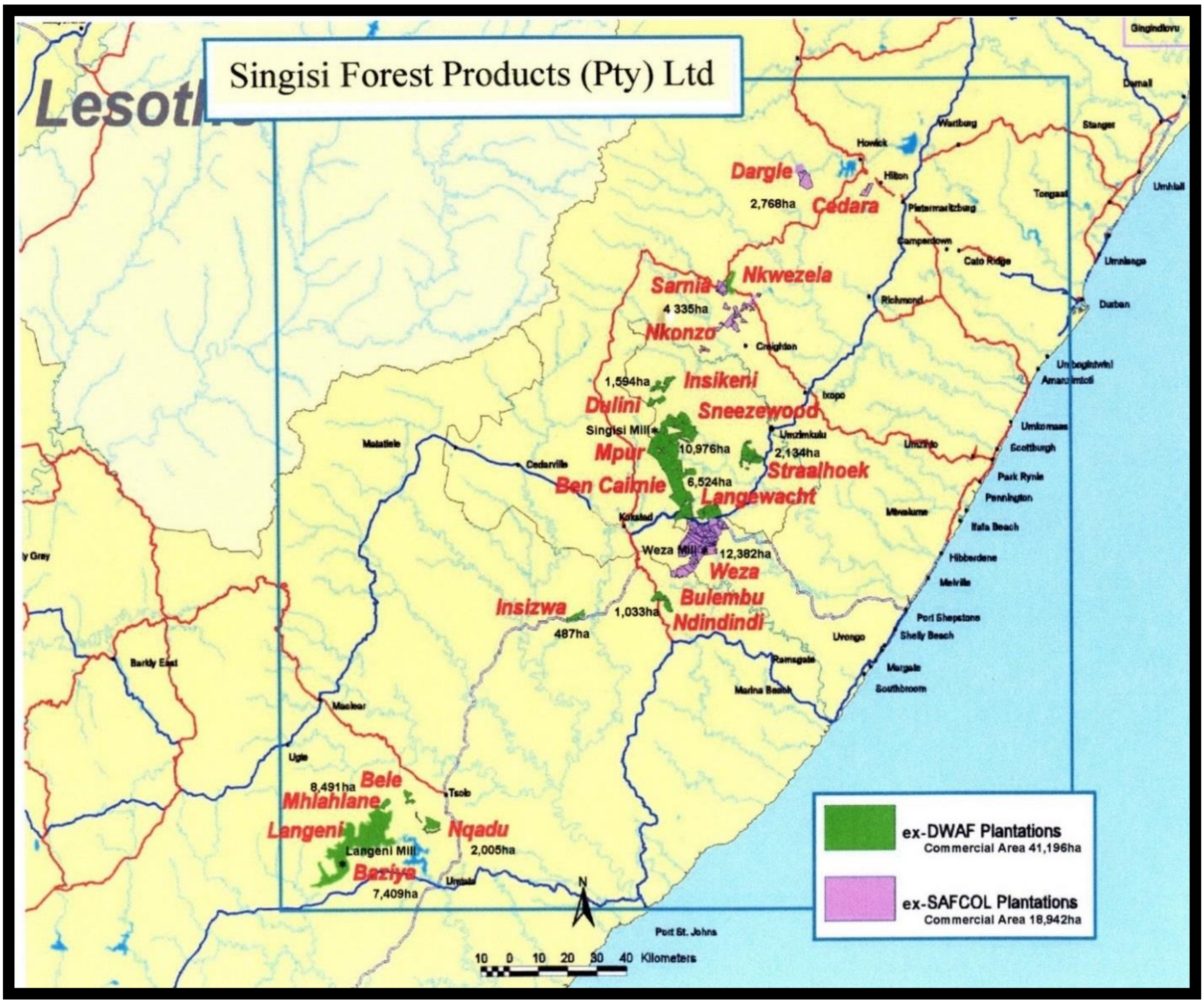


Figure 3.1: Map overview of Mpur, Langewacht Sneezewood (Whyle, 2016)

The annual rainfall for Langgewacht and Mpur plantations averages 1100 mm which is mostly summer rainfall (September to April). The geology of the area consists mainly of rocks of the Beaufort Group, but with some Ecca Sediments, and exposed Molteno beds on the escarpment (Whyle, 2016).

The study was conducted on the available Merensky range of compartments that represented the experimental treatment variants of site quality class and pruning-thinning combinations described in Section 3.2.1 as closely as possible. The ages of these compartments in 2016 when the data was collected ranged from 14.8 years to 24.1 years across the three study areas (Tables 3.3 and 3.4). While in this study, as is presented in Sections 3.4.2 and 3.4.3, controls were put in place to reduce the effect of age differences in checking and analysing variances, dealing with compartments of different ages in one experiment is common in research. Barszcz and Gjerdrum, (2008) in their research to analyse knottiness in Norway spruce, sampled 14 trees from three stands whose age differences ranged from 10 years to 45 years.

The selected compartments' details are shown in Tables 3.3 and 3.4. The compartments were grouped into treatments they belong to. This grouping made it possible to calculate the treatment average age and the treatment average stems per hectare. The average treatment age across all treatments was used to select the maximum cut off age applicable to all treatments for use as the base age in later analysis of variances between treatments. Since the youngest compartment in 2016 was aged 14.8 years, the selected cut off age for data collection and data analysis in this study was 14 years. The average treatment stems per hectare was used to determine the minimum and maximum cut offs for stems per hectare. In this study, a range from 900 to 1150 stems per hectare was accepted as being within the planting density range of 1111 stems per hectare.

Table 3.3: Sampled Site quality class I compartments

Treatment	**Plantation**	**Cpt**	**Effa**	**2016 Age**	**SI**	**PTPH**	**TPH @ 8**	**TPH @ 12**	**5 m prune age**	**7 m prune age**
$P_4T_2.SQ_1$	Sneezewood	B12	46.05	18.7	28.2	1143	637	467	8	10
$P_4T_2.SQ_1$	Mpur	A51	26.09	18.4	27.7	1143	696	492	8	10
$P_4T_2.SQ_1$	Langgewacht	L14b	11.78	18.1	27.6	1143	691	483	8	10
$P_4T_1.SQ_1$	Sneezewood	A19b	5.27	16.7	27.5	1143	1143	567	8	10
$P_4T_1.SQ_1$	Sneezewood	B34	21.38	18.7	27.9	1143	1143	525	8	10
$P_4T_1.SQ_1$	Mpur	C4	19.79	18.1	27.3	992	992	575	8	10
$P_4T_0.SQ_1$	Sneezewood	B11	35.10	18.7	27.4	1143	992	992	8	10
$P_4T_0.SQ_1$	Sneezewood	B25	16.33	18.7	28.9	1143	1143	1008	8	10
$P_4T_0.SQ_1$	Sneezewood	B27	28.61	18.7	27.4	1143	1143	992	8	10
$P_0T_0.SQ_1$	Mpur	A40	16.24	21.1	27.6	1111	1111	992	N/A	N/A
$P_0T_0.SQ_1$	Mpur	C36	22.06	24.1	28.1	992	992	975	N/A	N/A
$P_0T_0.SQ_1$	Langgewacht	D26	25.86	21.1	27.7	1111	1111	1000	N/A	N/A

Table 3.4: Sampled Site quality class III compartments

Treatment	Plantation	Cpt	Effa	2016 Age	SI	PTPH	TPH @ 8	TPH @ 12	5 m prune age	7 m prune age
$P_4T_2.SQ_3$	Mpur	A17	23.10	14.8	21.0	1111	575	467	9	11
$P_4T_2.SQ_3$	Mpur	A20	10.99	14.8	21.0	1111	671	467	9	11
$P_4T_2.SQ_3$	Mpur	A24	21.72	14.8	21.0	1111	623	500	9	11
$P_4T_1.SQ_3$	Sneezewood	A28	16.10	18.7	22.0	1143	1143	583	9	11
$P_4T_1.SQ_3$	Sneezewood	A29	21.87	18.7	22.0	1143	1143	550	9	11
$P_4T_1.SQ_3$	Sneezewood	B36b	20.26	18.7	21.5	1143	1143	567	9	11
$P_4T_0.SQ_3$	Sneezewood	A32a	15.99	18.9	19.2	1143	1143	967	9	11
$P_4T_0.SQ_3$	Sneezewood	B39	22.33	18.7	19.6	1143	1143	975	9	11
$P_4T_0.SQ_3$	Sneezewood	B49	33.54	19.1	19.6	1143	1143	992	9	11
$P_0T_0.SQ_3$	Sneezewood	B37	4.04	18.7	19.0	1143	1143	983	N/A	N/A
$P_0T_0.SQ_3$	Langgewacht	E2	26.87	19.1	20	1143	1143	1042	N/A	N/A
$P_0T_0.SQ_3$	Langgewacht	E3	27.27	19.1	20.5	1143	1143	1042	N/A	N/A

3.4 EXPERIMENTAL METHOD

The research employed 24 compartments in which 3 plots per compartment were used as sampling sites to cater for within compartment variation. In each of the set circular plots of 400 m^2 (radius 11.28 m), all trees within the plot were measured for DBH and total height. From each of the 3 plots set per compartment, the largest DBH tree whose original planting neighbours were either still live at data collection time or were only removed in a thinning (as evidenced by a cut stump) was selected for destructive sampling. A total of 72 trees were selected for destructive sampling (being cut into 2 cm discs at selected lengths for cross sectional stem analysis). As was informed by the findings of the feasibility study (Section 3.1.5), the adopted approximately 2 m interval length of stem segments where discs were collected for analysis were aligned with the 2.4 m long merchantable log pieces used in saw timber production as shown in Table 3.5.

Table 3.5: Relationship between merchantable log piece and collected disc height

Stem height level being assessed	Length of merchantable log piece	Length of stem from base in cumulative 2.4 m length units
Base disc	2.4 m	2.4 m
1.3 m disc	2.4 m	2.4 m
3.0 m disc	2.4 m	4.8 m
5.0 m disc	2.4 m	7.2 m
7.0 m disc	2.4 m	7.2 m
9.0 m disc	2.4 m	9.6 m
11 m disc	2.4 m	12.0 m
13 m disc	2.4 m	14.4 m
15 m disc	2.4 m	16.8 m

A total of 540 discs and 396 (2.4 m long) log pieces were sampled in the study (Table 3.5). These sampled 2.4 m long log pieces were then accumulated into 0-7.2 m and 7.2 -16.8 log units for knot related analysis of variance (Section 3.1.5). The total amount of discs and log pieces per treatment were influenced by the length of the merchantable section of the stem at age 14. The number of discs and log pieces per treatment are depicted in Table 3.6.

Table 3.6: Number of sampled discs and log pieces per treatment

Treatment	Total length of merchantable stem (m)	Number of discs sampled	Number of 2.4 m log pieces assessed
$P_4T_2.SQ_1$	15	81	63
$P_4T_1.SQ_1$	15	81	63
$P_4T_0.SQ_1$	13	72	54
$P_0T_0SQ_1$	13	72	54
$P_4T_2.SQ_3$	11	63	45
$P_4T_1.SQ_3$	11	63	45
$P_4T_0.SQ_3$	9	54	36
$P_0T_0.SQ_3$	9	54	36
TOTAL		540	396

3.4.1 Data collection from destructively sampled 2.4 m log units

A Nikon d3400 DSLR camera with an 18-55 mm lens mounted on a camera stand 30 cm from each log piece was used to take photographs of the base end cut surfaces of the 540 discs sampled. The photographs taken were used for extracting the relevant information for growth and knot analysis by means of the Image-j software as was done by Abramoff *et al*., (2004); Lerm *et al*., (2013); Duchateau *et al*., (2015). Before any measurements were done, calibration of the Imagej-1.45 system was done to convert all measurements from pixels to millimeters. The extracted data was organized in Microsoft excel for further analysis.

