
Modelling the influence of stocking on longitudinal and radial variation in wood properties of *Pinus radiata* on a warm Northland site

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Branislav Zoric

The New Zealand School of Forestry
University of Canterbury

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ABSTRACT

The objective of this study was to determine how final stocking influences tree growth and radial and longitudinal variation in wood properties at a *Pinus radiata* D. Don plantation located at one of the warmest forest sites in New Zealand, Forsyth Downs forest in Northland. This thesis addressed both the effect of stocking on stand basal area, height, diameter and branch diameter and the effect of stocking on wood properties microfibril angle (MFA), module of elasticity and density. Finally, how ring width influences wood properties and whether this variable accounts for the treatment effects was investigated.

Stocking, height and ring number and all interactions between these variables significantly affected ring width. Ring width by itself was significant as a predictor of density, but when it was combined with other class level variables it was insignificant (i.e. does not account for treatment effects), and it did not add anything to a model with only class effects. There was a significant impact of ring number on density while ring width was insignificant in the same model.

MFA was significantly affected by ring width, height and ring number in the tree, and all interactions, apart from the three way interaction, but not by stocking. Ring width was significant in the MFA model both by itself and when it was combined with other variables. Ring width accounted for the stocking effect.

The best model of MOE included the class level effects of stocking, height and ring number within the tree, and all interactions between these variables, and ring width, as a continuous variable. While there was a significant effect between stockings this was relatively weak compared to the other main effects. Ring width largely accounted for the effect of stocking, but not that of ring number, or height.

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CHAPTER ONE

GENERAL INTRODUCTION

INTRODUCTION

Intensive forest management requires developing and planting the best trees, understanding and improving the crop and the site, increasing productivity, creating value in the right place with the right technology and at the same time satisfying customer requirements. Selection of an appropriate initial and final stocking is a very important determinant of the final crop product outturn and value.

Many previous studies around the world have found an increase in modulus of elasticity as stocking increases; for example for *Cryptomeria japonica* (Wang and Ko, 1998), *Tsuga heterophylla*, *Picea sitchensis* (Wang *et al.*, 2001), *Picea mariana* (Zhang *et al.*, 2002), and 11-year-old *P. radiata* (Lasserre *et al.*, 2004). A study in a Canterbury forest site has shown that increasing initial stocking from 833 stems/ha to 2500 stems/ha increased stiffness in the first 10 growth rings by 40% (Lasserre *et al.* 2004). Research shows that there is no interaction between stocking and clone, at a number of sites (Lasserre *et al.*, 2008), indicating that gains achieved through use of high stockings and improved clonal material may be additive.

The Tikitere spacing trial was assessed at age 21 by MARVL (Maclaren and Knowles, 1999a). This study found that greater volumes were produced at higher stockings, also volumes of small branched saw logs were much more abundant at higher stockings.

In a spacing study of Sitka spruce it was found that planting distance at establishment affects structural performance of timber including log grade, knot number and knot size, and the proportion of juvenile wood; all are negatively affected as planting distances increase. (Brazier and Mobbs, 1993).

Forest companies plant a greater number of trees than are required for final crop stocking to ensure good selection, full site occupancy and particularly for *Pinus radiata* to exercise greater control over tree form (Valentine, 1970), and branch diameter. Felling

of inferior trees down to a range of final crop stockings is undertaken to improve form and vigour of residual crop trees (Maclaren, 1995).

Currently, waste thinning occurs between 5 and 11 years across the forestry estate in New Zealand; anything in excess of 11 years is usually for production purposes. Naturally, there is a fine balancing act between timing of thinning, allowing greater certainty in selecting dominant future crop trees and minimising operational costs and potential damage to residuals. Earlier thinning operations have the added benefit of increased potential growth gains in the residual crop trees, rather than the greater amount of waste wood and delayed or decreased potential production gain one associates with later thinning operations. Delayed production (commercial) thinning can also leave the stand more vulnerable to wind damage. However, early thinning can increase the size of the juvenile core and branch diameter. Somerville (1989) found more damage occurred during storms with lower stockings. Also at the Tikitere trial, wind damage increased with lower stocking (Knowles *et al.* 1999b).

Much information has been collected on the effect of the initial and final stocking on individual tree growth but very little on the effect of the final crop stocking on wood quality at different stockings (Whyte and Woollons 1990, Woollons and Whyte 1994, McKinley *et al.* 2000). Although many growth functions have been developed based on measurement data over time wood characteristics are rarely included in these models.

In the past, log diameter served both as an indicator of likely sawn conversion rates, and stress grading conversion rates. Larger logs were assumed to have more mature wood of higher stiffness, so size became a surrogate for stiffness. However, there are many situations where a smaller log can be of higher quality than a large one, through improved stiffness. Currently, log price/log diameter differentials are used to model the trade-off between maximising stand volume, and increasing average tree (log) sizes in the stand under varying thinning regimes, because New Zealand forestry managers are not able to differentiate the wood properties values in the existing yield, cutting strategy and price models.

Wood density is often considered the best indicator of quality for many species, including *P. radiata*, with density levels generally matched to quality for the end use, particularly those involving structural applications and fibre recovery (Bamber and Burley

1983; Walker, 2001; Xu and Walker, 2004). Because of the importance of wood density in radiata pine, substantial historic data is available documenting variation in density within and between trees, and in relation to site, silviculture and genetics, (Harris, 1965; Cown *et al.*, 1991; Cown, 1999). The broad wood density database for *P. radiata* established by Scion Ltd over many years has enabled the development of effective sampling procedures to map wood density variation within a resource (Kimberley and McConchie, 1997) and the development of a wood density prediction algorithm. Other important wood properties particularly spiral grain, tracheid length, microfibril angle (MFA), internal checking have been measured much less intensively and the national trends are neither documented, nor predictive algorithms available (Treloar and Lausberg, 1995). Additionally, site types, silvicultural practices and breeds have changed dramatically since the early wood density surveys were completed.

Two of the most important wood properties include density and MFA. In combination these properties determine modulus of elasticity (MOE) of wood (Walker and Butterfield 1996). The properties MFA and MOE are the wood characteristics that have most influence on end use value.

The MFA of wood is strongly linked to the length of the tracheids that comprise the wood. For a pulp and paper mill, this has a significant influence on the quality of pulp and paper, and this is readily valued, as pulp and paper grades are strongly related to pulp or paper quality (Kibblewhite 2004). MFA also influences the longitudinal shrinkage of wood and so affects wood stability (Walker, 2006). This is of value to the forest owners and wood processor through reduced downgrade of lumber (Harris, 1977; Donaldson, 1995). There are no tools and measurement protocols to measure the MFA of logs or trees directly in an operational situation.

The generally low MOE of logs in the New Zealand *P. radiata* resource is a major limitation to profitable processing of the resource. MOE is most highly valued in structural lumber as the lumber grades are priced according to the MOE of the lumber. There are significant price differentials for lumber based on MOE, particularly around the threshold values for MOE that distinguish acceptably stiff lumber from lumber that is not stiff.

A lot of analyses and experts all suggest that in "normal" grading systems like F or MSG (which are very similar, the main difference being that MOR specs of MSG are lower than in F system that was developed for hardwoods) that 8 GPa clearwood begins to separate non-structural from potentially structural zones of the sawlog (Table 1.1). In addition to MOE the MSG grading system is also sensitive to branch diameter.

Table 1.1 Minimum requirements for MSG structural lumber grade

MSG Grade	Min. MOE (GPa)	Targeted MOE (GPa)	Indicative Max Knot (mm)	Indicative Log SED (mm)
Pulp	n/a	n/a	n/a	100
Industrial	n/a	<4	<140	100-200
MSG6	4	6	<140	200-300
MSG8	5.3	8	<60	300-400
MSG10	6.7	10	<60	300-400
MSG12	8	12	<60	300-400

Wood stiffness or longitudinal modulus of elasticity (MOE) is one of the most important wood properties for solid timber applications (Evans and Ilic, 2001). Modulus of elasticity measures the resistance of a material to deflection, with the average MOE of *P. radiata* increasing with tree age. This occurs as a result of the MOE increasing rapidly with increasing cambial age or ring number from the pith. Corewood has lower and often unsatisfactory levels of MOE. For several reasons, including faster growth due to better silvicultural and genetic quality, rotations in New Zealand have become shorter, all of which increases the proportion of corewood within a tree thus affecting the quality of the timber produced (Jayawickrama, 2001).

The importance of management in manipulating corewood properties such as MOE has been demonstrated. Recent research has shown that initial stand spacing and genetics have an affect on corewood properties (Lasserre, 2005; Waghorn 2007). The corewood zone is recognised as being of inferior quality for numerous end-uses, in particular, solid timber applications and is aggravated by a much greater variability that

arises from the rapidly changing properties within the corewood itself (Huang *et al.*, 2003). However, if clones are selected for improved stiffness and then coupled with optimal silvicultural practices for higher stiffness, then stiffness of the corewood region can be increased.

Initial and final stand spacing can have a major influence on stem characteristics and intrinsic wood properties including MOE (Lasserre, 2005). Lasserre *et al.* (2007) found how MOE, MFA and density vary with stocking in *P. radiata* trees on Canterbury site at age 5. MOE has been found to increase 34%, from 2.6 GPa to 4 GPa while MFA decreased 18% from 38° to 31° across stocking gradients from 833 stems/ha to 2500 stems/ha. Also there was no significant relationship between basic density and stocking. These trends in MOE across a stocking gradient were confirmed in 17 year old trees growing on the Canterbury plains (Waghorn *et al.*, 2007).

However, the occurrence of these poor corewood characteristics at lower stocking rates has not halted the decline in stocking rates over past decades or recent years. Final stocking and time of thinning may affect MOE in numerous ways. Mason (2001, 2005) has indicated that “Tree sway, canopy height, radial growth rate and stem slenderness or taper are all possible mechanisms regulating MOE development that stand spacing may influence”. By assessing how stand spacing impacts on MOE, and determining how the above factors dictate MOE formation, forest managers will be provided with valuable information allowing for the determination of optimal final spacing that will allow for greater control of MOE by silviculturalists.

Coupled with stand spacing, another method to improve plantations is genetic improvement. In 1953 an intensive *P. radiata* breeding programme commenced with emphasis placed upon improvement in growth rate and stem form. A further breeding programme also started in the late 1960s with selection emphasis placed on longer internodal length to produce an increased proportion of clearwood (Wilson and Carson, 1990). The main breeding effort was established in 1987, in which a rating system was designed to rank seedlots for genetic quality. The rating system is based on growth and form (GF), where a higher improvement rating assures greater genetic improvement (Burdon, 1995). New Zealand’s *P. radiata* genetic improvement programme has been shown to deliver large gains in traits such as diameter and volume, straightness, log

quality and branch cluster frequency (Jayawickrama, 2001). Although it has been found in genetic gain trials that higher GF rated stock has better attributes (Wilson and Carson, 1990), little is known about differences in key wood properties such as stiffness between different genetic materials. “Therefore, wood properties have become a major thrust in New Zealand’s *P. radiata* breeding programme due to a realisation that there will be significant benefits in having improved wood properties in future forests (Sorensson *et al.*, 1997). The present future in genetics of *P. radiata* is clonal forestry, which has great potential advantages for increased genetic gains and crop uniformity, but has inherent risks, in that it results in reduced genetic diversity through large-scale clonal propagation”.

Moreover, many researchers believe that the economic importance of rising overall wood stiffness becomes more important as either rotation age decreases, or stockings increase. Under either scenario log diameter decreases which increases proportion of the corewood in both the butt and second logs.

Recent research has shown the strong influence of environment on MOE. In particular MOE appears to be positively related to air temperature through a direct influence on MOE and an indirect positive influence on stem slenderness, which in turn, is positively related to MOE (Watt *et al.*, 2006). A number of spacing trials have been dissected in cooler climates such as Canterbury (Waghorn *et al.*, 2007, Lasserre *et al.*, 2005). These studies strongly illustrate the positive influence of final crop stand density on MOE. However, they also show that there is limited potential on these sites to improve the yield of corewood structural grade, as corewood values of MOE at even high stockings are still below MSG thresholds. Little research has replicated these sort of studies in warm locations in New Zealand where it is more likely that high stockings will result in structurally acceptable wood within the corewood zone.

AIMS AND SCOPE OF THIS THESIS

The general objective of this study was to determine how final stand density influences wood properties and growth in a clonal *P. radiata* plantation (GF7) located at one of the warmest forest sites in New Zealand at Forsyth Downs forest in Northland.

The specific objectives are:

- a) To determine how stocking influences growth from age 5 to age 24 years at stockings of 200 stems/ha, 350 stems/ha, 500 stems/ha and 1100 stems/ha;
- b) Determine how stocking influences longitudinal and radial variation in wood properties (density, MFA, & MOE);
- c) Develop models of wood properties, which account for radial and longitudinal variation and variation attributable to stocking;

Experiment Location

The experimental site was located at Opouteke Forests (Forsyth Down) approximately 55 km west of Whangarei and around 40 km north of Dargaville (latitude 35°41.5'S, longitude 173°50.1'E, altitude 370 m a.s.l.).

Description of trial

This study was carried out on data from an experiment established by the ex. Carter Holt Harvey Forests. The thinning trial was situated at Forsyth Downs, Mangakahia District of ex Carter Holt Harvey Forests Ltd. in the Northland region. The experimental site was located on a north east aspect at an elevation ranging from 350 to 385 m and slope between 5° and 15°. The site was on Waimatenui clay soils of moderate to high fertility with an average rainfall of 1,180mm per year, with most rainfall occurring during winter (42.5 % of the annual rainfall occurs between May and August). The driest months were January and November, averaging 5% and 6% of the annual rainfall respectively. Dry spells (period of 15 days or more having less than 1 mm of rain per day) may occur during summer and early autumn.

The mean annual temperature at Forsyth Downs is 14.7°C (Moir *et al.* 1986). When compared to the national plantation site range of 8.0 to 15.6°C (Watt *et al.*, 2005) this forest has one of the highest mean annual temperatures in New Zealand. January and February are the warmest months with the mean temperature averaging 19°C, and July is the coldest month (mean monthly temperature of 10°C). Daily temperature variations were minor, with few extremes of temperature or frosts (Moir *et al.* 1986).

The previous land use at this site was pastoral. Establishment practices following planting included, spot spraying with Velpar for grass control and hand fertilising with elemental phosphorus as super phosphate at a rate of 10 g per tree.

The area was planted in winter 1982 at an initial stocking of 1,667 stems/ha (2 × 3 m) with *P. radiata* seedlings from GF 7 stock and thinned in 1987 (5 years) to 200, 350, 500 and 1,100 stems/ha. Diameters of all stems were measured at breast height (1.4 m) prior to thinning. Trees were thinned from below.

Measurements were undertaken on an annual basis until age 16 and four years later at ages 20, 23 and 24 for diameter at breast height and tree height (random sample over the diameter range) for all residual stems in the experimental plots. Data have been stored in the Scion PSP database.

Thesis Strategy

This thesis comprises five chapters.

Chapter One provides a general introduction and some review of literature, with a particular focus on the effect of stand densities (initial and final crop stocking) on wood properties.

Chapter Two examines the effect final crop spacing has on stand growth characteristics of *P. radiata* in Forsyth Down. Physical properties assessed include basal area, height, diameter, and branch diameter. The second aim of Chapter Two is to develop predictive models of diameter, height and basal area sensitive to spacing to determine how growth progresses at this site over time, and the point at which growth asymptotes are attained.

Chapter Three assesses the effect that final spacing has on wood properties of *P. radiata*. This chapter considers how MFA, MOE and density are affected by the main and interactive effects of ring number, height and stocking. This chapter also examines the potential for cutting structural grade timber within the corewood at high stockings.

Chapter Four assesses how the continuous variable ring width influences wood properties and specifically whether there are significant treatment effects remaining after the effect of ring width has been accounted for.

The final Chapter presents concluding remarks, integrates the findings from previous chapters to determine optimal stocking at this site, and suggests further research that could be carried out. As well as highlighting the key findings of this thesis, chapter five also places the results in a wider context, and discusses possible future directions of the modelling work.

CHAPTER TWO

ASSESSING THE EFFECT OF DIFFERENT STOCKINGS ON STAND GROWTH OF 24 YEAR OLD PINUS RADIATA IN NORTHLAND

2.1 INTRODUCTION

Over the last ten years there has been extensive research examining the effect of final crop stockings on stand growth of *P. radiata* in New Zealand. The stocking trials of J. Shirley and D. Elliott were analysed by Whyte and Woollons in 1990. The following conclusions were made from the analysis of the older spacing trials:

- a) Basal area growth up to age 24 increased with residual stocking up to 700 stems/ha;
- b) Gains in average diameter for 200 stems/ha stockings were not likely to be as marked as earlier predicted by researchers
- c) Mean top height increasing with stocking

The Forsyth Downs trial was analysed by Woollons *et al.* (1994). The age 12 results clearly supported those of Whyte and Woollons (1990). The 350 stems/ha stocking appeared to grow as well as the 500 stems/ha, but the 200 stems/ha showed marked depression in growth, and was growing along a markedly different growth curve. In 1998 the Forsyth Down trial was analysed by Elaine Wright. At the time of analysis the age of the trial was 16 years. While the trials were too young to obtain conclusive results the preliminary trends did not conflict with the earlier findings of Whyte and Woollons (1990).

The combined results of the spacing trial analysis indicated that with a stocking below 300 stems/ha, stand volume growth was markedly depressed. There seemed to be

insufficient trees on the ground to make full use of the site. While the remaining trees grew to a slightly larger size, this effect was quite small, and in no way compensated for volume losses due to lack of growing stock. From all the research the final crop stockings seem to fall into three natural groupings;

- a) Less than 300 stems/ha where site occupancy was not fully utilised
- b) Between 300-500 stems/ha where site occupancy was occurring and there was a reasonable trade-off between piece size and volume growth
- c) Over 500 stems/ha where there is a reduction in tree diameter that could comprise the amount of timber that would be acceptable for structural or pruned grades.

The cut-off between these three groups was arbitrary and in fact may be different for different sites. At that stage there was insufficient evidence to suggest that they were different for different sites, but the majority of these trials are now older and there is an excellent opportunity to reassess them to recognise the growth asymptotes more accurately.

Following the past research the objective then becomes, what is the stocking that allows forest companies to cut a large fraction of the log into high value structural grade, with a large proportion of MSG8, and most of the pith cut out to at least MSG6 grade. Growth will have an important bearing on this, as this will affect how many logs can be cut, as there are small end diameter cutoffs for the different grades (e.g. Table 1.1).

The objective of this chapter was to model the growth of the Forsyth Downs trial at age 24 and determine how the growth rate and asymptote scales with stocking for basal area, mean diameter and mean top height.

2.2 METHODS

This study was carried out on data from an experiment established by the ex. Carter Holt Harvey Forests. The thinning trial was situated at Forsyth Downs, Mangakahia District of ex Carter Holt Harvey Forests Ltd. in the Northland region. The experimental site was located on a north east aspect at an elevation ranging from 350 to 385 m and slope between 5° and 15°. The site was on Waimatenui clay soils of moderate to high fertility with an average rainfall of 1,180mm per year, with most rainfall occurring during winter (42.5 % of the annual rainfall occurs between May and August).

The Forsyth Downs trial was a randomized block design, with 4 treatments and 4 replicates on 16 plots with an inner measurement area of 0.1 hectare per plot.

At age 5, sixteen 0.4 ha plots were overlaid using a randomized block design, with four treatments and four replicates. *P. radiata* (GF7) was planted on high fertility clay in 1982 at 1,667 stems/ha and thinned (from below) in 1987 to 200, 350, 500 and 1,100 stems/ha. Diameters of all stems were measured at breast height (1.4 m) prior to thinning. Measurements of diameter at breast height (dbh) were undertaken on an annual basis until age 16 and at ages 20, 23 and 24. Diameter at breast height was measured on all trees. Tree height was measured on a random sample of 15 trees over the diameter range in each plot. Data have been stored in the Scion database.

Thinning experiments are difficult to analyse thoroughly. Problems arise because different densities are deliberately created at the outset of the trial. Multiple measures usually unevenly spaced in time are subsequently obtained from the experiment.

“Consequently analyses of variance are essentially irrelevant because of the very nature of the treatments, and covariance is compromised in that post thinning covariates will be strongly correlated with treatments. Efficient analysis can be obtained by modelling growth data through time by use of sigmoid functions or orthogonal polynomials then analysing the respective coefficients by ANOVA or discriminate techniques”. (Woollons, 1994).

In order to accommodate the difficulties identified by Woollons the following analyses were applied to the trial. The sigmoidal Chapman Richard model was fitted to plot level data of diameter, height and basal area. Bias was determined by examining plots of residual values against predicted values and against independent variables. Equation parameters were examined, and plotted against stocking to identify trends.

The Chapman Richard equation was used in the form as follows:

$$y = a(1 - \exp(-\beta x))^\gamma \quad [2.1]$$

Where y is diameter at breast height (dbh), height or basal area, x is age, a is the asymptote and β and γ the growth and shape parameters.

Petterson height equation coefficients were calculated for each measurement age in each plot and used for the mean top height calculation based on the diameter data. The Petterson equation was as follows:

$$H = 1.4 + (b + a/dbh)^{-2.5}$$

2.3 RESULTS

Diameter at breast height (DBH)

After examination of the actual diameters by treatment, diameter was modelled by many anamorphic, polymorphic and yield functions using non-linear regression. Of the polymorphic, anamorphic and yield functions tested, the Chapman Richard yield equations showed one of the highest precision in fitting maximum and mean diameters at breast height data. Chapman Richard equation had normal, unbiased residuals distribution and therefore was chosen for further modelling.

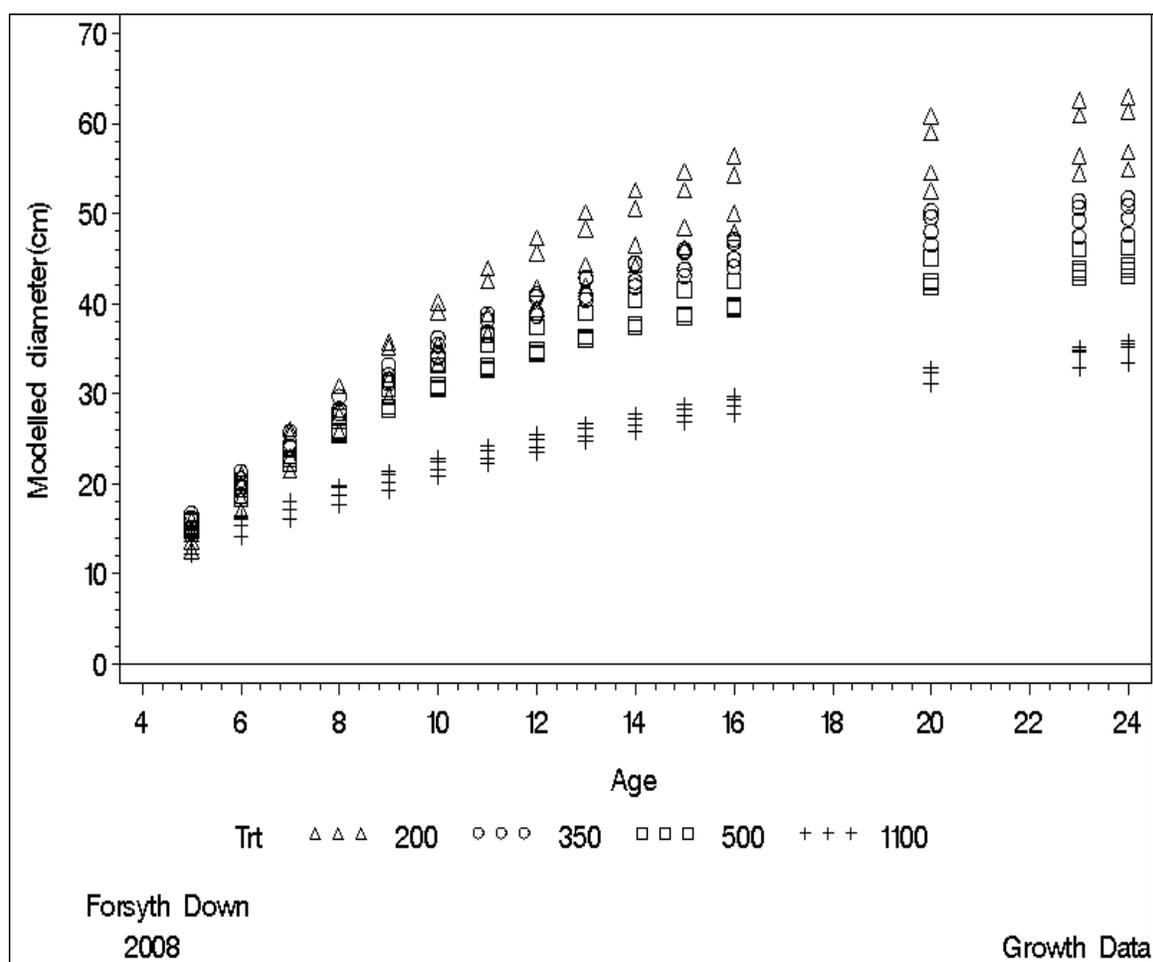


Fig. 2.1. Modelled plot level diameter plotted against age and stocking; 200 stems/ha is shown at the top of the graph followed by 350, 500 and 1,100 stems/ha.

A plot of modelled and measured mean diameter is shown in Fig. 2.2, Fig. 2.3 shows the residuals of the mean diameter models plotted against age by treatment, indicating a reasonably unbiased fit at predicted diameters above 20 cm. Residual standard deviation, variance and standard error mean for the Chapman Richard yield equation were 0.92, 0.85 and 0.059 cm respectively.

At all stockings diameter reached a threshold around age 16 years after which gains were relatively small. Compared to the lowest stocking diameter the highest stocking diameter was reduced by 24 cm or 40%, by age 24. Mean diameters at age 24 were 60, 52, 46 and 36 cm for stocking of 200, 350, 500 and 1,100 stems/ha respectively.