3.4.2 Determination of age at a specified height and its reduction to age of 14 years

With the oldest available sets of compartments that suited the $P_4T_2.SQ_3$ category being 14 years old, all treatment variables were reduced to 14 years for comparability. For all trees with age greater than 14 years, growth ring number 14 from the pith at the base disc was used to cut off their base disc to 14 years. Additional growth after 14 years in subsequent discs (1.3, 3, 5, 7, 9, 11, 13 and 15 m) was “cut off”. In other words, only the tree stem data up to age of 14 years was used in this study. Growth after 14 years was not considered. Also, the knot sizes at 14 years were used, not the size of knot at felling. This reduction in age to 14 years did not affect the scope of the research which was to investigate the difference in final standing volume and final knot properties between conventional and single stage thinning regimes. As a result of the age reduction to 14 years, it followed that the final standing volume and the final knot properties are at age 14 years.

To determine the age at a specified disc height, a formula modified from Kariuki, (2002) and Pretzsch, (2009) was used as follows:

Age at height X =Growth rings at base –Growth rings at height X. **Equation 3.1**

Based on the equation above, treatment $P_4T_{2.}SQ_3$ compartments with 14 growth rings at base and 5 growth rings at the height of 7 m would have its age at a specified height calculated as follows;

1. Age at base height = Growth rings at base (14) –Growth rings at 7 m (5) = 9 years.

Based on the findings of Kariuki, (2002) and Pretzsch, (2009), for a base disc that had 14 growth rings and the next disc at 1.3 m had nine growth rings, the difference of the five growth rings was excluded in all the measurements done at 1.3 m disc height. This meant that all the response attributes at the base disc measured up to 14 growth rings met the 14 years benchmark, while the response attributes at the 1.3 m disc attributes measured up to nine growth rings also met 14 years benchmark. By maintaining the growth ring year number 14, for all the 72 trees sampled, growth analysis and knot properties analysis was done to the same reduced age of 14 years.

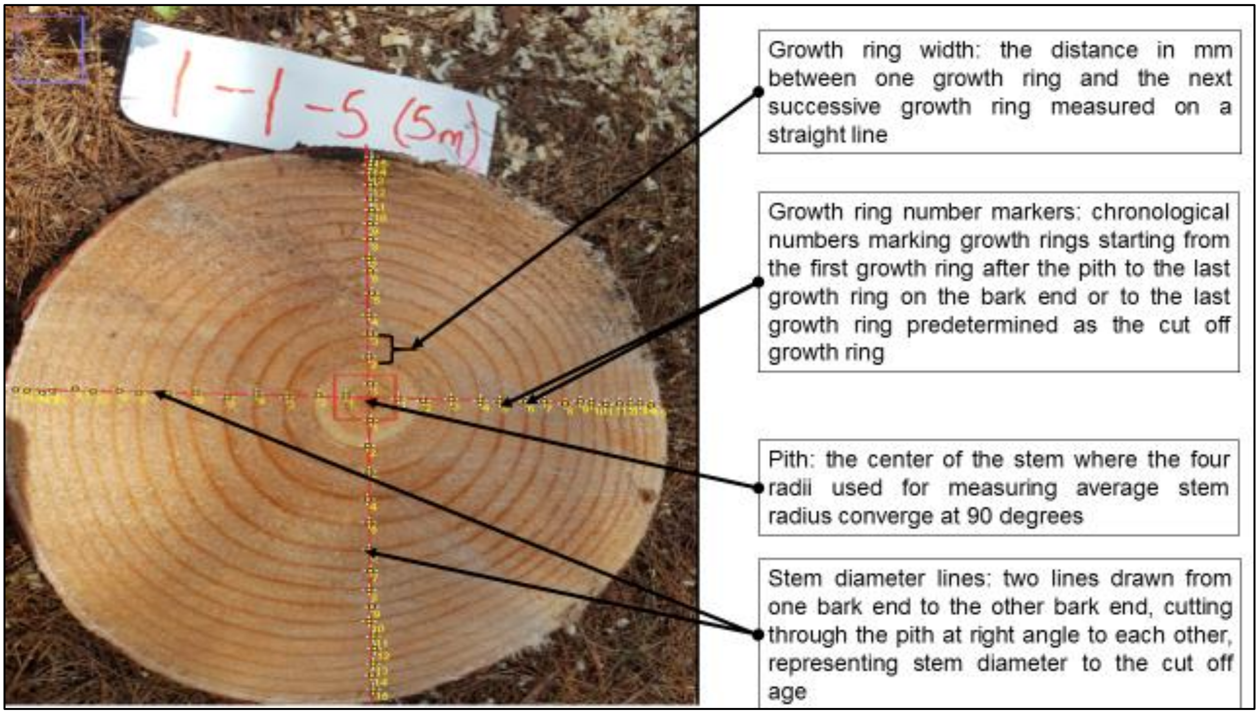
After reducing the number of years to the age of 14 years for all the specified heights in the way described in this section, the number of years taken to reach a specified height, for all compartments sampled were as recorded in Table 3.7.

Table 3.7: Number of growth ring years per height per treatment

Stem Height	**Number of years taken to attain a specified height per treatment**							
	$P_4T_2.SQ_1$	**$P_4T_1.SQ_1$**	**$P_4T_0.SQ_1$**	**$P_0T_0.SQ_1$**	**$P_4T_2.SQ_3$**	**$P_4T_1.SQ_3$**	**$P_4T_0.SQ_3$**	**$P_0T_0.SQ_3$**
Base	0	0	0	0	0	0	0	0
1.3 m	2	2	2	2	3	3	3	3
3 m	3	3	3	3	5	5	5	5
5 m	4	5	5	4	7	7	7	7
7 m	6	6	7	5	9	9	9	9
9 m	7	8	8	8	11	11	11	11
11 m	9	9	10	10	13	12	13	14
13 m	10	10	11	12	14	13	14	
15 m	12	11	14	14		14		
17 m	14	12		N/A				
19 m		14						

<u>3.4.3 Growth ring width based diameter measurement</u>

After reducing the ages of all sampled discs at specified heights to the same age of 14 years as described in Section 3.4.2, growth rings were numbered along four lines representing the radius from the pith to the bark end (Figure 3.2). The growth ring width between consecutive growth rings was measured, starting with the first growth ring after the pith and ending with the last growth ring marking the cut off age of 14 years. Growth ring width was measured from the end of the late wood section of a ring to the end of the latewood section of the next ring. An average of the four summed growth ring widths was adopted as the radius of the disc from the pith to the cut off age of 14 years. The adopted radius was then used to calculate diameter of discs at specified heights. This process of determining diameter of the stem was repeated at every specified height up the merchantable stem with the yellow numbers shown in Figure 3.2 and the process stipulated in Section 3.4.2 being used in ensuring that at the specified height, the year 14 cut off age is maintained.



Growth ring width: the distance in mm between one growth ring and the next successive growth ring measured on a straight line

Growth ring number markers: chronological numbers marking growth rings starting from the first growth ring after the pith to the last growth ring on the bark end or to the last growth ring predetermined as the cut off growth ring

Pith: the center of the stem where the four radii used for measuring average stem radius converge at 90 degrees

Stem diameter lines: two lines drawn from one bark end to the other bark end, cutting through the pith at right angle to each other, representing stem diameter to the cut off age

Figure 3.2: Numbering of discs to determine year 14 growth ring cut off

The trees of treatment $P_4T_{2.}SQ_3$ which were 14 years at the time of data collection were used to check the correlation of the diameters measured from photographs to the diameters of the same trees measured manually. Figure 3.3 is the illustration of the relationship between photograph measurements and manual measurements. From the results of the nine trees from treatment $P_4T_{2.}SQ_3$, a coefficient of determination of **R^2 = 0.99** demonstrated a strong linear relationship as shown by the equation in Figure 3.3. Based on this strong linear relationship between photograph measurements and manual measurements demonstrated on $P_4T_{2.}SQ_3$ diameter measurements, photograph measurements were accepted as an accurate depiction of stem diameter measurements for all treatments.

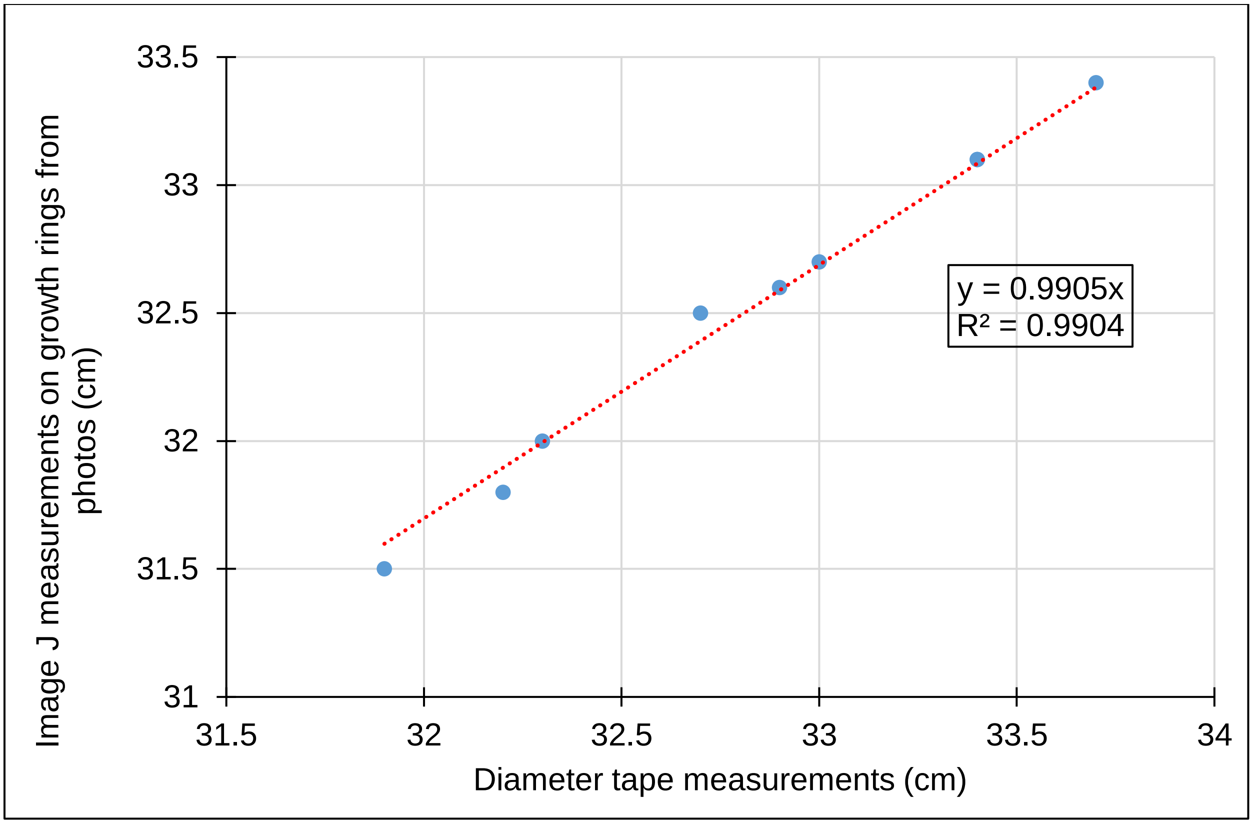


Figure 3.3: $P_4T_2.SQ_3$ comparison between photograph and manual measurements

3.5 RING WIDTH DE-TRENDING

The adopted growth ring widths described in Section 3.4.3 were subjected to some de-trending process using regression analysis to remove the effect of age and time. The de-trending exercise removed the age effect and allowed for a homogeneous analysis of growth trends over time between the treatments. To do the de-trending process polynomial trend lines to the second degree were plotted using the adopted growth ring widths as the series points (growth ring years on the x-axis and growth ring width on the y-axis). A polynomial trend line to the second degree with its equation based on a regression trend was added to the time series trends. In an excel spreadsheet, the adopted growth ring widths were assigned an observation number, with the first growth ring width measured after the pith being allocated observation number one, the next allocated observation number two and so on until the last measured growth ring width.

The regression equation from the plotted trend line series was of the following form:

$y = (bx^2 - bx) + a$ **Equation 3.2**

Where:

y = is the dependant variable

$(bx^2 - bx) + a$ = is the trend that gave the plotted line the slope

The trend in equation 3.2 was defined as shown in the following equation;

$Trend = (b*time^2 - b*time) + a$ **Equation 3.3**

Where;

b = regression coefficient from the regression equation,

time = the observation numbers allocated to the growth ring widths

a = constant from the regression equation.