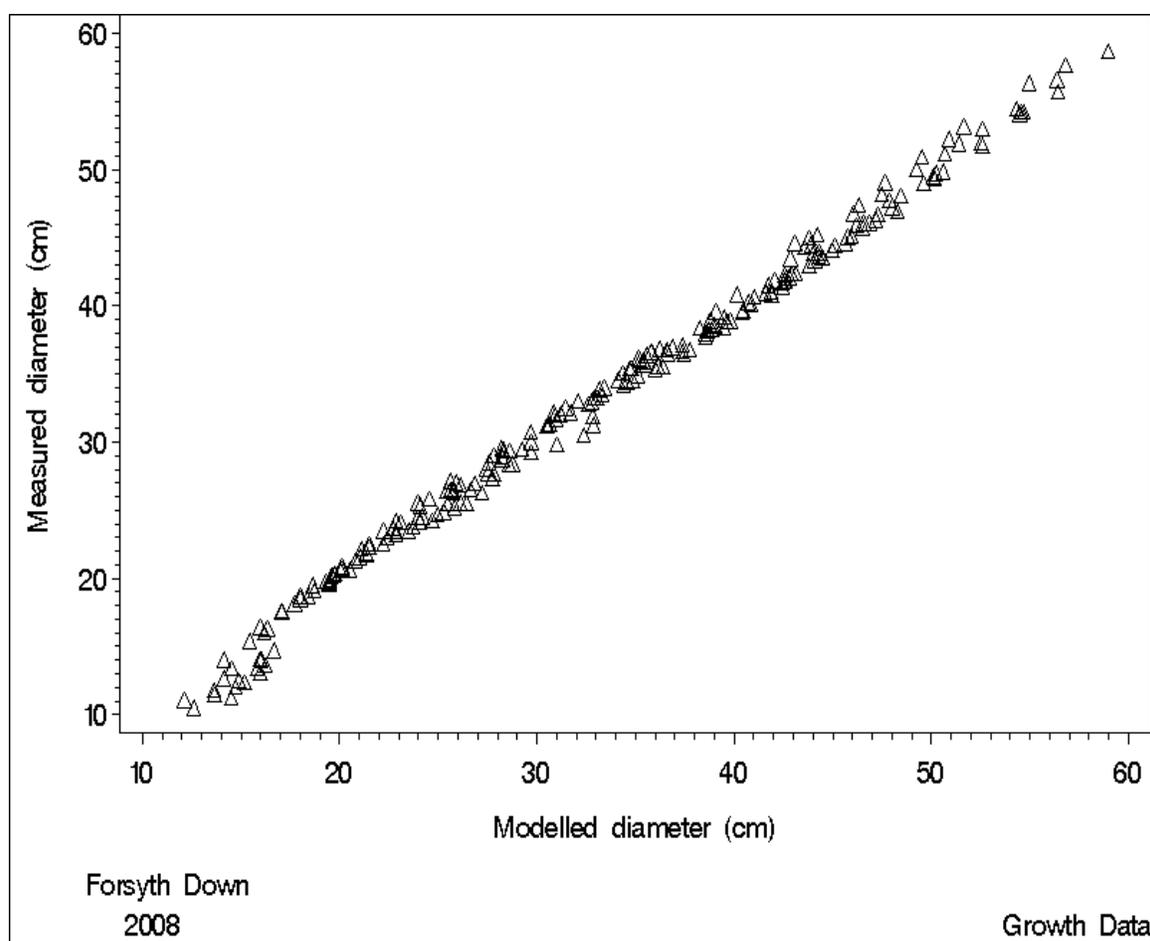


Fig. 2.2. Measured diameter plotted against predicted diameter.

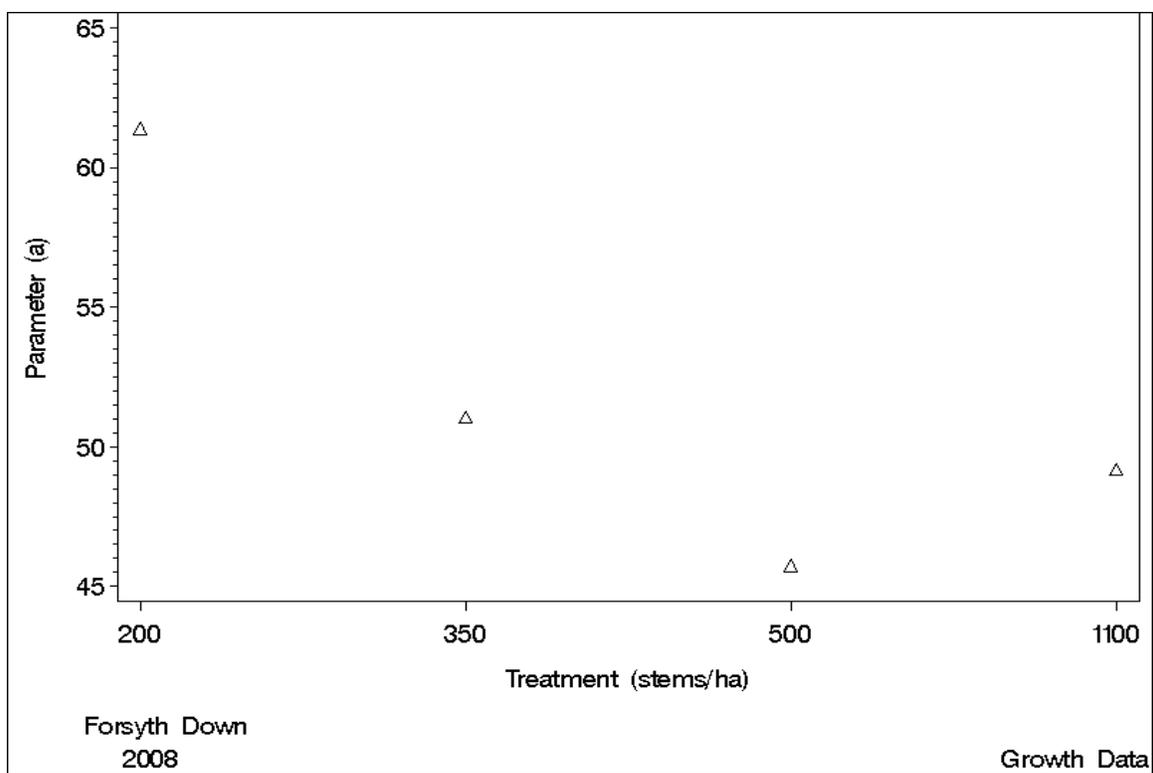


Fig. 2.4. Relationship between the asymptote (α) parameter and stocking.

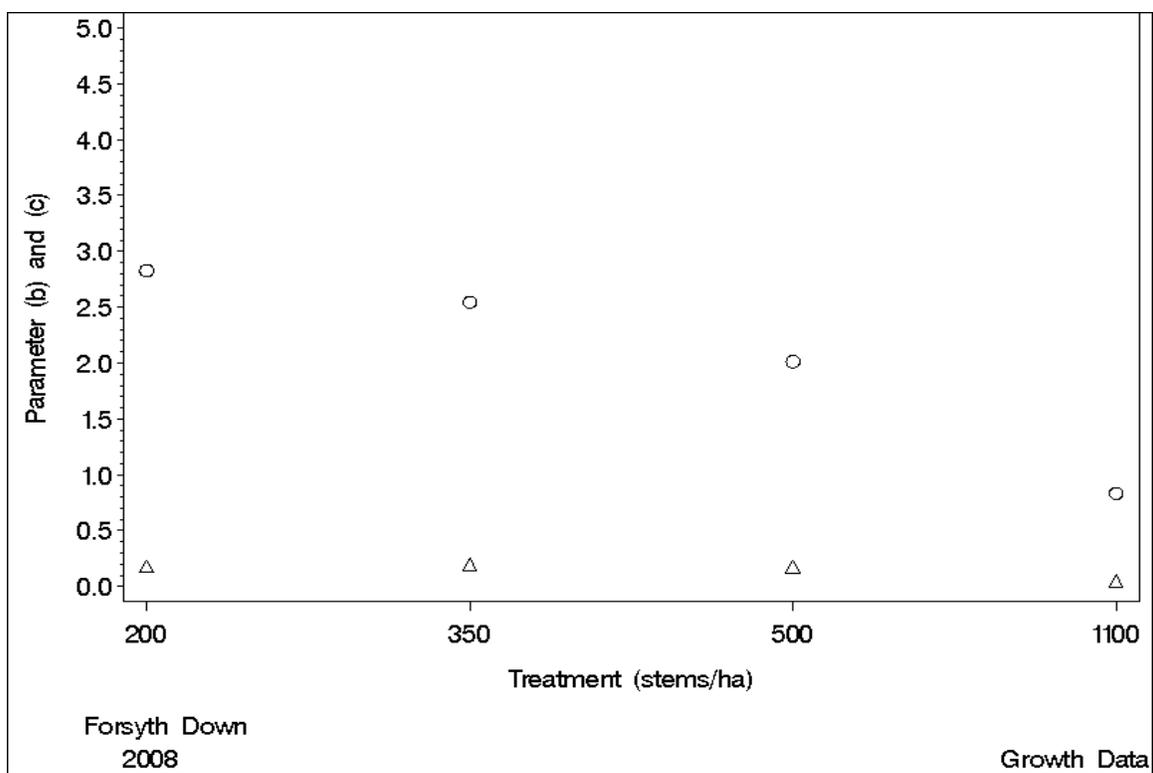


Fig. 2.5. Relationship between growth rate β (circles) and shape γ (triangles) parameters and stocking.

DBH distribution

Distribution models represent the relative frequencies of trees of different sizes within an even-aged stand by means of a distribution. Diameter distributions were described using a reverse Weibull function. Estimation of parameters was achieved by percentile estimators, as functions of mean stand statistics. Treatment tables were developed and treatment statistics of standard deviation (variance), maximum dbh and average dbh were used to convert to Weibull distribution parameters.

The probability density function of the Weibull had the following form:

$$f(x) = \frac{c}{b} \left(\frac{x-a}{b} \right)^{c-1} e^{-\left(\frac{x-a}{b} \right)^c} \quad [2.2]$$

where a , b , and c are the location, scale, and shape parameters of the Weibull distribution, respectively, and x is dbh.

The Figures 2.6, 2.7, 2.8 and 2.9 show the mean top diameter and mean diameter distributions for all treatments at age of 24 and their estimated parameters (Table 2.2).