To remove the trend in the growth ring widths, the following de-trending formula was applied;

De-trended growth rings = growth ring widths / (trend -1) **Equation 3.4**

Equation 3.4, incorporating the expanded definition of trend in Equation 3.3 read as follows:

*De-trended growth rings = (growth ring widths/(b*time + a)-1)* **Equation 3.5**

The de-trended results were multiplied by 100 so that they can be read in percentage points. The final de-trending formula read as follows:

*De-trended growth rings = 100(Growth ring widths/(b*Time + a)-1)* **Equation 3.6**

3.6 GROWTH DETERMINATION

The growth of the conventional thinning regime and the single stage thinning regime was compared in response variables diameter growth, mean individual tree growth and mean stand volume. Mean individual tree volume growth analysis was derived from the disc based DBH and the measured length of the stem from which the disc was collected. The mean stand volume at age 14 years of each of the eight treatments was calculated from the mean diameters of each treatment (nine representative trees per treatment). By using only the selected trees reduced to 14 years to calculate the volume of a stand, this study compared volume growth of all treatments at the same base age. The method of using representative trees to calculate stand volume drew inference from Carron, (1968) and Kariuki (2002) in which both, as cited in Kariuki, (2002), argued that due to the homogeneous conditions in an even aged stand, fewer statistically drawn samples are adequate to reflect the volume growth effect caused by site quality and treatment effect. In the case of this study, a single case per replication (nine trees per treatment) was adequate enough to do any analysis of variance between conventional and single stage thinned trees.

3.7 KNOT CHARACTERISATION

This study isolated knot attributes guided by the findings and processes recorded in Smith *et al.,* (1997); Barszcz *et al*., (2010); Wang *et al., (2015)* who classified knots as follows:

1. Sound knots- knots that were healthy and of the same visual quality as the surrounding wood, showing no visible signs of rotting after branch occlusion (Figure 3.4).
2. Unsound knots- knots that were not healthy and were showing signs of rotting after branch occlusion (Figure 3.4).

Unsound knot- bark in between stem and knot; No tight connection between knot wood and stem wood; visible signs of rotting, different wood texture to that of the stem.

Sound knot – No bark between knot wood and stem wood; knot wood engrained into the wood of the main stem, similar wood texture to that of the stem, No visible signs of rotting

Figure 3.4: Definition of knots used in the study

3.7.1 Knot size measurements

At every specified height and age, the knot size boundaries were defined from the first growth ring number on the pith side where the knot emerged to the last growth ring number on the bark side where the knot ended or to the cut off ring number 14 (whichever came first). For each knot sampled, the first measurements were done radially, or across the grain (in line with the diameter line measurement), with the second measurement done at right angles to the first measurement or tangentially (Figure 3.5). The average of the two measurements was adopted as the knot diameter. This method of knot size measurement combined the branch diameter and the branch angle.

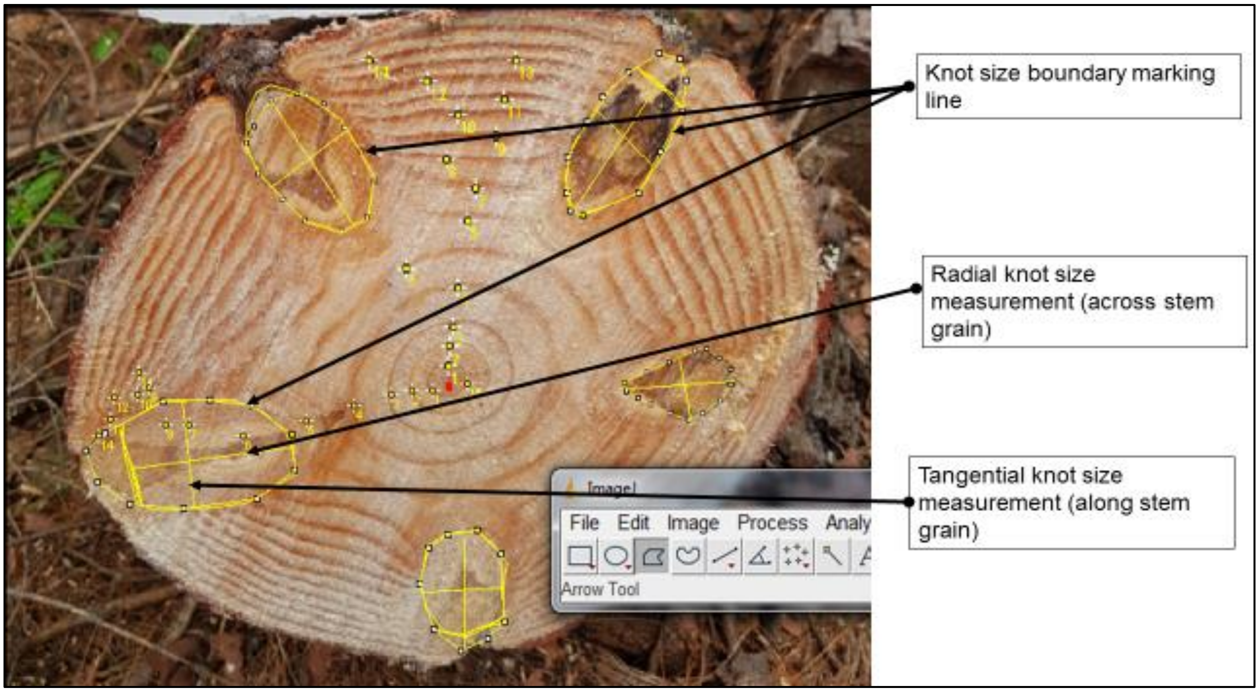


Figure 3.5: Knot size boundaries markers and knot diameter markers

The knot diameters at every disc height were recorded against the specific corresponding disc diameter for ease of determining relative knot diameter. The average knot diameters per log section was determined based on the full range of collected knot diameters on each log unit, for all the log pieces and specified disc heights constituting that log unit (as indicated in Section 3.4).

3.7.2 Knot sound to unsound ratio

The number of knots per log section was determined by summing up all the knots per disc height collected from base to tip end of the merchantable stem. As was done by Barszcz and Gjerdrum (2008), the frequency of knots by category of healthiness and tightness was adopted as the main proxy for distinguishing treatment effects on knot properties for the sites under analysis (Barszcz and Gjerdrum (2008)).

Within each log unit described in Section 3.1.5, this study analysed;

1. The location of the largest knots by healthiness and tightness category.
2. The location of the smallest knots by healthiness and tightness category.

3. The knot sound to unsound ratio trend (decreasing, increasing or remaining constant along the stem).

3.7.3 Relative knot diameter

This attribute was measured to regulate the effect of age differences on treatment variances since relative knot diameter includes the effect of growth rate of both the stem and the branches. Relative knot diameter is the expression of the individual knot diameter as a ratio of the stem diameter where the knot occurred (Barszcz and Gjerdrum). This attribute is important because according to Barszcz and Gjerdrum (2008) and Barszcz *et al* (2010), the effect knots on timber quality is dependent upon their locality, size, healthiness and frequency on the merchantable log piece.

3.8 THE DATA ANALYSIS METHODOLOGY

The experimental design in this study was to test the interaction effect of two treatment factors (site quality and pruning-thinning combination) on growth of trees in a stand and wood quality of individual trees in the stand. Where a significant interaction existed, such interaction was described further through post hoc tests. Where there was no significant interaction only the main effects were described. Normality was tested using the Shapiro-Wilk test and homoscedasticity was tested using the Levene test. Where data was normally distributed post hoc tests were done with the Tukey HSD test. Where data was not normally distributed or was not homogeneous, further post hoc statistical analysis were carried out with the non-parametric Kruskal-Walis test.

CHAPTER 4 THE RESULTS

4.1 THE GROWTH IMPLICATIONS OF SINGLE STAGE THINNING REGIME

The growth related statistics of all treatments are shown in Table 4.1. In presenting the implications of changing from conventional to single stage thinning regime Table 4.1 results for quadratic diameter, mean individual tree volume and standing volume at 14 years are referred to.

Table 4.1: Summary table of all growth related findings at 14 years of age.

Cpts per treatment	SI	SPHA	Dq (cm)	Mean individual tree vol (m^3)	Mean Stand basal area (m^2/ha)	Standing vol (m^3/ha)
$P_4T_1.SQ_1$	27.6	556	34.6	0.47	52.3	265.0
$P_4T_2.SQ_1$	27.8	481	35.2	0.50	46.8	238.8
$P_4T_0.SQ_1$	27.9	997	23.9	0.19	44.8	194.2
$P_0T_0.SQ_1$	27.8	989	22.1	0.17	38.1	167.6
$P_4T_1.SQ_3$	21.8	567	30.9	0.29	42.4	162.2
$P_4T_2.SQ_3$	21.0	478	32.5	0.32	39.7	151.4
$P_4T_0.SQ_3$	19.5	978	19.9	0.10	30.5	95.8
$P_0T_0.SQ_3$	19.8	1022	18.5	0.09	27.6	86.1

4.1.1 Implications on mean quadratic DBH

As shown in Table 4.1, conventionally thinned trees in SQ_3 had on average 1.6 cm more quadratic mean diameter than single thinned trees (p value <0.0001). In SQ_1, the difference in mean quadratic diameter was not statistically significant (p value 0.185). Table 4.1 shows that the largest difference in quadratic diameter was observed in SQ_3 between conventionally thinned trees that had on average 14 cm more mean quadratic diameter than the trees of the unpruned unthinned treatment (p value <0.0001). 13.0 cm was the difference in quadratic diameter that was observed between the same treatments in SQ_1 (p value <0.0001). The differences in mean quadratic diameter shown in Table 4.1 were all statistically significant with the exception of one between $P_4T_1.SQ_1$ and $P_4T_1.SQ_1$ (p value 0.185).

Further to what is shown in Table 4.1, the trend for quadratic diameter across site quality and pruning-thinning treatments is illustrated in Figure 4.1.

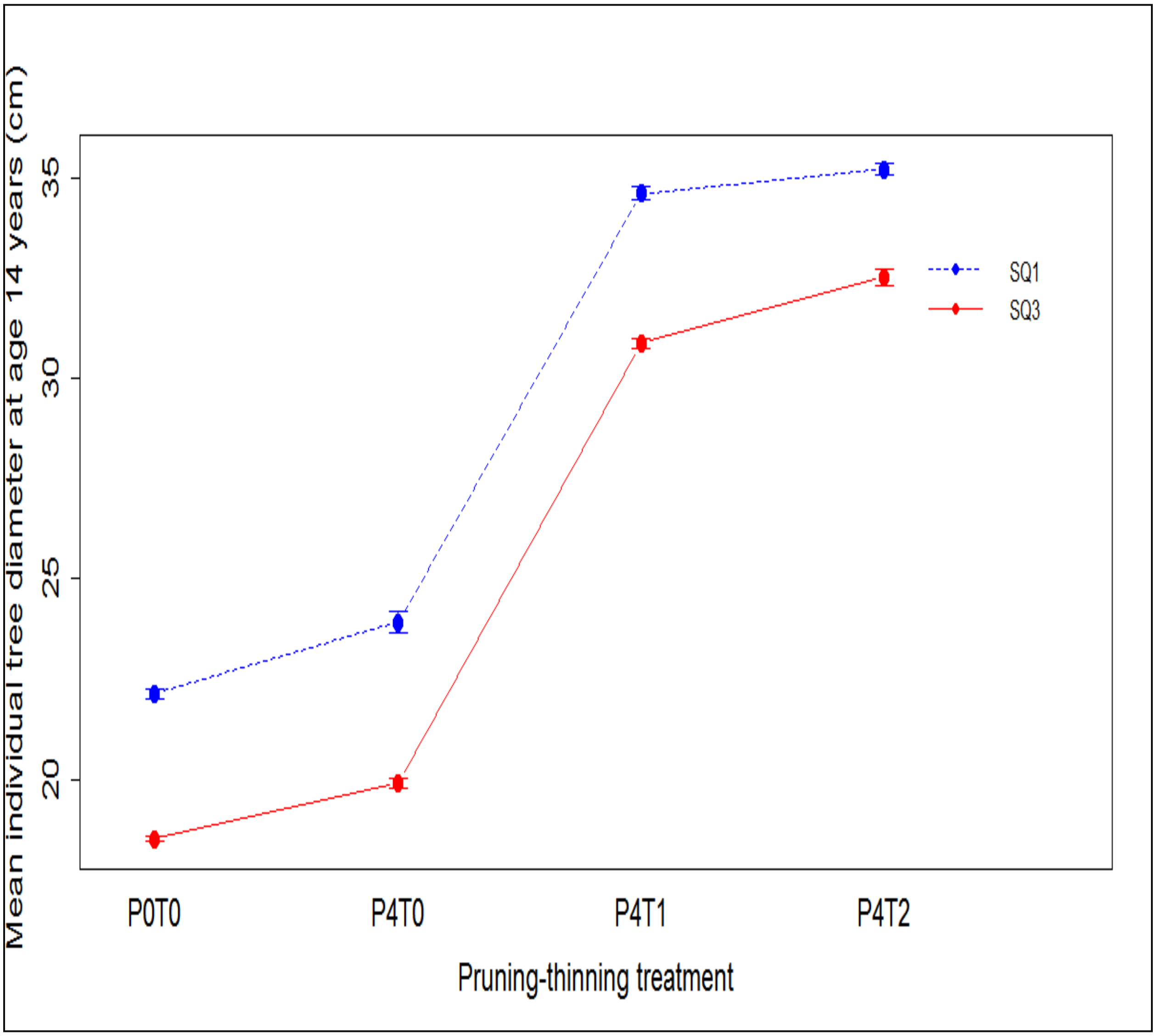


Figure 4.1: Quadratic mean DBH interaction plot (with standard error bars)