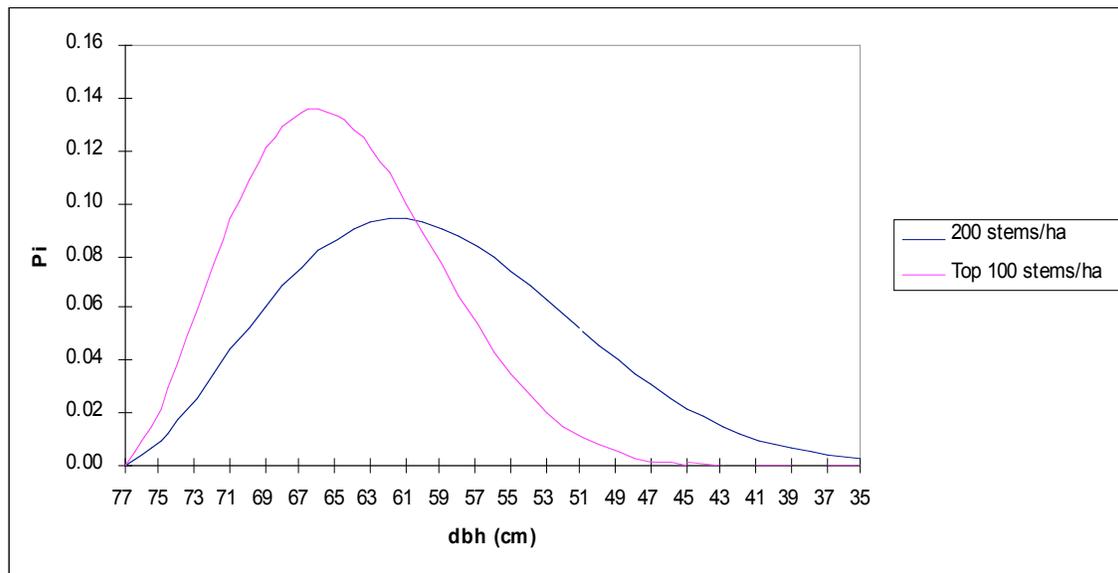


Fig. 2.6. Mean top diameter and mean diameter distributions for 200 stems/ha

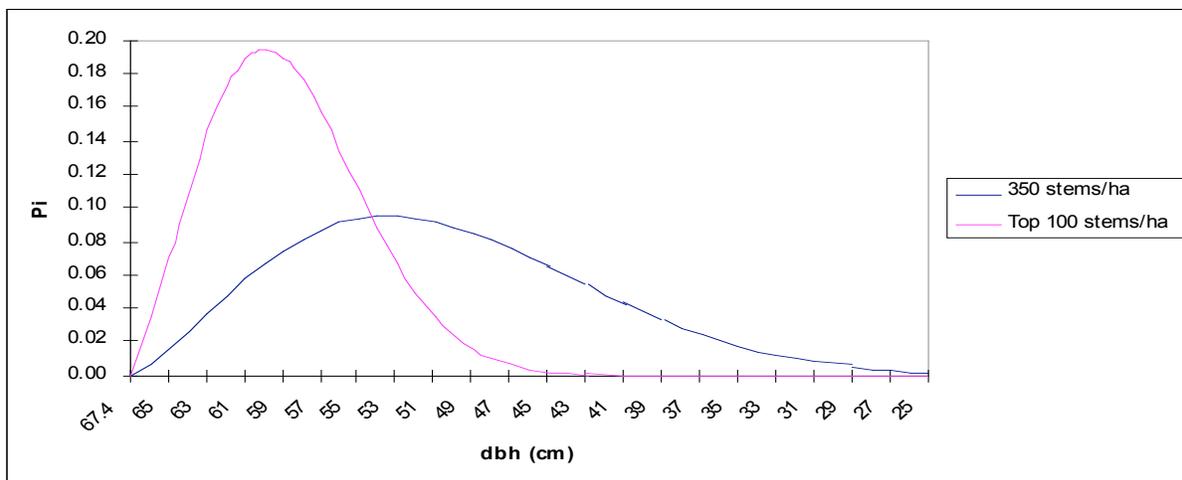


Fig. 2.7. Mean top diameter and mean diameter distributions for 350 stems/ha

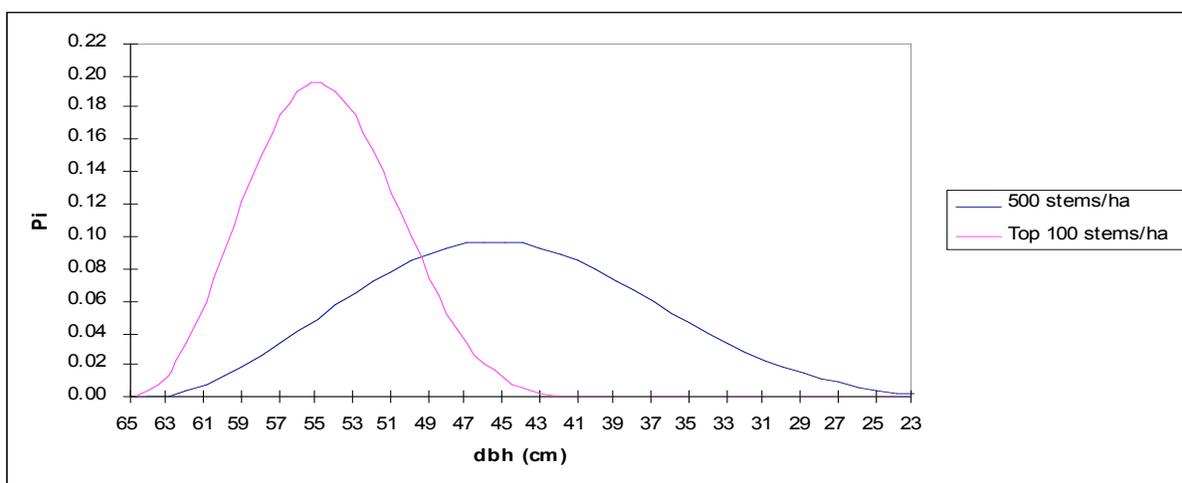


Fig. 2.8. Mean top diameter and mean diameter distributions for 500 stems/ha

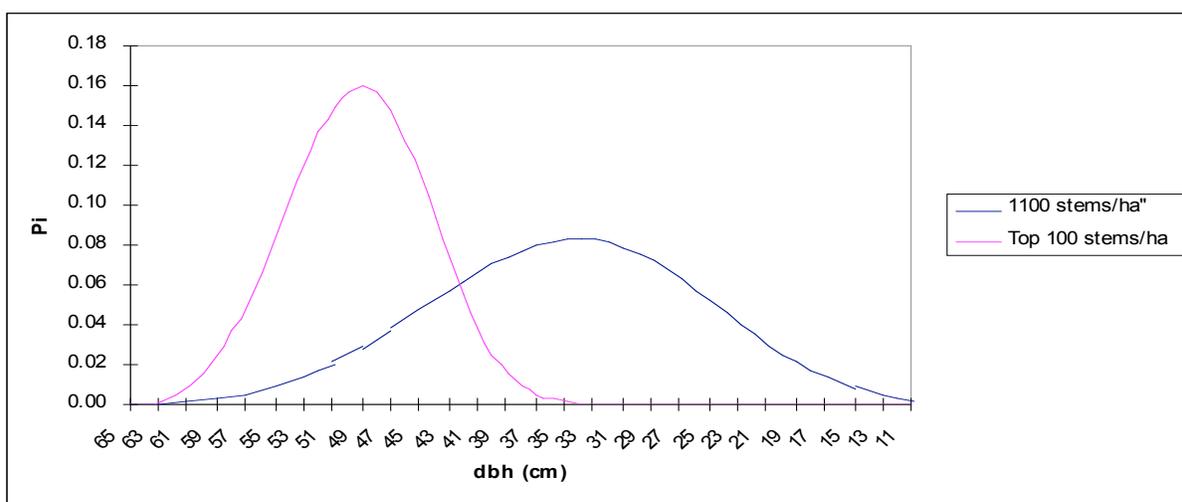


Fig. 2.9. Mean top diameter and mean diameter distributions for 1,100 stems/ha

Table 2.2. Weibull distribution parameters of mean top dbh by stocking, where a , b , and c are the location, scale, and shape parameters

<u>Diameter</u>									
Stocking	Max	Mean	Std D	$\Sigma k_i z^i$	z	$1/c$	a	$\Gamma(1+1/c)$	B
200	77.6	65.5	5.5	-0.20	0.47	0.44	77.6	0.89	19.7
350	67.5	59.6	2.5	-0.19	0.51	0.49	67.5	0.89	18.2
500	65.3	55.5	3.5	-0.21	0.36	0.33	65.3	0.89	10.9
1100	66.1	50.3	4.1	-0.21	0.26	0.27	66.1	0.90	17.5

The time and rate of growth at the inflexion point was analytically determined by dividing logarithmic parameter values. Time at the inflection points were different by one year between each stocking level.

Height

The definition of mean top height used by Scion is that adopted by the New Zealand Institute of Forestry, and given by Goulding (1995): “The height predicted by the Petterson height/dbh curve for a dbh corresponding to the quadratic mean dbh of the 100 largest trees per hectare (based on dbh) in a stand”.

Figure 2.10 shows the relationship between the quadratic mean dbh of the 100 largest trees per hectare and their corresponding heights.

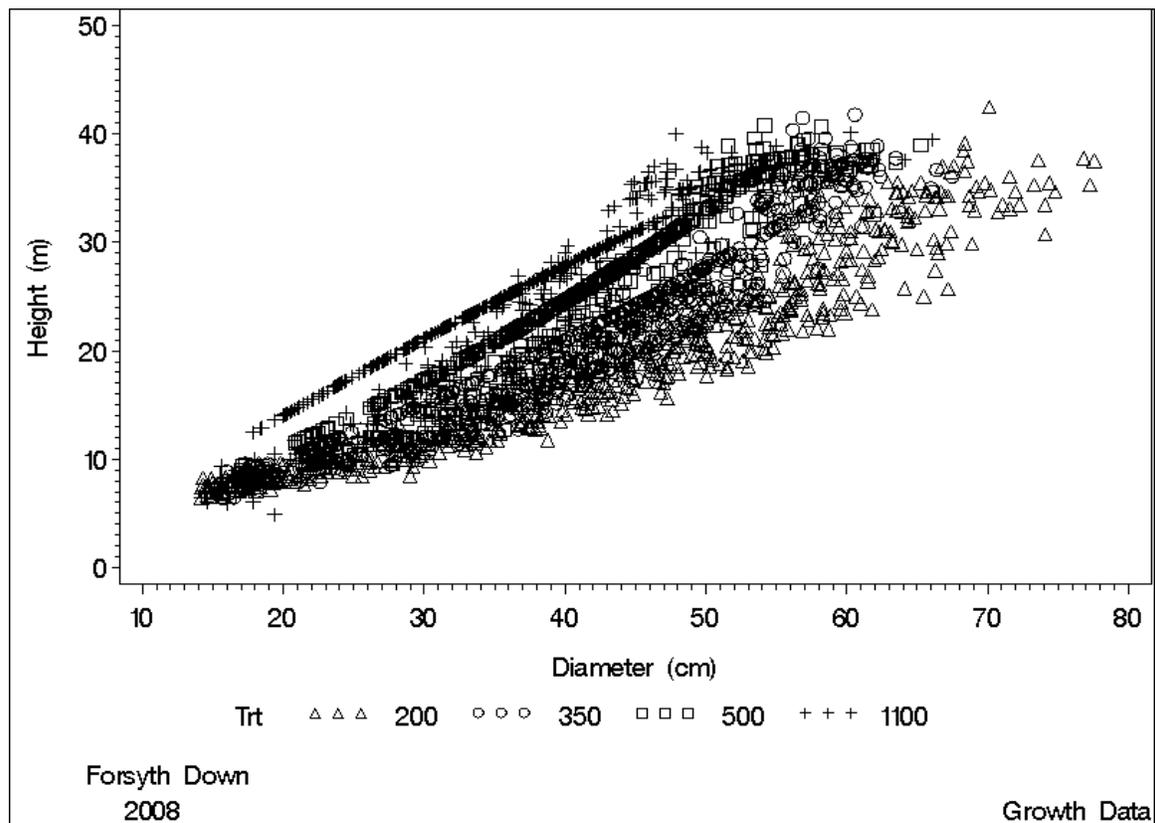


Fig. 2.10. Relationship between the quadratic mean dbh of the 100 largest trees per hectare and their corresponding heights, by stocking.

Petterson height equation coefficients were calculated for each measurement age in each plot and used for the mean top height calculation based on the diameter data. The Petterson equation was as follows:

$$H = 1.4 + (b + a/dbh)^{-2.5} \quad [2.3]$$

Treatments height parameters were a representation of the correlation between height and diameter. Petterson heights were plotted against dbh for each treatment and age.

Table 2.3. Estimated Petterson parameters by stocking at ages 16, 20 and 24

Treatments	Age 16		Age 20		Age 24	
	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>
200	-0.31	0.29	2.16	0.23	3.94	0.18
350	2.72	0.22	1.80	0.22	0.67	0.23
500	4.41	0.17	4.63	0.16	0.84	0.22
1100	2.30	0.21	3.51	0.18	1.63	0.21

Parameter *a* generally increased with age and stocking while parameter *b* decreased. Analyses of variance showed a significant ($P < 0.0001$) age effect for the parameter *b* but the effect of stocking and the age interaction was non-significant. No significant differences between stockings or age were noted for the parameter *a*.

After examinations of the actual heights by stocking, mean top heights were modelled by Chapman Richard equation, which had normal, unbiased residuals distribution and was therefore chosen for further modelling.

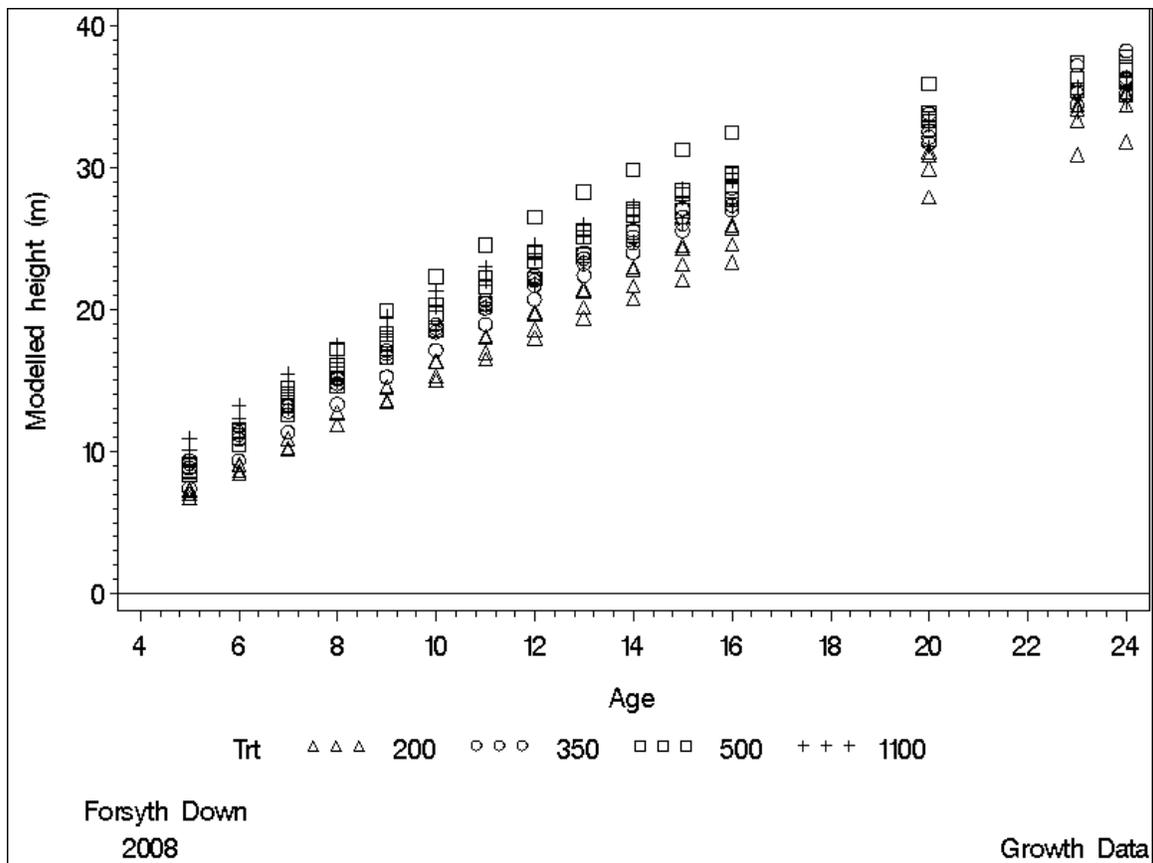


Fig. 2.11. Modelled plot level mean top height data plotted against age by stocking; 500/1100 stems/ha at the top of the graph followed by 350 and 200 stems/ha.

A plot of modelled and measured mean top height is shown in Figure 2.12. Figure 2.13 shows the residuals of the mean top height models plotted against age by stocking, indicating unbiased fit. Residual standard deviation, variance and standard error mean for the Chapman Richard yield equation were 0.528, 0.278 and 0.034 m respectively.

Compared to the highest stocking the lowest stocking mean top height was reduced by 3.2 m or 10%, by age 24. The actual mean top height at age 24 was 35, 37, 38 and 37 m for 200, 350, 500 and 1,100 stems/ha respectively.

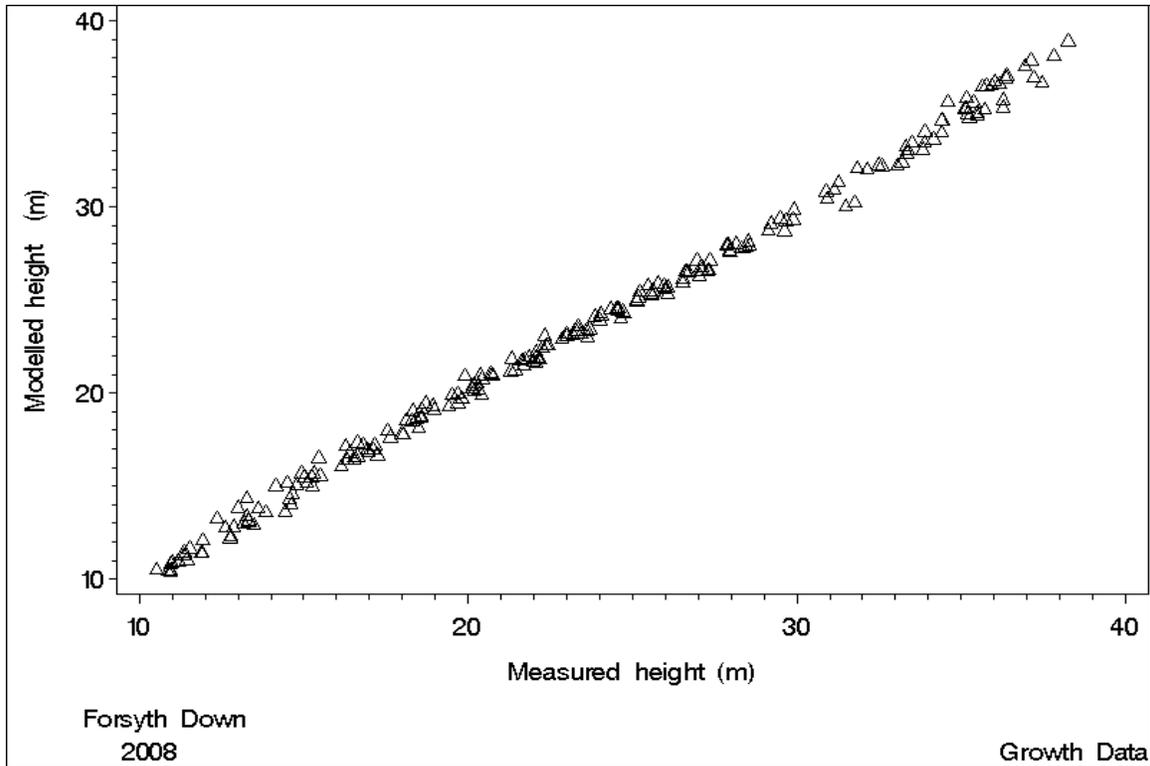


Fig. 2.12. Measured mean top height plotted against predicted mean top height

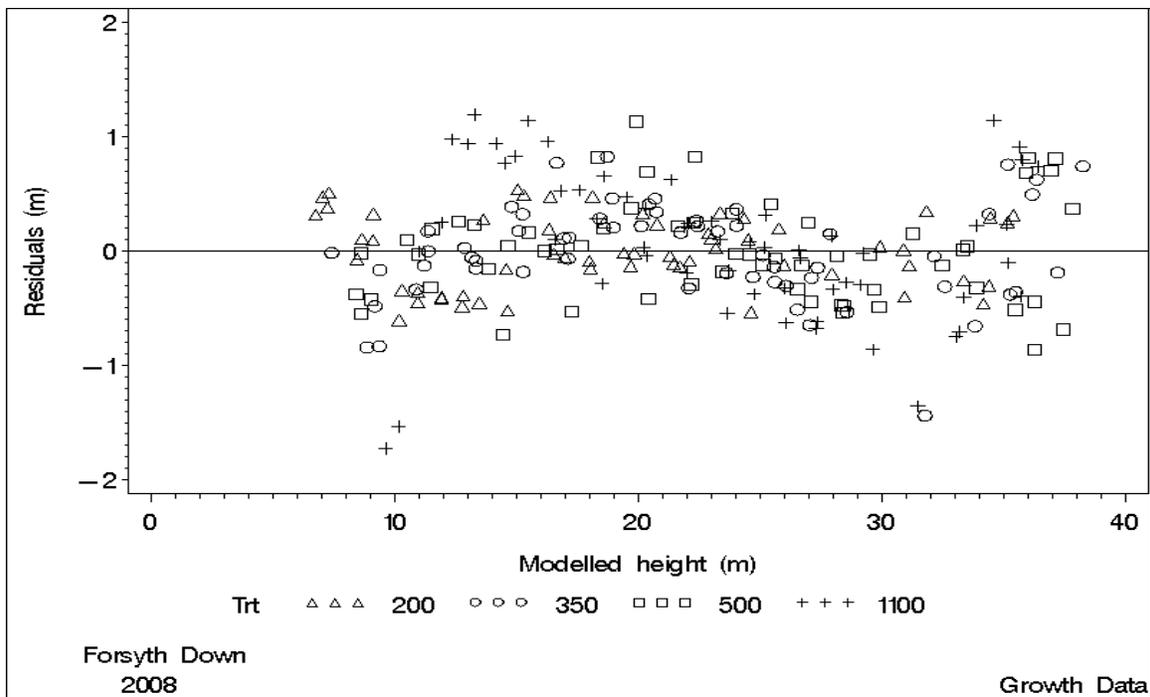


Fig. 2.13. Residuals of mean top height plotted against predicted values by stocking

For mean top height stocking significantly affected the asymptote ($P < 0.0001$), growth rate ($P < 0.0001$) and shape parameter ($P < 0.0001$). Both the shape and growth rate

parameters significantly decreased with stocking (Figures 2.14 and 2.15) and significantly differed between most stockings. In contrast, the asymptote increased with stocking and also significantly differed between most stockings (Table 2.4, Figure 2.14).

Table 2.4. Means and multiple comparisons for each parameter. Means followed by different letters significantly differ at $P=0.05$.

Treatment	Tukey (α)	Mean (α)	Tukey (β)	Mean (β)	Tukey (γ)	Mean (γ)
		(m)				
200	A	42.52	A	0.09	A	1.44
350	A	43.17	B	0.11	A	1.91
500	B	51.10	C	0.06	B	1.38
1100	B	52.59	D	0.06	A	1.42

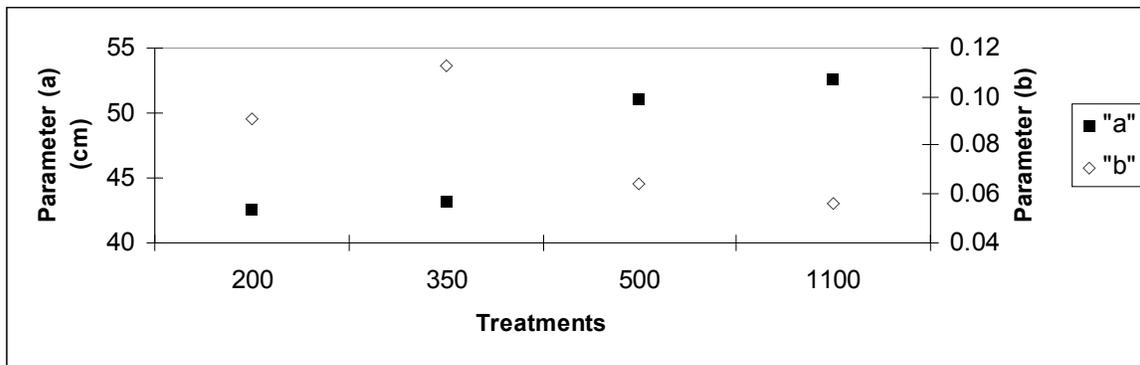


Fig. 2.14. Relationship between the asymptote α and growth rate β parameters and stocking

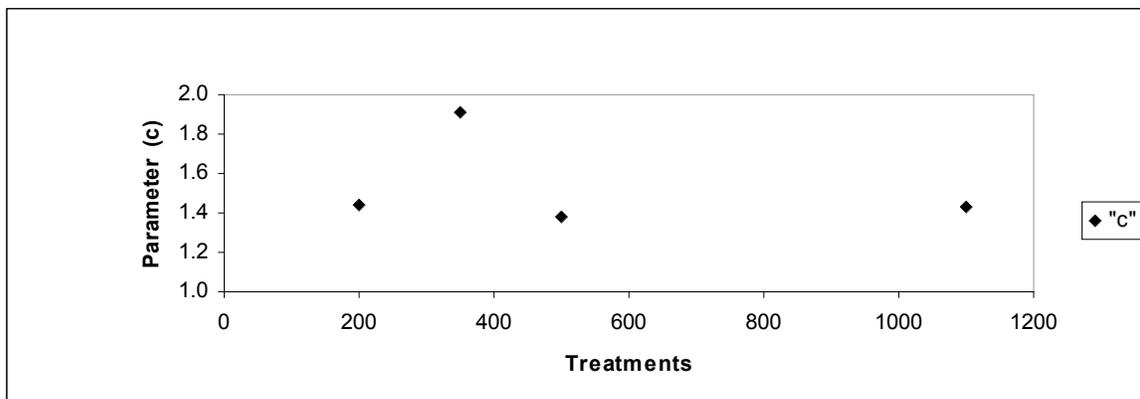


Fig. 2.15. Relationship between the shape parameter γ and stocking

Basal area (m²/ha)

Examination of basal area versus age trends indicated diverging growth patterns for the different thinning treatments occurred early on in the experiment and ranged from a high of 74 m²/ha for 500 and 1,100 stems/ha down to 54 m²/ha for 200 stems/ha at age 24 years ($P=0.001$). The GLM procedure and Tukey's studentised range test showed that the 200 stems/ha treatment was statistically different from any other treatment in basal area at age 24.

After examination of the actual basal area by treatments, basal area was modelled by Chapman Richard equation, which had normal, unbiased residuals distribution and therefore was chosen for further modelling.

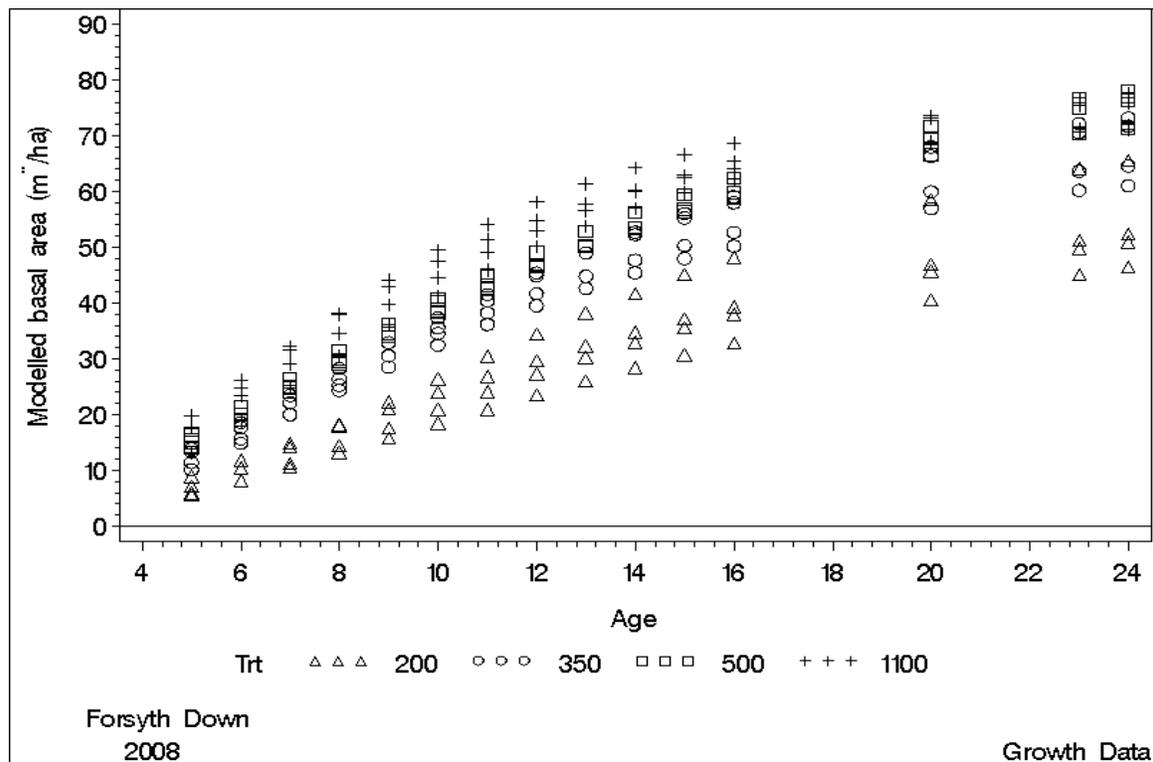


Fig. 2.16. Modelled plot level basal area data plotted against age by stocking; 1,100 stems/ha at the top of the graph followed by 500, 350 and 200 stems/ha.

A plot of modelled and measured basal area is shown in Figure 2.17. Figure 2.18 shows the residuals of the basal area models plotted against age by treatments, indicating a reasonably unbiased fit at predicted basal area above 20 m²/ha. Residual standard

deviation, variance and standard error mean for the Chapman Richard yield equation were 2.51, 6.30 and 0.16 m² ha⁻¹ respectively.