The quadratic mean diameter observed at 14 years was higher in SQ_1 across all treatments than it was in SQ_3 (Figure 4.1). Figure 4.1 shows that the thinned stands (P_4T_1

and P_4T_2) had higher quadratic mean DBH than unthinned stands (P_4T_0 and P_0T_0). In both site qualities, Figure 4.1 shows a slight difference in quadratic diameter between P_4T_0 and P_0T_0. In statistically significant differences of 1.7 cm (SQ_1) and 1.3 cm (SQ_3), treatment P_4T_0 yielded more quadratic diameter than P_0T_0 at 14 years. In comparing P_4T_0 and P_4T_1 treatments between both SQ_1 and SQ_3, a higher quadratic mean DBH was observed in P_4T_1 compared to that of P_4T_0 (Figure 4.1). Comparing treatments P_4T_1 and P_4T_2, Figure 4.1 show that trees subjected to P_4T_2 treatment had a higher quadratic DBH than trees subjected to the single stage thinning.

A check on whether the diameter results reported in Table 4.1 were as a result of an interaction between treatments produced the results shown in Table 4.2.

Table 4.2: ANOVA results for treatment effects on DBH

Treatment	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Pruning-thinning	3	2705.8	901.9	3684.513	< 0.0001***
Site Quality	1	221.9	221.9	906.494	< 0.0001***
Pruning-thinning x Site quality	3	4.4	1.5	6.002	0.00114 **
Residuals	64	15.7	0.2		
Signif. codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**					

Table 4.2 show that there was a statistically significant interaction between the effects of site quality and pruning-thinning combination on individual mean quadratic DBH ([F (3, 64) = 6.002, p = 0.00114 **]). With a p value of 0.00114 ** depicting an interaction, the null hypothesis that there is no significant interaction between pruning-thinning combination and site quality on quadratic mean DBH is rejected.

4.1.2 Implications on mean individual tree volume

With a p value of 0.027, single thinned stands in SQ_1 had on average 0.02 m^3 less mean individual tree volume than conventionally thinned stands in the same site quality class (Table 4.1). In SQ_3, single thinned stands had 0.03 m^3 less mean individual tree volume than conventionally thinned stands (p value 0.001). Pruned and not-thinned (P_4T_0) stands on SQ_1 had on average 0.02 m^3 more mean individual tree volume than unpruned and unthinned (P_0T_0) stands in the same site quality class. The difference in the mean individual tree volume in stands subjected to P_4T_0) and P_0T_0 treatments was not statistically significant on SQ_3 (p value 0.591). At p values <0.001, both single thinned stands and conventionally thinned stands had on average 0.3 m^3 (SQ_1) and 0.2 m^3 (SQ_3) more individual tree volume than unthinned and unpruned stands (P_0T_0), respectively.

Further to Table 4.1, the illustration of the interaction of site quality and pruning-thinning on mean individual tree volume in Figure 4.2 show that all pruning-thinning treatments in SQ_1 had higher mean individual tree volumes than all pruning-thinning treatments in SQ_3. As shown in both Table 4.1 and Figure 4.2, in both site qualities the thinned stands (P_4T_1 and P_4T_2) had more individual tree volume than the unthinned stands (P_4T_0 and P_0T_0).

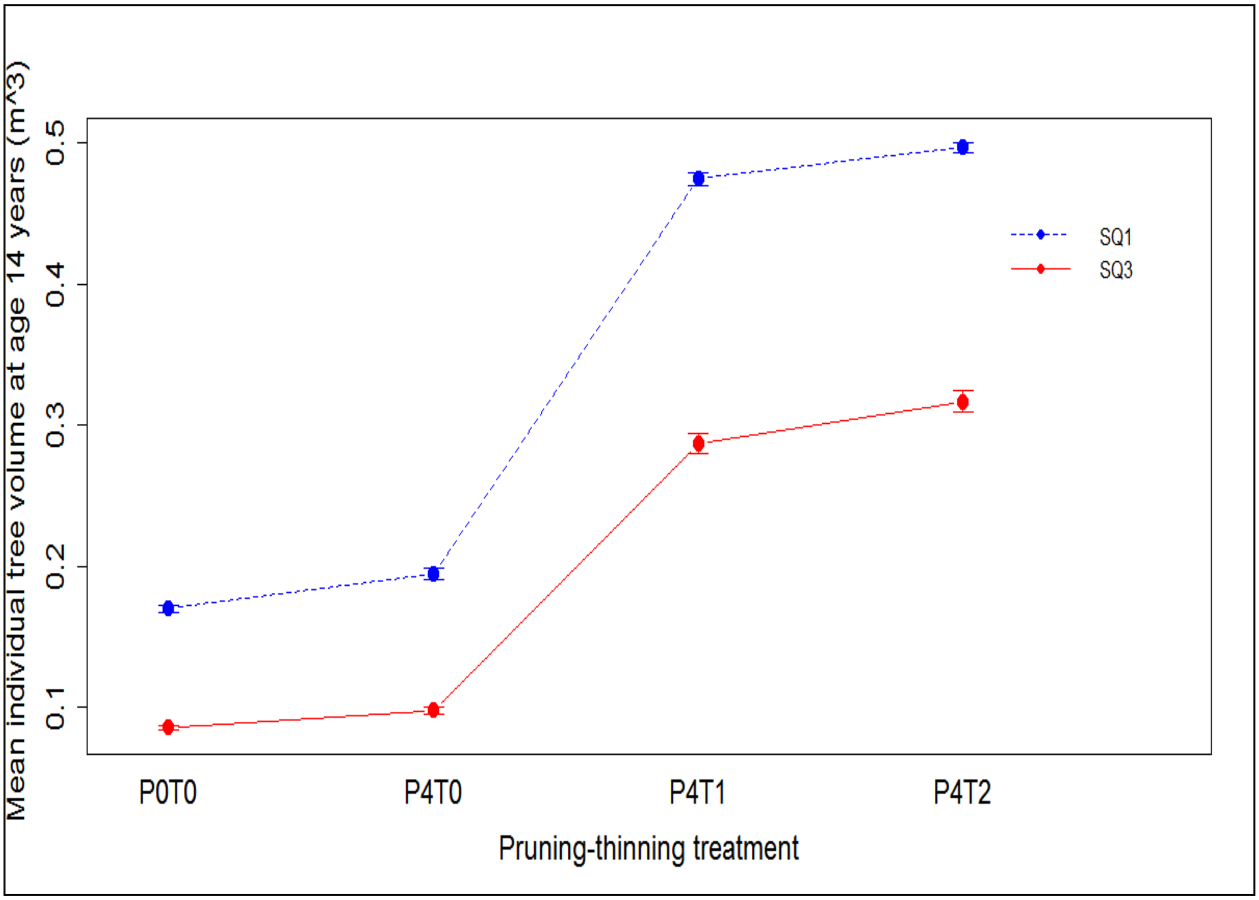


Figure 4.2: Mean individual tree volume interaction plot (with standard error bars)

When comparing P_4T_0 and P_4T_1 treatments in both site qualities, the thinning done in P_4T_1 led to a higher yield of mean individual tree volume in P_4T_1 than was produced in P_4T_0. The difference between treatments P_4T_1 and P_4T_2 in both site qualities had been scaled down by the age reduction to 14 years. Since both treatments P_4T_1 and P_4T_2 had only two full growth seasons to respond to the thinning treatment at year 12, the mean individual tree volume shown in Figure 4.2 was at 14 years.

An ANOVA test with an interaction term run on the mean individual tree volume data is shown in Table 4.3.

Table 4.3: ANOVA results for treatment effects on mean individual tree volume

Treatment	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Pruning-thinning	3	1.1950	0.3983	2019.65	< 0.0001 ***
Site Quality	1	0.3389	0.3389	1718.56	< 0.0001 ***
Pruning-thinning x Site quality	3	0.0397	0.0132	67.05	< 0.0001 ***
Residuals	64	340.1	5.3		
Signif. codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**					

As shown in Table 4.3, there was a statistically significant interaction between the effects of site quality and pruning-thinning combination on individual mean tree volume ([F (3, 64) = 67.05, p = < 0.0001***]). With a p value of < 0.0001*** depicting an interaction, the null hypothesis that there is no significant interaction between pruning-thinning combination and site class quality on mean individual tree volume is rejected.

4.1.2 Implications on mean stand volume

From Table 4.1, the difference in standing volume at age 14 years of 10.4 m^3/ha between conventionally thinned stands and single thinned stands in SQ_3 was not statistically significant (p value 0.317). At a p value of <0.0001, single thinned stands in SQ_1 had on average 26.1 m^3/ha greater mean stand volume than conventionally thinned stands (Table 4.1). Pruned and not-thinned (P_4T_0) stands on SQ_1 had on average 26.5 m^3/ha more mean stand volume than unpruned and unthinned (P_0T_0) stands in the same site quality class (p value <0.0001). The difference in the mean standing volume between treatments P_4T_0 and P_0T_0 was not significant when the treatments are in SQ_3 (p value 0.449). At both p values of <0.0001, single thinned stands had on average 97.3 m^3/ha (SQ_1) and 76.0 m^3/ha (SQ_3) more mean stand volume than unthinned and unpruned stands respectively, while conventionally thinned had on average 71.2 m^3/ha (SQ_1) and 65.3 m^3/ha (SQ_3) more mean stand volume than unthinned and unpruned stands, respectively.

Figure 4.3 is an illustration of the interaction of site quality and pruning-thinning interaction on mean stand volume at age 14 years. As is shown in Figure 4.3, all pruning-thinning treatments in SQ_1 had higher mean stand volumes at age 14 years than all pruning-thinning treatments in SQ_3. While P_4T_2 had less standing volume than P_4T_1, it had more standing volume than both P_4T_0 and P_0T_0 (Figure 4.3). Also notable from both Figure 4.3 and Table 4.1, is that in both site qualities the thinned stands (P_4T_1 and P_4T_2) had higher standing volume than the unthinned stands (P_4T_0 and P_0T_0) at age 14 years.