Compared to the highest stocking basal area, the lowest stocking basal area was reduced by 21 m²/ha or 28%, by age 24. The actual basal area at age 24 was 53, 67, 74 and 73 m²/ha for 200, 350, 500 and 1,100 stems/ha respectively.

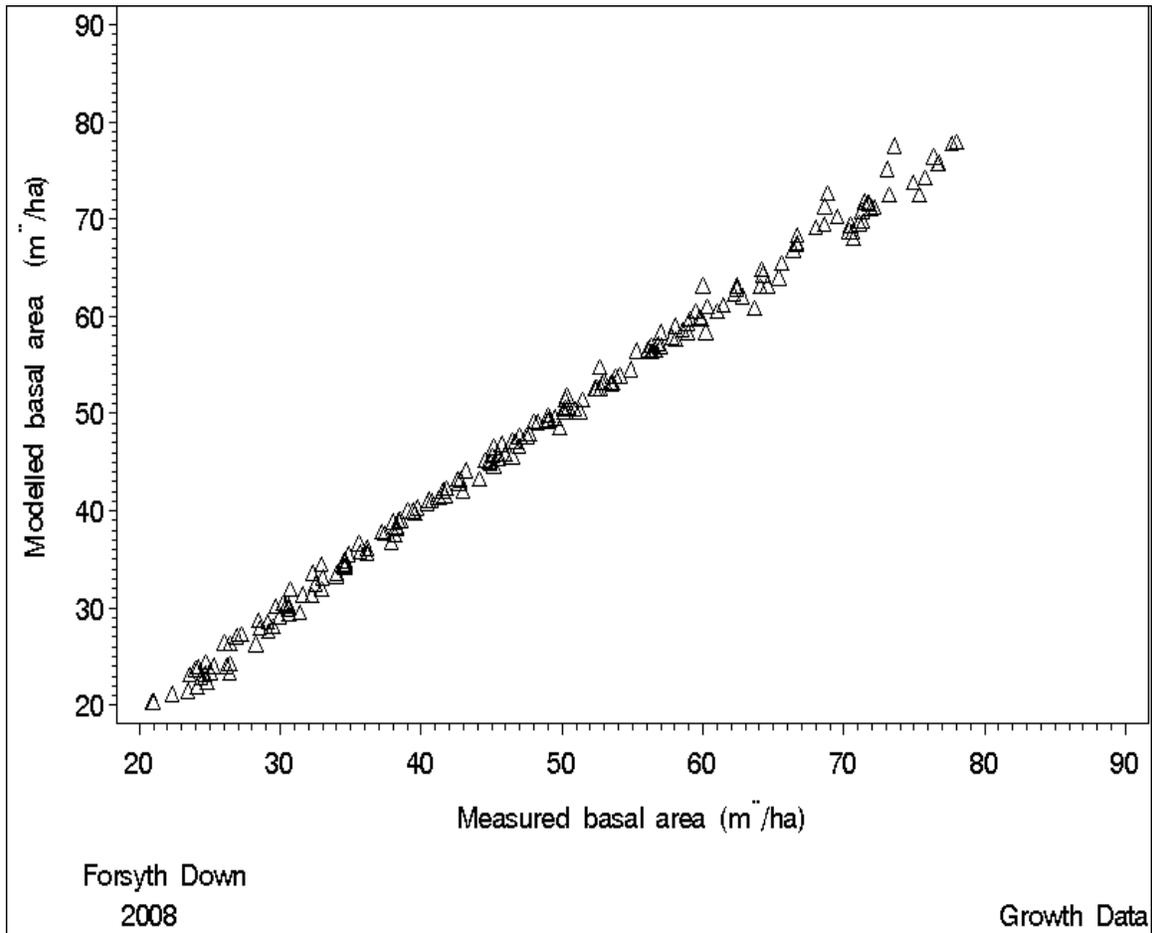


Fig. 2.17. Measured basal area plotted against predicted basal area.

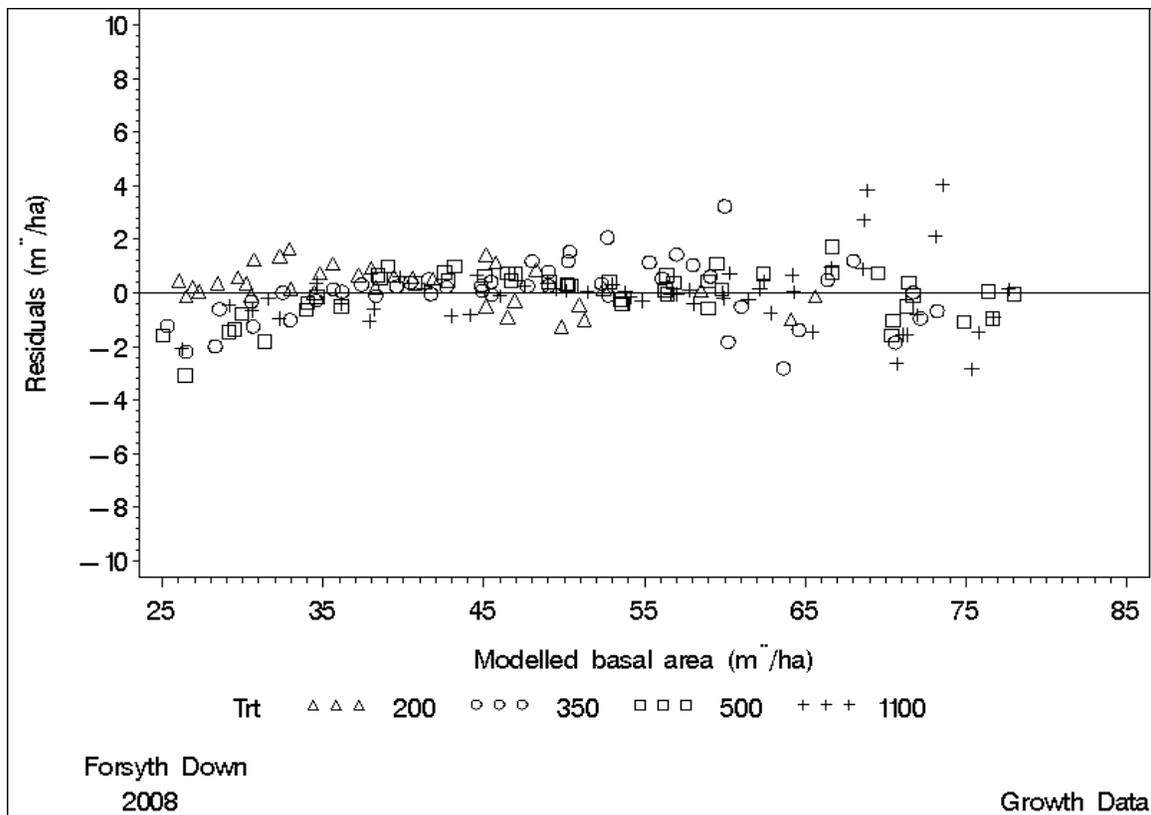


Fig. 2.18. Residuals of basal area plotted against predicted values by treatments

For basal area, stocking significantly affected the asymptote ($p < 0.0001$), growth rate ($p < 0.0001$) and shape parameter ($p < 0.0001$). The parameter value (α) depicting maximum asymptotic yield generally increased with an increase in residual stems/ha ($p = 0.0001$) while the maximum growth rate (β) and shape parameter (γ) decreased with an increase in residual stocking ($p = 0.0001$) (Figures 2.19 and 2.20) and significantly differed between most stockings (Table 2.5).

Table 2.5. Means and multiple comparisons for each parameter. Means followed by different letters significantly differ at $P = 0.05$.

Treatment	(m ² /ha)					
	Tukey (α)	Mean (α)	Tukey (β)	Mean (β)	Tukey (γ)	Mean (γ)
200	A	67.48	A	0.11	A	2.59
350	B	74.78	B	0.14	B	2.62
500	C	84.13	C	0.12	B	2.20
1100	B	77.35	D	0.18	C	2.93

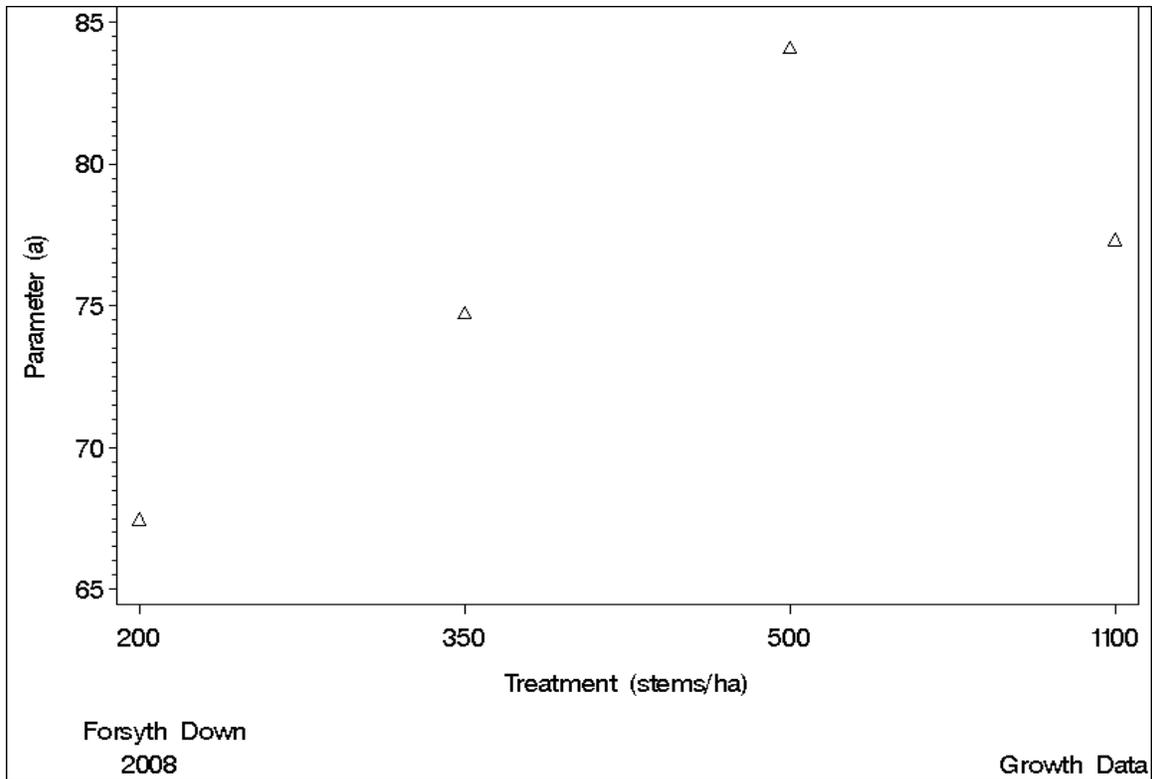


Fig. 2.19. Relationship between the asymptote (α) and stocking

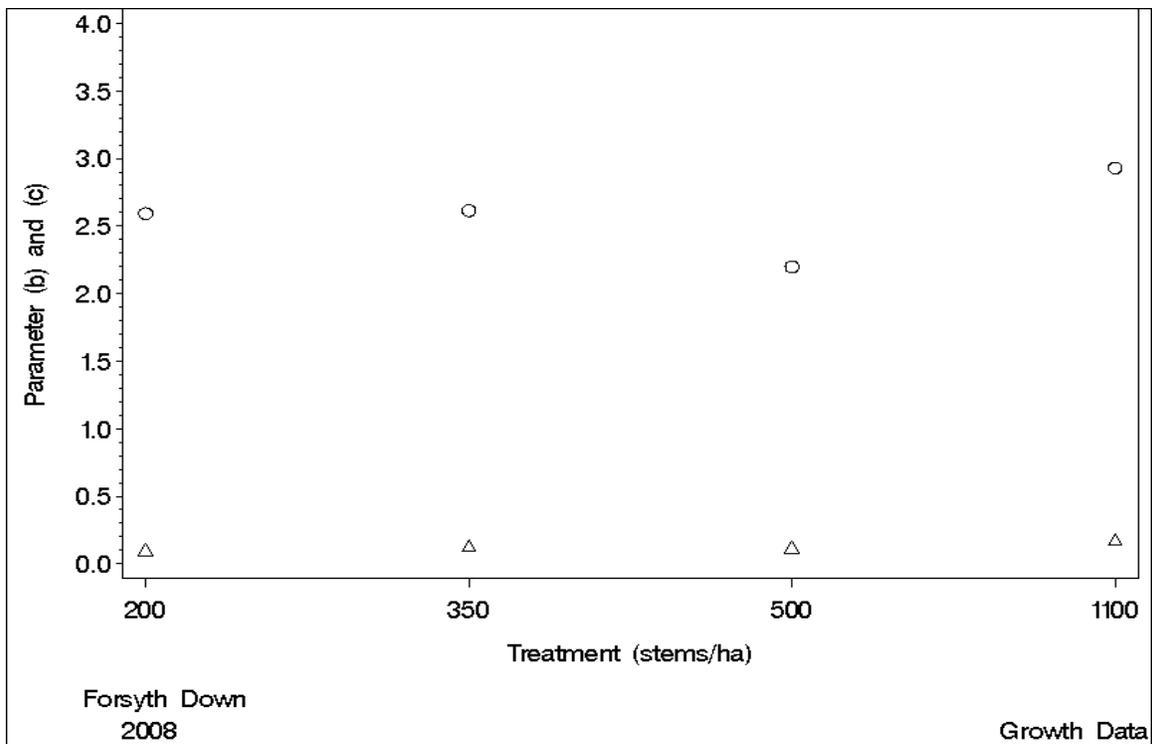


Fig. 2.20. Relationship between stocking and growth rate β (circles) and shape γ (triangles) parameters.