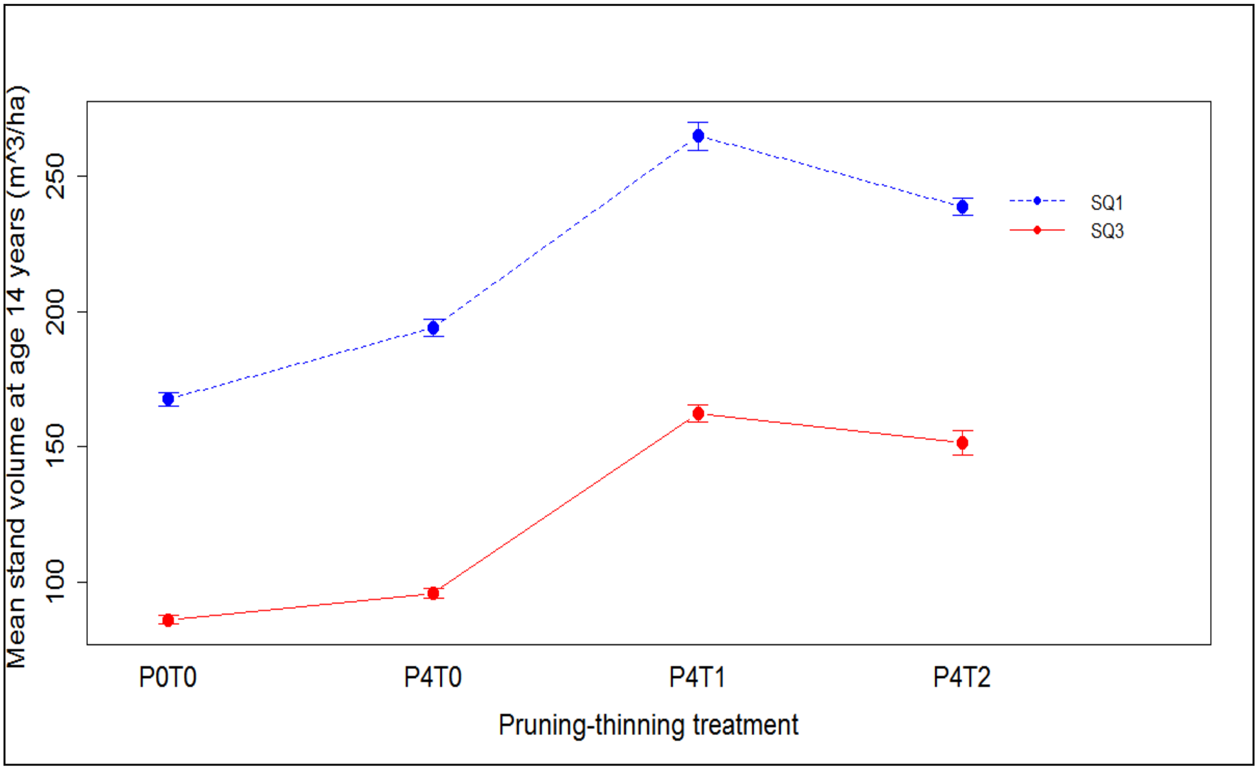


Figure 4.3: Mean stand volume interaction plot (with standard error bars)

When comparing unthinned treatments P_0T_0 and P_4T_0 from Figure 4.3 and Table 4.1, in SQ_1, unthinned stands were more responsive to pruning intervention than they were in SQ_3. The same interaction effect was observed when comparing the unthinned P_4T_0 treatment and the single thinned P_4T_1 treatment. As shown in Figure 4.3, in both site qualities, the thinning done in P_4T_1 led to a higher mean stand volume in P_4T_1 than was observed in P_4T_0. The results in Table 4.1 however showed that both P_4T_1 and P_4T_0 in SQ_1 were more responsive to the treatment intervention than they were in SQ_3.

Between treatments P_4T_1 and P_4T_2, Figure 4.3 and Table 4.1 results show that the difference in standing volume in both treatments was small (26.1 m^3/ ha for SQ_1 and a statistically non-significant 10.7 m^3/ ha for SQ_3). Since at 14 years, treatments P_4T_1 and P_4T_2 had only two full growth seasons to respond to the thinning treatment at year 12, to check whether the time to respond to thinning had an effect on the trend of results shown in Table 4.1, reference was made to the mean stand basal area for treatments. This was done because basal area relies on a simple, direct dbh measurement whereas volumes were estimated using a regression height approach which is more indirect. Table 4.4 illustrates the mean stand basal area for treatments at 14 years.

Table 4.4: Mean stand basal area (m^2/ha) for treatments at age 14 years

Treatment	mean	sd	median	trimmed	min	max	range	se
P_4T_1: SQ_1	52.34	3.45	53.8	52.34	48	56	8	1.15
P_4T_2: SQ_1	46.8	1.86	47	46.8	44	50.3	6.3	0.62
P_4T_0: SQ_1	44.81	2.71	44.5	44.81	41.2	48.7	7.5	0.9
P_0T_0: SQ_1	38.06	1.38	38.1	38.06	35.7	40.1	4.4	0.46
P_4T_1: SQ_3	42.39	1.49	42.1	42.39	39.9	44.5	4.6	0.5
P_4T_2: SQ_3	39.71	3.24	39.9	39.71	33.8	45.9	12.1	1.08
P_4T_0: SQ_3	30.48	1.69	30	30.48	28.7	33.3	4.6	0.56
P_0T_0: SQ_3	27.57	1.54	27.5	27.57	25.5	29.9	4.4	0.51

As shown in Table 4.4, P_4T_1 treatments in each site quality category had the highest mean stand basal area in both site qualities followed by P_4T_2. The trend shown by the mean stand basal area was the same trend shown by the mean stand volume for all treatments. Therefore, although both treatments P_4T_1 and P_4T_2, at the scaled down age of 14 years, had both had only two full growth seasons to respond to the thinning at year 12, mean stand basal area figures confirmed that P_4T_1 yielded higher standing volume than P_4T_2 at the age of 14 years (Figure 4.3 and Table 4.1).

The results of an ANOVA run with an interaction term produced the results shown in Table 4.5.

Table 4.5: ANOVA results for treatment effects on mean stand volume

Treatment	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Pruning-thinning	3	90232	30077	302.408	< 0.0001 ***
Site Quality	1	154152	154152	1549.902	< 0.0001 ***
Pruning-thinning x Site quality	3	1293	431	4.333	0.00764 **
Residuals	64	6365	99		
Signif. codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**					

The results in Table 4.5 shows that there was a statistically significant interaction between the effects of site quality and pruning-thinning combination on mean stand volume at age 14 years ([F (3, 64) = 4.333, p = 0.00764***]). Since the interaction is significant, the pruning-thinning effect on mean stand volume depended on site quality.

4.2 THE GROWTH RING WIDTH LINK TO THE RESPONSE OF DBH TO TREATMENTS

To qualify the results shown in Table 4.1, a trend analysis of the base disc growth ring widths for SQ_1 and SQ_3 was done using polynomial trend line to the second degree (Figure 4.4). The growth ring width results for 14 years and the corresponding trend lines are shown in Figure 4.4. Notably, from Figure 4.4 a general decline in growth ring widths was observed for all treatments across site qualities from approximately year three up to year eight. While the growth ring widths of treatments $P_4T_{1.}SQ_1$ and $P_4T_{1.}SQ_3$ not thinned at year eight continued the decline between year nine and year thirteen, the growth ring widths for treatments $P_4T_{2.}SQ_1$ and $P_4T_{2.}SQ_3$ that received a thinning at year eight increased between the same period (Figure 4.4).

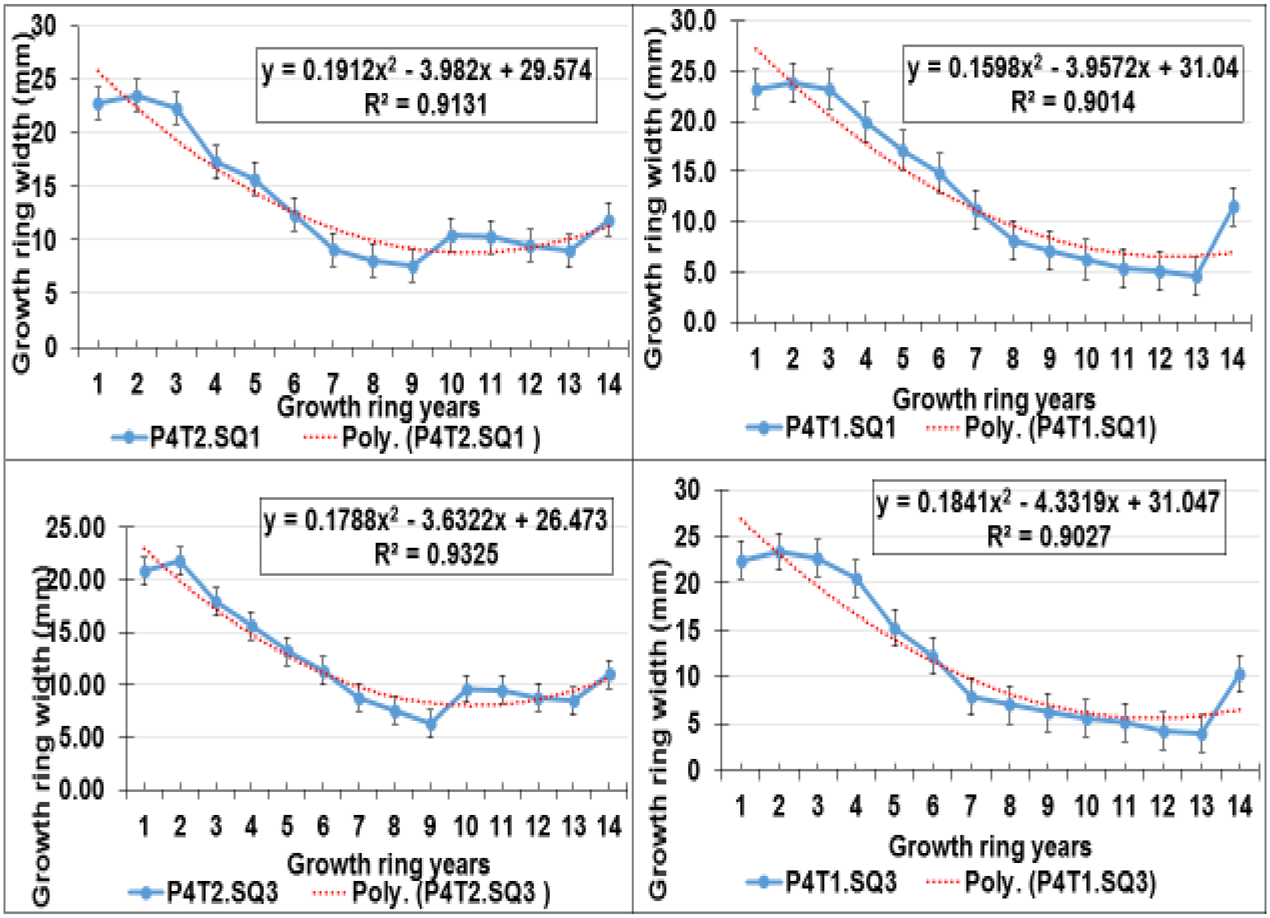


Figure 4.4: Fourteen year average growth ring widths from the base disc

In year thirteen, the growth ring widths for treatment $P_4T_2.SQ_1$ again increased in response to the second thinning done at year twelve (Figure 4.4). The growth ring widths for treatment $P_4T_1.SQ_1$ also increased in year thirteen in response to the single stage mid rotation thinning done at year twelve (Figure 4.4). A similar trend was observed for treatments $P_4T_2.SQ_3$ and $P_4T_1.SQ_3$ at year thirteen.

De-trending the growth ring widths data for treatments using regression analysis as described in Section 3.5 gave results shown in Figure 4.5. The de-trending allowed for a clearer interpretation of the percentage change in growth ring widths of trees across treatments. Figure 4.5 shows the de-trended growth ring width comparison of the conventionally thinned treatment and the single thinned treatment in both SQ_1 and SQ_3.

The growth ring widths for the conventional thinning treatment ($P_4T_2.$ SQ_1) responded to the first thinning at year eight with a 35.9 % increase (Figure 4.5). During the same period, there was a gradual decline in growth ring widths of approximately 15 % observed in the single thinned treatment ($P_4T_1.$ SQ_1) that did not get thinned at eight years. Similarly, the growth ring widths for the conventional thinning treatment ($P_4T_2.$ SQ_3) responded to the first thinning at year eight with a 43.3 % increase in growth ring width (Figure 4.5). During the same period, the single thinned treatment ($P_4T_1.$ SQ_3) that did not get thinned at eight years, maintained the growth ring widths fluctuating up and down between three and five percent from year eight to year eleven.

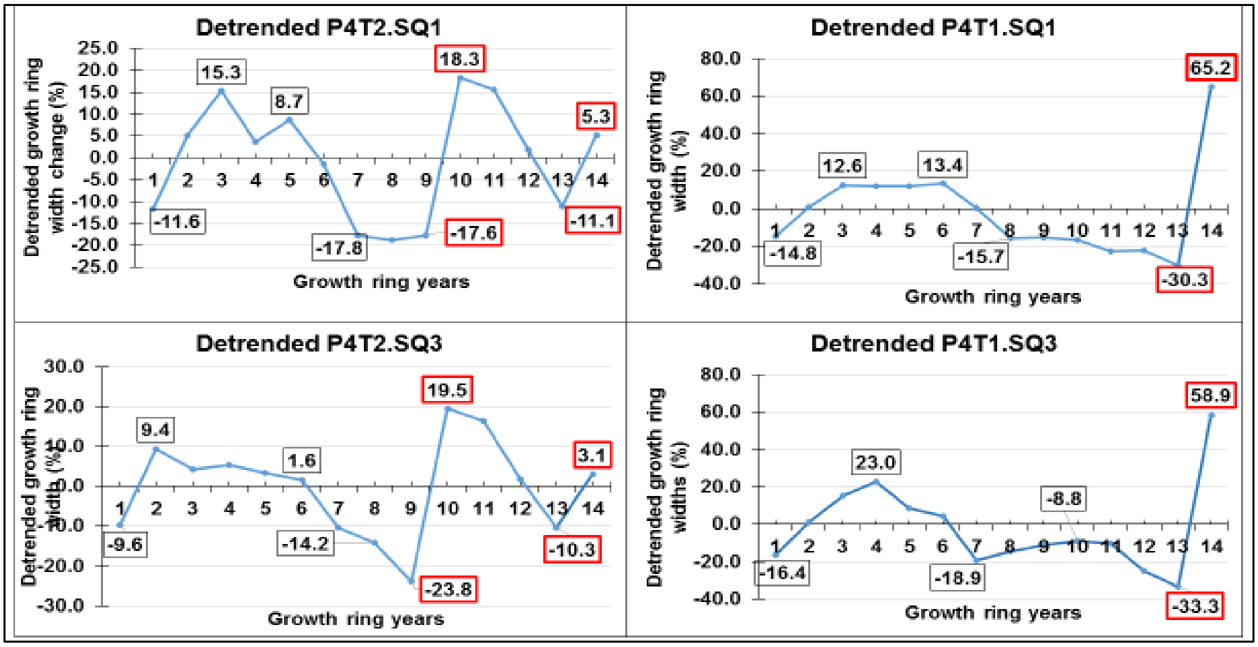


Figure 4.5: $P_4T_{2.}$ SQ_1 growth ring widths with trend and without trend

After receiving the second thinning at year twelve, the conventionally thinned treatment ($P_4T_{2.}$ SQ_1) responded with a lesser magnitude compared to the response observed at first thinning, posting a 16.4 % increase in growth ring widths (Figure 4.5). After receiving its first thinning at twelve years, the single stage thinning treatment ($P_4T_{1.}$ SQ_1), had a remarkable increase in growth ring width of 95.5 %. Similarly, the growth ring widths for the conventional thinning treatment ($P_4T_{2.}$ SQ_3) responded to the second thinning at year twelve with a comparably smaller 13.4 % increase in growth ring width (Figure 4.5). The single thinned treatment ($P_4T_{1.}$ SQ_3) that got its first thinning at twelve years, also responded to its first thinning with a tremendous 92.2 % increase in growth ring width. Irrespective of site quality class, Figure 4.5 results demonstrated that the response rate to a thinning decreased drastically from the first to the second thinning.

The growth ring widths sequence from planting to 14 years illustrated in Figure 4.4 and expanded on in Figure 4.5 explain the trends of mean quadratic DBH described in Section 4.1.1, which in turn had an influence on the trend of mean individual tree volume explained in Section 4.1.2. Figure 4.5 further clarify how the quadratic mean DBH and mean individual tree volume of single thinned stands was not very much behind that of the conventionally thinned stands at the cut off age of 14 years.

4.3 THE KNOT PROPERTY IMPLICATIONS OF SINGLE STAGE THINNING REGIME

The knot property statistics of all treatments are shown in Table 4.6. The implications of changing from conventional to single stage thinning regime on sound to unsound ratio and on mean knot diameter at 14 years throughout this section referred to Table 4.6.

Table 4.6: Summary table of all knot property findings of the study

Cumulative log unit lengths per treatment	Share of knots in treatment per log unit		Mean knot diameter (cm)		Mean relative knot diameter	
	Sound knots	Unsound knots	Sound knots	Unsound knots	Sound knots	Unsound knots
$P_4T_1.SQ_1$ (0-7.2 m)	77%	23%	3.1	1.9	0.11	0.08
$P_4T_1.SQ_1$ (7.2-16.8 m)	60%	40%	1.8	1.2	0.11	0.07
$P_4T_2.SQ_1$ (0-7.2 m)	85%	15%	3.2	2.8	0.11	0.1
$P_4T_2.SQ_1$ (7.2-16.8 m)	66%	34%	1.9	1.8	0.1	0.09
$P_4T_0.SQ_1$ (0-7.2 m)	56%	44%	3.1	2.4	0.14	0.12
$P_4T_0.SQ_1$ (7.2-16.8 m)	59%	41%	1.9	1.5	0.12	0.09
$P_0T_0.SQ_1$ (0-7.2 m)	7%	93%	5.3	3.3	0.25	0.16
$P_0T_0.SQ_1$ (7.2-16.8 m)	80%	20%	1.9	2.1	0.13	0.12
$P_4T_1.SQ_3$ (0-7.2 m)	74%	26%	2.8	2.1	0.12	0.1
$P_4T_1.SQ_3$ (7.2-16.8 m)	57%	43%	1.7	1.5	0.11	0.09
$P_4T_2.SQ_3$ (0-7.2 m)	78%	22%	3.1	2.4	0.13	0.11
$P_4T_2.SQ_3$ (7.2-16.8 m)	65%	35%	1.7	1.6	0.1	0.1
$P_4T_0.SQ_3$ (0-7.2 m)	55%	45%	3.1	2.2	0.16	0.12
$P_4T_0.SQ_3$ (7.2-16.8 m)	64%	36%	1.6	1.2	0.1	0.08
$P_0T_0.SQ_3$ (0-7.2 m)	17%	83%	2.9	3	0.19	0.17
$P_0T_0.SQ_3$ (7.2-16.8 m)	68%	32%	2.1	1.5	0.16	0.12

4.3.1 Implications on mean knot diameter

As shown in Table 4.6, the 0-7.2 m log unit of conventionally thinned trees in SQ_1 had on average 0.1 cm larger mean knot diameter than the 0-7.2 m log unit of single thinned trees (p value 0.019). In SQ_3, the 0-7.2 m log unit of conventionally thinned trees had 0.3 cm more mean knot diameter than that of single thinned trees (p value 0.067). In Table 4.6, the largest difference in mean knot diameter within the 0-7.2 m log unit was observed in SQ_1 between single thinned trees and the unthinned and unpruned trees, in which the mean knot diameter for single thinned trees was 0.6 cm smaller (p value <0.0001). The 0-7.2 m log unit of P_4T_0 in SQ_1 also had on average 0.6 cm smaller mean knot diameter than the same log unit of P_0T_0 (p value <0.001). Within the 7.2 -16.8 m log unit, the only statistically significant difference in mean knot diameter was between treatments P_4T_1 and treatment P_4T_0 in SQ_1. Herein, the mean knot diameter of P_4T_1 was 0.3 cm smaller than the average in P_4T_0 (p value 0.04).

Further to what is shown in Table 4.6, the trend for mean knot diameter across log unit and site quality-pruning-thinning treatments is illustrated in Figure 4.6.

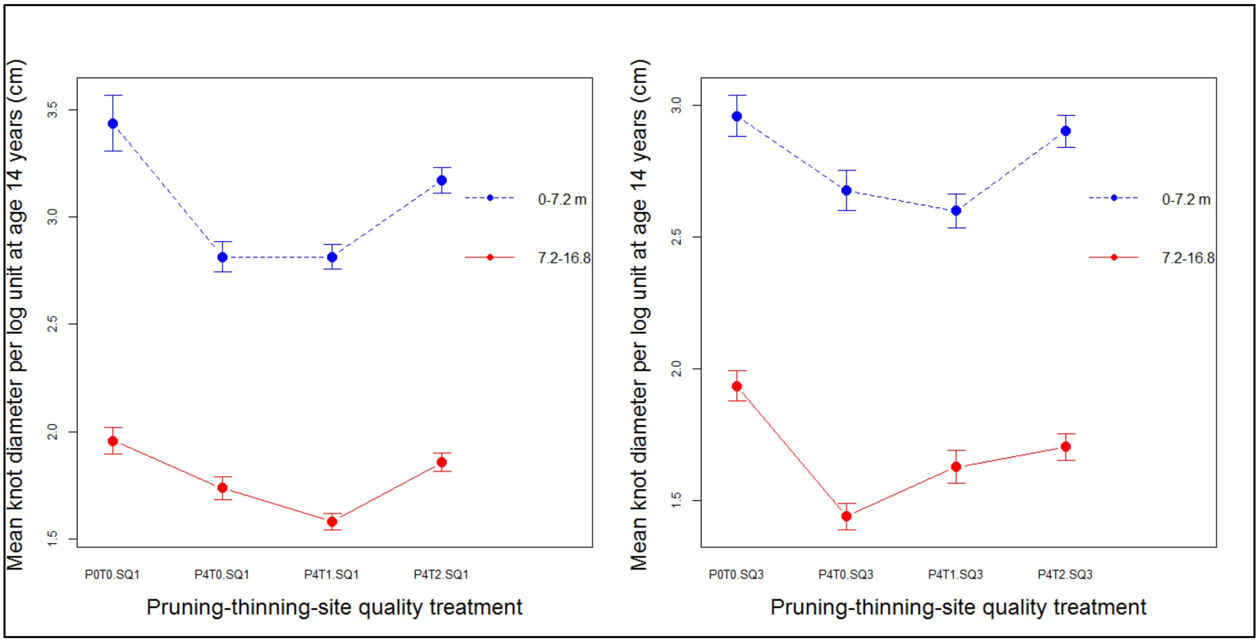


Figure 4.6: Treatment interaction effect on mean knot diameter per log unit.

As is shown in Figure 4.6, the log unit length 0 -7.2 m had a larger mean knot diameter than the log unit 7.2 -16.8 m across all treatments. When comparing unthinned treatments P_0T_0 and P_4T_0 (irrespective of site quality), the pruning intervention in both log units resulted in a decrease in mean knot diameter (Figure 4.6). A complex interaction effect was observed when comparing the unthinned P_4T_0 treatment and the single thinned P_4T_1 treatment (Figure 4.6). In SQ_1, the thinning done in P_4T_1 did not have any net effect on mean knot diameter of the 0-7.2 m log unit, while in SQ_3, the thinning done in P_4T_1

resulted in a decrease in mean knot diameter (Figure 4.6). Between treatments P_4T_1 and P_4T_2, irrespective of site quality, both log lengths (0 -7.2 m and 7.2 -16.8 m responded to the pruning-thinning treatment with an increase in mean knot diameter. The response of mean knot diameter to the interaction was however more pronounced in the 0 -7.2 log unit than it was in the 7.2 -16.8 m log unit (Table 4.6).

To check whether the knot diameter results shown in Table 4.6 were as a result of an interaction between treatments or not, an ANOVA with an interaction term was run. The results are shown in Table 4.7.

Table 4.7: ANOVA results for treatment effects on knot diameter

Treatment	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Pruning-thinning-site quality treatment	7	104	14.9	19.62	< 0.0001***
Log unit	1	713.3	713.3	945.031	< 0.0001***
Pruning-thinning-site quality x Log unit	7	11.5	1.6	2.176	0.0335 *
Residuals	2200	1660.5	0,8		
Signif. codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**					

The results in Table 4.7 show that there was a statistically significant interaction between the effects of pruning-thinning-site quality treatment and log unit on mean knot diameter ([F (7, 2200) = 2.176, p = 0.0335*]). Since the interaction was statistically significant, the null hypothesis for the interaction that there is no significant interaction between pruning-thinning-site quality combination and log unit on mean knot diameter is rejected (p value 0.0335*).