2.4 Discussion

The thresholding that occurred in the basal area and diameter growth curves by age 20 indicates that the optimum rotation age may be relatively low at this forest. At all stockings of 500 stems per hectare and less log size requirements for domestic market were met at age 20. Average diameter for stockings 200, 350, 500 and 1100 stems/ha at age 20 were 56, 48, 42 and 31 cm respectively. Although gains were made in average dbh after this point they were relatively low with dbh at age 24 and 30 for 500 stems per hectare reaching respective values of 46 and 47 cm. A 10 cm difference in diameter between 1,100 stems ha and 500 favour the use of the lower stocking, for structural grade regimes that could fully satisfy the small end diameter domestic log size requirements. The divergence, in dbh, which started after age 5, is likely to be related to the onset of canopy closure in the more highly stocked plots. Similar results were found by Knowles *et al.*, (unpubl) at the Tikitere trial.

The diameter distributions for the top 100 trees at different stockings were consistent with results found by Woollons and Whyte (1989) at a Kaingaroa thinning trial. Furthermore findings from this research were similar to spacing trial at Canterbury (Waghorn *et al.* 2007) where Waghorn found that tree diameter growth diminished with stocking during the fifth growing season. Also Tikitere trial results were similar where stocking did not affect individual tree diameter growth until the fifth growing season (Knowles *et al.* 1999b). Menzies *et al.* 1989 found similar results except that competition began during the fourth growing season on a very productive farm site.

Mean top height at age 20 indicates site index, with values at this site ranging across the stand densities from 30 m to 34 m. Mean top height for stockings 200, 350, 500 and 1100 stems/ha were 30, 32, 34, and 32 metres respectively. This variation in height between stockings was not significant and this result supports previous research of Carmean (1975) and Lanner (1985) and is not in the line with Maclaren *et al.* (1995), Carson *et al.* (1999) and Knowles *et al.* (1999b) who found that both mean height and mean top height increased significantly with stocking, albeit across a greater stocking range.

The parameters quantifying growth size, rate, and shape of basal area have been tested for differences among the stocking treatments and concluded that the parameter

value α depicting maximum asymptotic yield increased with an increase in residual stems/ha. These findings are in the line with Kaingaroa thinning trials analysis by Woollons *et al.* 1989. Findings from this research were similar to a spacing trial at Canterbury where Waghorn *et al.* (2007) found that culmination of basal area was earlier for higher stockings.

Although final asymptotes were estimated based on mathematical equations it is worth noting that often these asymptotes were beyond the data range. For this reason it is very important to carry on further measurement of this trial until at least age 40.

CHAPTER THREE

EFFECT OF STOCKING ON RADIAL AND LONGITUDINAL VARIATION IN WOOD PROPERTIES

3.1 INTRODUCTION

Two important determinants of wood quality include density and microfibril angle (MFA). These two properties in combination determine the module of elasticity (MOE) of wood (Cowdrey and Preston, 1966; Cave, 1966; Walker and Butterfield, 1996, 1998). The effect of MFA on corewood MOE has long been recognised as being more important than that of density (Donaldson, 1995),

The MFA of wood is strongly linked to the length of the tracheids that comprise the wood. For a pulp and paper mill, this has significant implications for the quality of pulp and paper, and this is readily valued, as pulp and paper grades are strongly related to pulp or paper quality (Kibblewhite, 2004). Microfibril angle also influences the longitudinal shrinkage of wood and thus affects wood stability.

Modulus of elasticity is most highly valued in structural lumber. Under machine stress grading the lumber grades are priced according to the MOE of the lumber. There are significant price differentials for lumber based on MOE, particularly around the threshold values for MOE that distinguish acceptably stiff lumber from lumber that is not stiff.

A lot of analyses and experts all suggest that in "normal" grading systems like F or MSG (which are very similar, the main difference being that MOR specs of MSG are lower than in F system that was developed for hardwoods) that a MOE of eight GPa begins to separate non-structural from potentially structural zones of the sawlog.

It is also important to know that timber is graded as a population. Therefore, lower stiffness wood can still make MSG6 provided that there is higher stiffness wood in the population of interest to compensate. The current MOE thresholds required for the different structural grades are described in Table 3.1.

Table 3.1. Minimum requirements for machine stress graded MSG structural lumber.

MSG Grade	Min MOE (GPa)	Targeted MOE (GPa)	Indicative Max Knot (mm) ^a	Indicative Log SED (mm) ^b	Indicative Lumber Value (\$/m ³) ^c
Pulp (Chips)	n/a	n/a	n/a	100	80
Industrial	n/a	>4	>140	100-200	190
MSG6	4	6	>140	200-300	230
MSG8	5.3	8	>60	300-400	340
MSG10	6.7	10	>60	300-400	370
MSG12	8	12	>60	300-400	390

a - Lumber grade depends on position, frequency, angle and area of the knot(s) position.

b - Mill profitability depends of the log size but smaller SED would produce stiffer wood than large ones.

Larger SED logs are more efficient to produce lumber in most sawmills.

c - Minimum price for various lumber products

Boards from juvenile wood are often sold as industrial lumber or are chipped for pulp. Although the corewood may comprise up to 50% of the recoverable volume, this is typically not utilised for structural grade due to inferior wood properties such as MOE. Given the differential in price between pulp and structural grade it would be of considerable benefit if structural grade could be cut from the currently unutilised corewood.

Previous research has widely shown that MOE exhibits a positive increase with stocking. However, as most of this research has been undertaken on cool sites with low MOE, the use of high stockings has not been sufficient to push values of corewood MOE beyond thresholds required for structural grade. For example at a reasonably high level of stocking (833 stems ha⁻¹) Lasserre (2005), found that MOE was less than 8 GPa over the first 11 rings. Given that temperature has been shown to have a strong positive influence on MOE (Watt *et al.*, 2006) use of high stockings to produce timber with utilisable corewood is most likely to occur on warm sites.

Using data obtained from a stocking trial in Northland the objective of this chapter was to determine how stocking influences radial and longitudinal variation in

wood properties and maximum branch diameter. Future research would elaborate how stand density affects the minimum age at which thresholds for structural grade were exceeded.

3.2 METHODS

Site and experiment treatments

This study was carried out on data from an experiment established by the ex-Carter Holt Harvey Forests. The thinning trial was situated at Forsyth Downs, Mangakahia District of ex-Carter Holt Harvey Forests Ltd. in the Northland region. The experimental site was located on a north east aspect at an elevation ranging from 350 to 385 m and slope between 5° and 15°. The site was on Waimatenui clay soils of moderate to high fertility with an average rainfall of 1,180mm per year, with most rainfall occurring during winter (42.5 % of the annual rainfall occurs between May and August).

The Forsyth Down trial was established as a randomized block design, with 4 treatments and 4 replicates that included a total 16 plots with an inner measurement area of 0.1 hectare per plot. The area was planted in winter 1982 at an initial stocking of 1,667 stems/ha and spacing of 2 × 3 m with *Pinus radiata* seedlings from GF 7 stock and thinned in 1987 to 200, 350, 500 and 1,100 stems/ha. At age 5, sixteen 0.4 ha plots were overlaid using a randomised block design, with four replicates per spacing treatment. Diameters of all stems were measured at breast height (1.4 m) prior to thinning.

Measurements

Measurements were undertaken on an annual basis until age 16 and four years later at ages 20, 23 and 24 for diameter at breast height and tree height (random sample over the diameter range) for all residual stems in the experimental plots. Data have been stored in the PSP database, maintained by Scion.

Measurements of wood properties using SilviScan were made on 10 stems from each of the four spacing treatments. For each tree a single radius from each of 4 heights

(0, 1.4, 5 and 20m) were analysed using SilviScan.

SilviScan samples were prepared according to established procedures (i.e. soaked in ethanol for several weeks with two changes of ethanol) prior to dispatch to CSIRO, Melbourne. X-ray densitometry and x-ray diffraction (MFA) data have been collected from each of the four heights and used to estimate stiffness (MOE). SilviScan provided three forms of data that included;

1. X-ray densitometry from pith to bark (air-dry density)
2. X-ray diffraction from pith to bark (MFA, relative spiral grain)
3. Estimated stiffness from pith to bark (MOE), using density and MFA

Each SS sample yields a pith-to-bark profile of wood properties. The average wood property value for each core was determined as the simple average of the profile properties. Radial and tangential profiles of density, MFA and estimated MOE were assessed on each disc height at a sampling interval of 50 μm .

The height and the diameter of the largest branch of the first whorl above 6m on approximately 15 trees per plot were measured using callipers at age 20. Each trial plot had a circular measurement plot established along at one corner with the measurement plot centre at the trial plot corner. Plot radius varied with treatment stocking to achieve approximately equal numbers of trees per plot. The radius were as follows: 15.81m, 11.95m, 10.00m and 7.45 m for 200, 350, 500 and 1,100 stems/ha, respectively. The diameter of the largest branch in the first whorl above 6m was measured on every tree within the plot.

Data analysis

Statistical analysis was undertaken using SAS 9.3 software (SAS Institute, 2000). Analysis of variance was used to examine the main and interactive effects of stocking on MOE, MFA and wood density. A MIXED effects model was used to assess the main and interactive effects of stand density, disc height and ring number, included in the model as class level variables, on MOE, MFA and density. The main and interactive effects of

stand density, disc height and ring number on the wood properties were evaluated using the following model,

$$Y_{ijk} = \mu + \alpha_k + \beta_i + \gamma_j + (\beta\gamma)_{ij} + (\alpha\beta)_{ki} + (\alpha\gamma)_{kj} + (\alpha\beta\gamma)_{ijk} + e \quad [3.1]$$

where Y_{ijk} are MOE, MFA or density at i^{th} stocking, j^{th} disc height, k^{th} ring number, μ the overall mean, α the stocking, β the disc height, γ the ring number, $(\beta\gamma)$ the interaction between disc height and ring number, $(\alpha\beta)$ the interaction between stocking and disk height, $(\alpha\gamma)$ the interaction between stocking and ring number, $(\alpha\beta\gamma)$ the interaction between stocking, disc height and ring number, and e is the experimental error. The random effects included in the model were as follows; rep rep*stocking and tree(rep*stocking), where rep refers to the block number.

The influence of stocking on branch diameter was analysed using one-way analysis of variance using the GLM procedure. The means statement in PROC GLM was used for obtaining the means and standard error of the response variable for the four treatments 200, 350, 500 and 1,100 stems/ha. The class statement was used to classify treatments as a categorical variable.

3.3 RESULTS

Branch diameter

Stocking had a significant impact on the branch diameter ($P < 0.0001$). The negative relationship between branch diameter and stocking exhibited a 48% or 35 mm decrease in branch diameter from 73 mm at 200 stems/ha to 38 mm at 1,100 stems/ha (Fig. 3.1). Branch diameter on the first whorl above 6 m was also significantly ($P < 0.0001$) linearly and positively correlated with tree diameter ($R^2 = 0.84$).

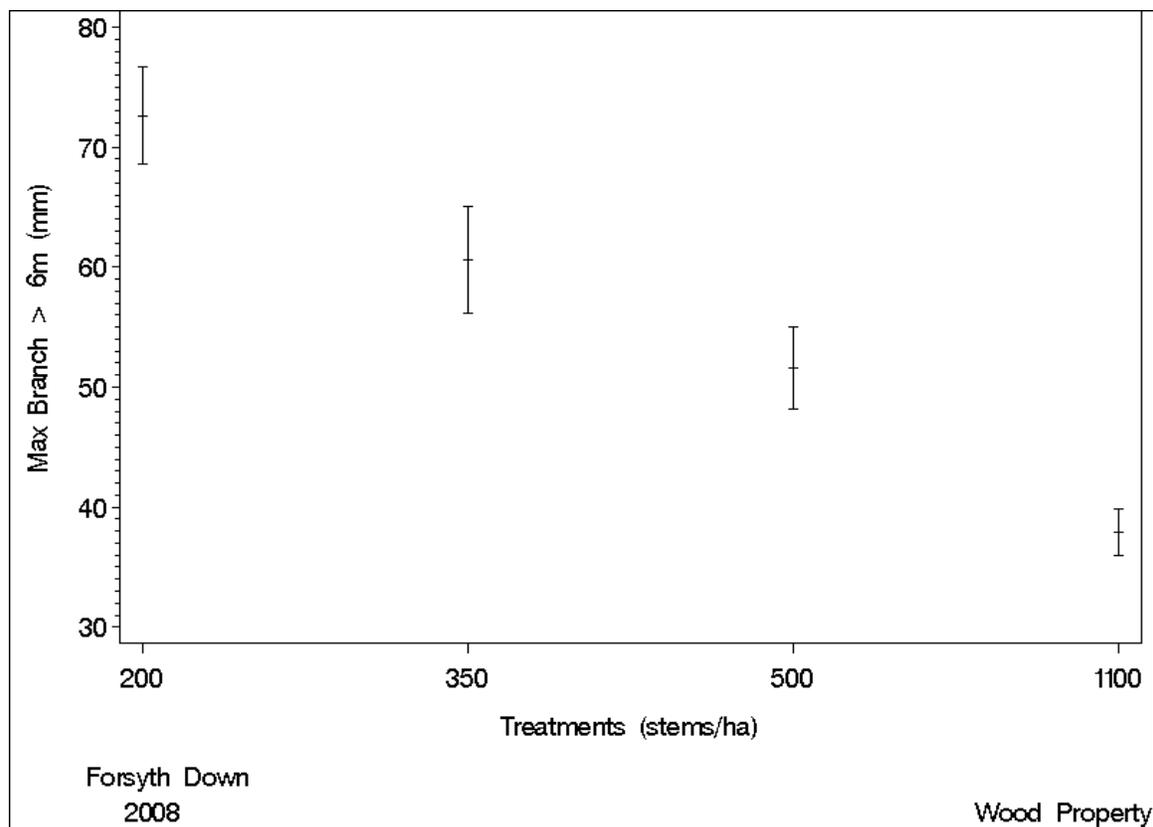


Fig. 3.1. Maximum branch diameter on the first whorl above 6 m plotted against stocking. Each value shows the mean \pm the standard error, from four plots

Density

Density was significantly affected by height and ring number in the tree but not the main effect of stocking (Fig. 3.2, 3.3 and 3.4). With the exception of the three-way

interaction, all interactions significantly affected density (Table 3.2).