4.3.2 Implications on relative knot diameter

The differences in the relative knot diameter within the 0-7.2 m log unit of conventionally thinned trees and that of single thinned trees in SQ_1 and SQ_3 were not statistically significant (p values of 0.09 for both site qualities). In Table 4.6, the largest difference in relative knot diameter within the 0-7.2 m log unit was observed in SQ_1 between single thinned trees and the unthinned and unpruned trees, in which the relative knot diameter for single thinned trees was 0.06 better (p value <0.0001). The differences in the relative knot diameter within the 7.2-16.8 m log unit of conventionally thinned trees and that of single thinned trees in SQ_1 and SQ_3 were not statistically significant (p values of 0.09 and 0.84 respectively).

The trend for relative knot diameter across log units and site quality-pruning-thinning treatments is illustrated in Figure 4.7.

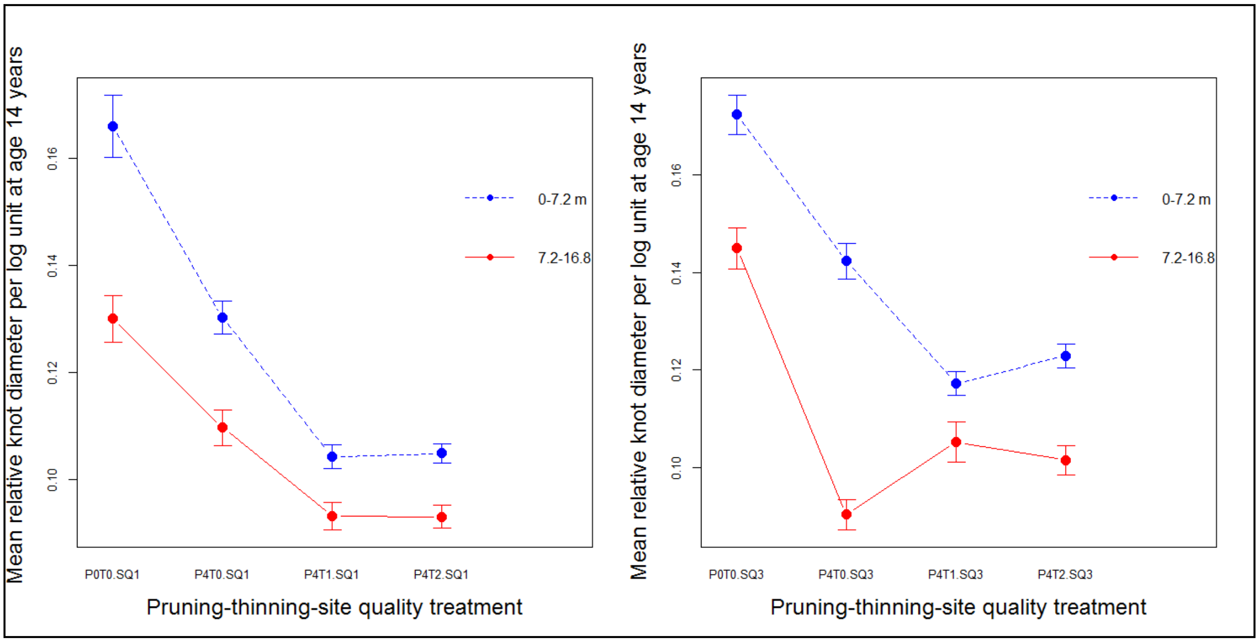


Figure 4.7: Treatment interaction effect on relative knot diameter per log unit

The pruning-thinning treatments within the log unit length 0 -7.2 m had better relative knot diameter ratios than the pruning-thinning treatments within the log unit 7.2 -16.8 m (Figure 4.7). When comparing unthinned treatments P_0T_0 and P_4T_0 in SQ_1, in both log units pruning led to a decrease in relative knot diameter. Similarly, when comparing the unthinned P_4T_0 treatment and the single thinned P_4T_1 treatment, in SQ_1, within both log units, the thinning done in P_4T_1 resulted in a decrease in relative knot diameter. In SQ_3, within the log unit 0-7.2 m, the thinning done in P_4T_1 also resulted in a decrease in relative knot diameter while within the log unit 7.2-16.8 m, the thinning done in P_4T_1 was followed by a sharp increase in relative knot diameter (Figure 4.7).

For treatments P_4T_1 and P_4T_2, in SQ_1, log length 0-7.2 m responded to the pruning-thinning treatment with an increase in relative knot diameter. Within the log unit 7.2 -16.8 m, the thinning done in P_4T_1 did not have any net effect on relative knot diameter since the relative knot diameter in P_4T_2 was the same as it was in P_4T_1. In SQ_3 the interaction of treatments was strong and log unit 0 -7.2 m responded to the thinning with an increase in relative knot diameter while log unit 7.2 -16.8 m responded to the thinning with a decrease in relative knot diameter (Figure 4.7).

A check whether or not the relative knot diameter results reported in Table 4.6 were as a result of an interaction between treatments produced the results reported in Table 4.8.

Table 4.8: ANOVA results for treatment effects on relative knot diameter

Treatment	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**
Pruning-thinning-site quality	7	1.141	0.16307	98.395	< 0.0001***
Log unit	1	0.221	0.22114	133.436	< 0.0001***
Pruning-thinning-site quality x log unit	7	0.069	0.00982	5.927	< 0.0001***
Residuals	2200	3.646	0.00166		
Signif. codes: 0 ‘*’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1**					

The results in Table 4.8 show that there was a statistically significant interaction effect of pruning-thinning-site quality treatment and log unit on relative knot diameter ([F (7, 2200) = 5.927, p = < 0.0001***]). With a p value of < 0.0001, the null hypothesis that there is no significant interaction between pruning-thinning-site quality combination and log unit on relative knot diameter is rejected.

4.3.3 Implications on sound to unsound ratios

Table 4.6 shows that in $SQ_{1,}$ the merchantable stems of trees in conventionally thinned stands had a higher share of sound knots (76 %) compared to the merchantable stems of trees in single thinned stands (68 %). In SQ_3 merchantable stems of trees in conventionally thinned stands also had a higher share of sound knots (74 %) compared to the merchantable stems of trees in single thinned stands (69 %). Multiple comparison test of treatments done to check which treatment categories had significantly different sound to unsound ratios showed that the differences in the sound to unsound ratios for all the treatment combinations in conventionally thinned stands and that of all treatment combinations in single thinned stands for both log units (0 -7.2 m and 7.2 -16.8 m) were not statistically significant (Kruskal-Wallis chi-squared = 4.4334, df = 15, p-value = <0.99). However, within the same merchantable stems the difference between log units 0-7.2 m and 7.2 -16.8 m were statistically significant (Kruskal-Wallis chi-squared = 4.2985, df = 1, p-value = 0.03815). Therefore the null hypothesis that there is no significant difference in the sound to unsound ratio of conventionally thinned stands and single thinned stands could not be rejected. The null hypothesis that there is no significant difference in the sound to unsound ratio of log unit 0 -7.2 m and 7.2 -16.8 m was however rejected.

CHAPTER 5 DISCUSSION

Growth studies are mostly conducted in long term experimental plots whose silvicultural history is well documented (Marsh, 1978; Pretzsch, 2009). This study was conducted in normal rotation compartments, where the scheduling and timing of the silvicultural operations were more suitable for operational objectives than for research purposes. However, as posted by Carron, (1968) and Kariuki, (2002), data collected through scientifically acceptable methods from even aged homogeneous stands of comparable age suffice in explaining growth and knot property trends.

5.1 GROWTH PARAMETERS

Growth ring widths in this study changed from one year to the next as trees in different treatments responded to the available growth resources as was determined by site quality and pruning-thinning treatments from time to time. In both the single thinned and the conventionally thinned stands, the growth ring widths increased successively for the first three years. This agrees to what is reported in Pretzsch, (2009) that when trees are planted in an even aged stand, there is initially an adequate supply of growth resources including space, which aid trees to grow exponentially during the first three to four years as they compete for dominance before canopy closure at approximately four years for pines on the study site. Growth ring widths on both treatments declined continuously from approximately year four to year eight as competition for growth resources intensified and some growth resources including space became limiting.

After receiving the second thinning at year twelve, the conventionally thinned treatment in both site qualities responded with a lesser magnitude compared to the response observed at first thinning (Figure 4.5). After receiving its first thinning at twelve years, the single stage thinning treatment in both site qualities had a remarkable increase in growth ring width. Single thinned stands managed to achieve this comparatively larger surge in growth ring width growth (92 -95 %) owing to the release of their tree canopies from intensive competition to which they had been subjected for approximately twelve years. Notably, by year twelve, all pruning treatments had been completed in both thinning regimes, and therefore trees in both regimes were responding to this increase in available growth resources including space at full canopy strength without disturbances due to recovery from any pruning related loss of leaf area.

Furthermore, unlike in conventionally thinned stands whose trees were partially responding to the remaining portion of the growth resources (having already tapped into a portion at year eight when they were in the process of recovering from loss of canopy branches to pruning), single thinned trees were responding to the available growth resources for the first time, at a time when their canopy was at full strength for maximum photosynthetic ability to manufacture carbohydrates for growth. This explains why the trees in the single thinned stands responded better to the single thinning at year twelve than the trees of conventionally thinned stands responded to the second thinning also at year twelve. This finding is supported by studies of Pretzsch, (2009) who stated that… "When the stand has been thinned already, and, as a result, growth acceleration has occurred repeatedly, its capacity to respond to thinning declines". He further added that, "a stand's capacity to respond to thinning with additional growth depends on the previous silvicultural treatment rather than on the physical stand age"- quoted from Pretzsch, (2009).

5.1.1 Mean stand volume

Contrary to the tree level findings in which both the mean DBH and the mean individual tree volume values for conventionally thinned trees were higher than those of single thinned trees, the standing volumes at age 14 years for conventionally thinned stands were lower than those of single thinned stands (Table 4.1). This deviation in trend was largely owing to the higher final stand density at age 14 for single thinned stands compared to that of conventionally thinned stands. The higher stand density advantage was however augmented by the response of grander magnitude to the mid-rotation thinning posted by trees in the single thinned stands, the resultant effect of which safeguarded their trees' diameters from falling far behind conventionally thinned trees.

When comparing the mean stand volume for unthinned treatments P_0T_0 and P_4T_0 the effect of pruning in both site qualities surprisingly led to an increase in the mean stand volume by an unexpected margin (Figure 4.3). This finding deviates from what is documented in Smith *et al* (1997); Kotze and du Toit (2012); that pruning leads to reduction (although temporary) in growth. The deviation encountered in this study is explained by the submissions in Pretzsch (2009) regarding an even age pure stand's gross primary productivity and net primary productivity. Due to the intense competition for limiting growth resources, unpruned and unthinned trees in P_0T_0 channelled a lot more growth assimilates towards branch development for competitive positioning to capture radiation for maximum photosynthesis compared to stem diameter and height development. In the absence of any pruning, this resulted in development of thick and tall branches supported by short and sturdy stems whose merchantable volume was very low. Further to this scenario, the unpruned and unthinned trees had a large fraction of photosynthetically inactive biomass in the forms of thick branches and lots of shaded leaves which led to high rates of respiration in comparison to the rate of growth contributory photosynthesis. According to Pretzsch, 2009 the rate of respiration in these circumstances for mature pine may be as high as 60%. A state of imbalance was probably reached in which the net primary productivity decreased due to the large loss in carbon during respiration. In this state of imbalance, pruning the photosynthetically inactive biomass resulted in an increase in growth.

Comparing treatments P_4T_1 and P_4T_2, the more intense thinning in P_4T_2 resulted in loss of volume growth. This means that single thinned stands in SQ_1 with an average of 26.1 m^3/ha more mean stand volume at age 14 years, performed better than conventionally thinned stands although in SQ_3 the difference was not statistically significant. This finding agrees with what is recorded in Pretzsch, (2009), who quoted Assmann (1961) in saying that, "volume growth increases with a reduction in stand density up to a certain optimum, and then decreases with a further reduction in density". According to Assmann (1961) the optimal stand density for a stand to be able to compensate growth for trees removed in a thinning is linked to stand basal area. In Pines if approximately 20 % of stand basal area could be removed, an accompanying loss of growth (approximately 5 %) is experienced (Pretzsch, (2009)). This in all probability could be what happened when a first thinning (single thinned stands) and a second thinning (conventionally thinned stands) was done at year twelve, to the extent where the stand basal area threshold was exceeded resulting in the loss of volume growth shown in Figure 4.3.

Based on the submissions of Assmann (1961), although the results shown in Figure 4.3 were for only two full growth seasons after the thinning, and an increase in years after thinning could change the magnitude of the loss of growth, the volume loss trend shown in Figure 4.3 would in all probability remain unchanged. This is because the mean stand volume figures in Table 4.1 are in agreement with the mean stand basal figures for the treatments in Table 4.4. After the thinning, single thinned stands had a higher basal area at 52.3 m^2/ha (SQ_1) and 42.39 m^2/ha (SQ_3) respectively than conventionally thinned stands at 46.8 m^2/ha (SQ_1) and 39.7 m^2/ha (SQ_3) respectively. Therefore, although both treatments P_4T_1 and P_4T_2, at the scaled down age of 14 years, had both had only two full growth seasons to respond the thinning at year 12, mean stand basal area figures confirmed that P_4T_1 had higher mean stand basal area values before thinning which they maintained even after the thinning to a level still higher than P_4T_2 (Figure 4.1 and Table 4.4).

5.1.2 Mean quadratic diameter and mean individual tree volume

Successive, annual growth ring widths represent what is seen and measured on the external as stem diameter changes (Pretzsch, 2009). This statement by Pretzsch, (2009) is echoed in this study when the tremendous growth ring width response of the conventionally pruned and single stage thinning regime between year thirteen and year fourteen resulted in a statistically not significant difference in the final mean DBH of single thinned treatments and conventionally thinned treatments in.SQ_1. This also agrees with the findings from the studies conducted by Kotze (2004) in which the diameter of *Pinus* *patula* trees from spacing trials planted at 1111 stems per hectare increased exponentially after the first thinning to 500 stems per hectare and then again after the second thinning to 250 stems per hectare (Kotze, 2004). The Kotze (2004) results is confirmation that thinning improves the diameter growth of trees in conventionally thinned stands. The study findings of Kotze and du Toit, (2012) further confirms that an aggressive single stage thinning regime invokes a valuable growth response that enable the trees within the stand to reach a target diameter at clear-felling in a comparatively shorter period.

Tree diameter increment is a good proxy for volume growth increment (Bowman *et al*., 2013). In this study, the relationship between mean DBH and mean individual tree volume was positive. In all treatments the mean DBH trend was similar to the mean individual tree volume trend. The closeness in the tree volume results of conventionally thinned stands ($P_4T_{2.}SQ_1$ or $P_4T_{2.}SQ_3$) to that of single thinned stands ($P_4T_{1.}SQ_1$ or $P_4T_{1.}SQ_3$) is also in line with other studies showing that growth of a tree is a function of an increase in height and diameter variables of that tree and how these variables jointly contribute to the increase in basal area, wood volume and biomass over time (Weiskittel *et al*., 2011; Kotze and du Toit 2012; Bowman *et al*., 2013). In line with the findings of this study, research has shown that height increases rapidly in the juvenile phase of growth, levels off and declines to lower levels of increase with age while diameter increases gradually over the lifetime of the tree (Hann and Larsen, 1991; Weiskittel *et al*., 2011; Bowman *et al*., 2013). Therefore while the diameter growth of single thinned trees lagged behind that of conventionally thinned stands before the thinning at year twelve, the height growth in single thinned stands kept up with that of trees in conventionally thinned stands. This height growth gave the trees in single thinned stands a compensatory ability which explains why the single stage thinning tree volume is not radically different from that of the conventionally thinned trees at the age of 14 years.

Between year eight and twelve, stand uniformity due to even age enabled the trees in single thinned stands to co-exist while locked in a state of equilibrium in which the trees neither gained nor lost diameter growth but maintained a stagnant rate of diameter growth just enough to support the tree as it gained in height growth at a faster rate than the tree would have gained in an environment of abundant availability of growth resources including space (Figure 4.4 and 4.5). This equilibrium was only sustainable for a short period of time beyond which mortality may have set in. However, the single stage thinning trees were released from the locked equilibrium of stagnant growth just on time (at year twelve) for them to respond to the release with a significant gain in growth. This finding agrees with what is reported in Buruh *et al*., 2016 that radial growth increases exponentially in the early juvenile years, followed by lagging growth when competition sets in and another surge in growth at the last phase when dominance in the canopy structure has been defined (Buruh *et al*., 2016).

5.2 KNOT PROPERTY PARAMETERS

The log unit 0-7.2 m is the prime log unit for saw log production enterprises as it contains the most volume percentage of the merchantable stem and is also usually priced higher than the 7.2 -16.8 m log unit. It was therefore important in this study to look closely at the knot characteristics of this log unit. In this study the log unit 0-7.2 m for the conventionally thinned stands had a higher percentage share of sound knots coupled with a smaller percentage share of unsound knots when compared to the same log unit in the single thinned treatments. This was due to the fact that the 0 -7.2 m log unit of the conventionally thinned stand was formed during the growth phase within the development of the stem which coincided with the scheduling and execution of consistent silviculture intervention in the form of correctly timed pruning and thinning treatments. While the removal of trees through thinning increased the availability of growth resources to remaining trees during this period which increased branch size (hence the corresponding large knot diameters on this log unit), the timeous pruning intervention in P_4T_0, P_4T_1 and P_4T_2 treatments timeously removed the branches before branch mortality could set in naturally and cause large dead knots. The knot characteristics observed in this study expound the effect of pruning in maintaining sound knots in timber. Both single thinned and conventionally thinned treatments had all four conventional prunings done on them hence the close similarity in the sound to unsound ratios as evidenced by statistically not significant differences in their knot sound to unsound ratio.

5.2.1 Mean knot diameter

Within the same merchantable stem, the log unit length 0-7.2 m recorded higher mean knot diameter values in all pruning-thinning treatments compared to the log unit 7.2 -16.8 m. This was because the log unit length 0-7.2 m was formed during the juvenile growth phase in which growth in the lower stem was higher compared to the declining growth rates in the upper crown of the old mature stem in which the 7.2 -16.8 m log unit was formed. Complementing the exponential stem growth during the juvenile growth phase was apparently an associated high rate of branch development to sustain the high carbohydrate demand in the tree’s physiological system. Better quality sites support higher growth rates in both the stem and in branches, hence the mean knot diameter in SQ_1 was greater than that of SQ_3.

The mean knot diameter in this study decreased with increase in height both along every selected log piece and along the cumulative merchantable stem length. The mean knot diameter increase trend observed in the study was consistent with the mean diameter growth increase trend of the same trees within the same treatments. Branch diameter growth and resultant knot diameter size were positively correlated to stem diameter growth. As growth resources including space become more available due to the two stage thinning, conventionally thinned trees developed branches with larger diameters than single thinned trees. This agrees with what is mentioned in Ikonen *et al (*2003) and Hein (2008) that knot sizes are closely related to branching which is also closely related to the amount of space the canopy has for a tree’s branches to grow in size. This means that thinning result in large branches, which take longer to occlude resulting in large knot diameters.

5.2.2 Sound to unsound ratios

Conventionally thinned stands had more sound knots compared to single thinned stands, a finding which is in line with the findings of Ballard and Long, (1988) and Moberg (1999) in which they found that trees in a wider espacement retained live branches for a longer period and hence had higher frequency of sound knots in their sawn timber than the trees in a narrower spacing. However, although single thinned stands had more unsound knots than conventionally thinned stands, their knots were comparably quite smaller. This is in line with the studies of Ikonen *et al* (2009) and Liziniewicz *et al* (2012) in which trees in denser espacements produced thinner branches and by implication also produced smaller knots if their merchantable stems were to be sawn into timber. The percentage of sound knots for trees in this study increased with height. These findings agree with the studies of Barszcz and Gjerdrum, (2008) in Norway spruce in which they presented in their research that knot healthiness is correlated to the location of the knot on the stem. In the Barszcz and Gjerdrum (2008) study, the largest percentage of sound knots, which also were the biggest sized knots, occurred within 60 to 90 percent of the merchantable stem length similar to this study, in which the majority of the sound knots were found in the 0-7.2 m long log unit.

Irrespective of the higher ratios of unsound knots to sound knots in single thinned stands when compared to conventionally thinned stands shown in this study, single thinned trees had smaller knots which by implication would cause less percentages of persistent grain distortion. This is because small branches develop small knots which comparatively take less time to occlude with clear timber after pruning compared to larger branches. This finding is supported by findings from Kotze, (2004) that after pruning is done, a sheath of new growth forms quicker over the stub when the braches are smaller. According to Smith *et al* (1997), the more the wood that is produced after the stubs are covered, the more the knot free timber is of superior strength, superior quality and of a higher market value based on end use, compared to the wood with the stub inclusion.

CHAPTER 6 CONCLUSION

This study concludes that the response variables mean stand volume, mean individual tree volume and quadratic mean DBH were driven by interaction of factor site quality with factor pruning-thinning combination. Response variables for knot property (mean knot diameter and sound to unsound ratio) were driven by the interaction of factor pruning-thinning-site quality combination and factor log unit position on merchantable stem. There was also some statistically significant evidence that relative knot diameter was affected by the interaction of treatment factors.

Conventionally thinned stands had larger mean DBH compared to single stage thinned stands at the age of 14 years. The difference in the mean individual tree volume of trees in a conventionally thinned stand was significantly different from that of the mean individual tree volume of trees in a single stage thinned stand on both site qualities. On average conventionally thinned stands had between 0.02 m^3 (SQ_1) or 0.03 m^3 (SQ_3) more mean individual tree volume than single thinned stands at the age of 14 years.

Single thinned stands had a higher standing volume at age 14 years compared to conventionally thinned stands owing to a higher standing density which overturned the DBH and mean individual tree volume deficit trend that single thinned trees had shown compared to conventionally thinned trees. Exceeding the standing volume of conventionally thinned stands by 26.1 m^3/ha (SQ_1), present the single thinned stands as having more standing volume than the conventionally thinned stands at age 14 years.

The mean knot diameter for the log unit ranging in length from 0-7.2 m in conventionally thinned stands was on average either 0.36 cm (SQ_1) or 0.30 cm (SQ_3) larger than the mean knot diameter for the same range log unit 0-7.2 m in single thinned stands. Higher up the merchantable stem, the mean knot diameter for log unit of length range 7.2 -16.8 m in conventionally thinned stands was on average 0.27 cm larger than the mean knot diameter for the same range log unit 7.2 -16.8 m in single thinned stands in SQ_1. In SQ_3, the difference in the mean knot diameter for log unit 7.2 -16.8 m in both treatments was not statistically significant (p value 0.99).

The merchantable stems of trees conventionally thinned contained a higher share of sound knots (76 % for SQ_1 and 74 % for SQ_3) compared to that of merchantable stems of trees single thinned (68 % for SQ_1 and 69 % for SQ_3 respectively). This finding was consistent with stands that received conventional pruning. Irrespective of the thinning regime a stand was subjected to, the timeous execution of pruning is important in maintaining a sound to unsound ratio that has a higher percentage of sound knots.

Based on the findings of this study, it is hereby concluded that at the age of 14 years, the single thinned regime at stand level, has more standing volume compared to the conventionally thinned regime. Due to the fact that the difference in the sound to unsound ratios of the single thinned stands and that of conventionally thinned stands was not statistically significant, there was no evidence in this study that the knot property of the single thinned regime is worse off than that of the conventionally thinned stands.

In light of the potential high standing volume of the single stage thinning regime, this study recommends further tests on the density and stiffness of the timber from the single thinned regime to determine if there are any underlying significant differences in these inherent qualities of timber between the trees in a single thinned stand and the trees in a conventionally thinned stand. It is also recommended that a follow up data collection on trees of the treatment $P_4T_{2.}SQ_3$ be done when the trees of treatment $P_4T_{2.}SQ_3$ have reached the age of nineteen (19) years so that a comparison of the growth and knot properties would be made across the treatments without reducing the age to 14 years.

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