Table 3.2. Analysis of variance table describing the main and interactive effects of stocking, height and ring number on density

Effect	F Value	Pr > F
Stocking	3.37	0.0960
Height	95.11	<.0001
Ring Number	117.34	<.0001
Stocking x Height	3.06	0.0012
Stocking x Ring Number	4.35	<.0001
Height x Ring Number	9.02	<.0001
Stocking x Height x Ring Number	0.68	0.9992

Density increased from pith to bark reaching a maximum of 550 kg/m³ at approximately ring 17-19 before declining to 450 kg/m³ at ring 22 (Fig. 3.4). Density exhibited a linear decline with tree height (Fig. 3.3) by 10 % from 510 kg/m³ at a height of 0 m to 460 kg/m³ at a height of 20 m. Although there was a increase in density with stocking (Fig. 3.2) this was not significant.

The significant interaction between ring number and stand stocking was due to divergence in density, between high and low stocking treatments that occurred after the thinning (Fig. 3.6). The significant interaction between ring number and height was attributable to the lower density at high ring numbers for the 20 m section.

While there was a significant interaction between height and stocking this was relatively weak compared to the other interactions (Table 3.2). This interaction was attributable to rank changes in density between 500 and 350 stems per hectare treatments across the height range (Fig. 3.5).

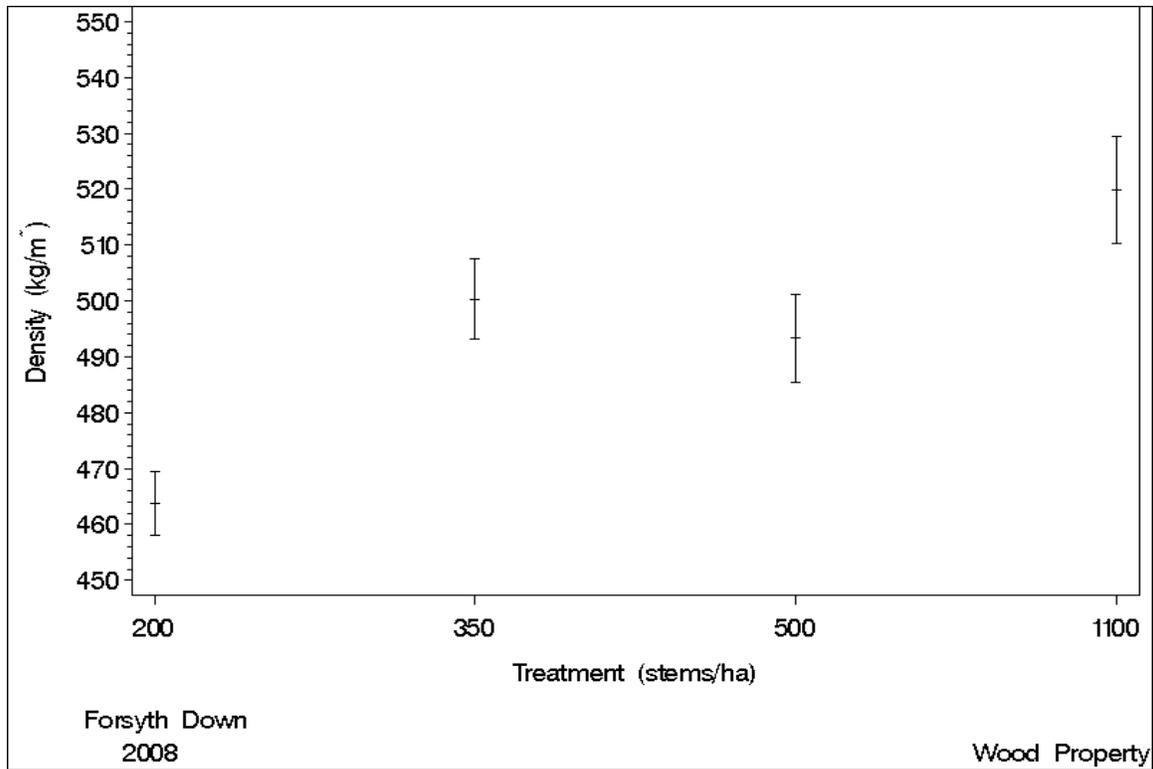


Fig. 3.2. Relationship between density and stocking. Each value shows the mean \pm the standard error, from 10 trees.

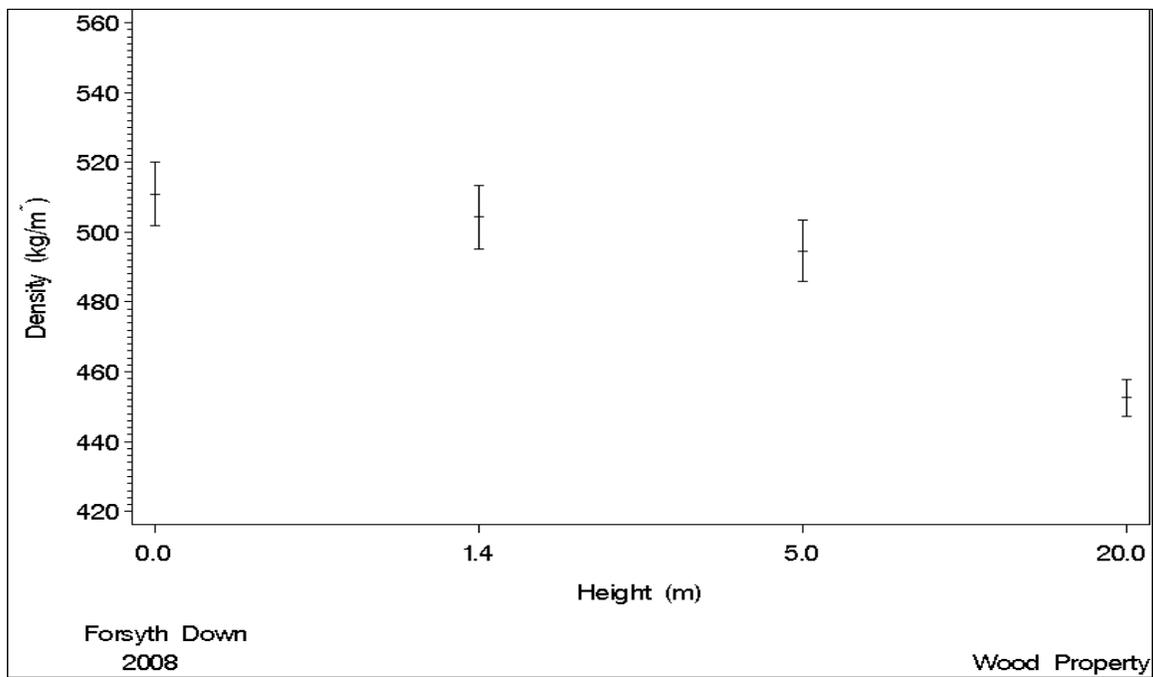


Fig. 3.3. Relationship between density and tree height. Each value shows the mean \pm the standard error from 40 trees.

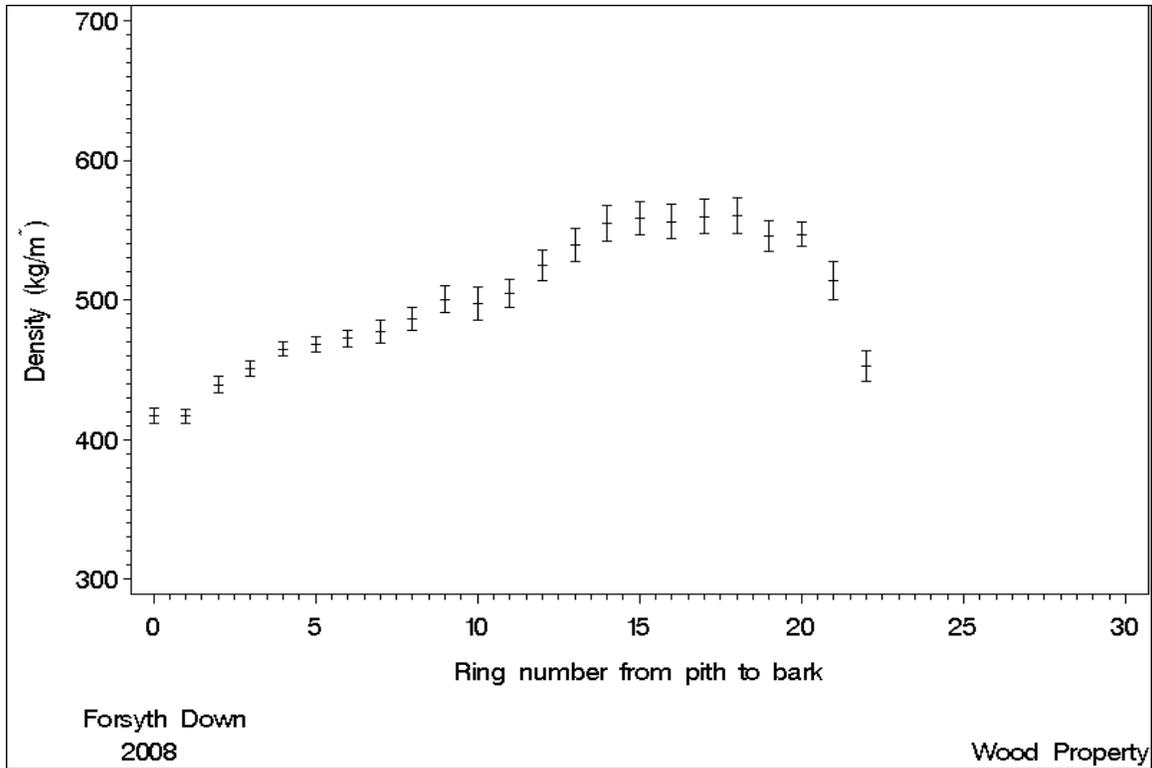


Fig. 3.4. Relationship between density and ring number. Each value shows the mean \pm the standard error from 40 trees.

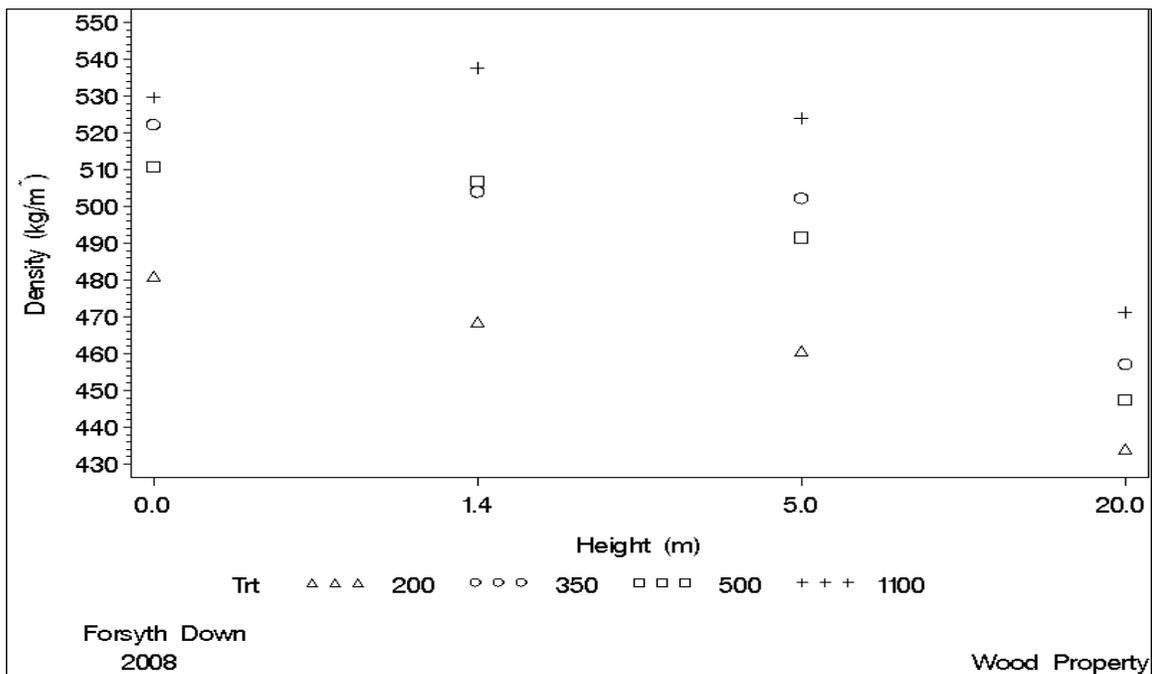


Fig. 3.5. Relationship between density and height, by stocking.

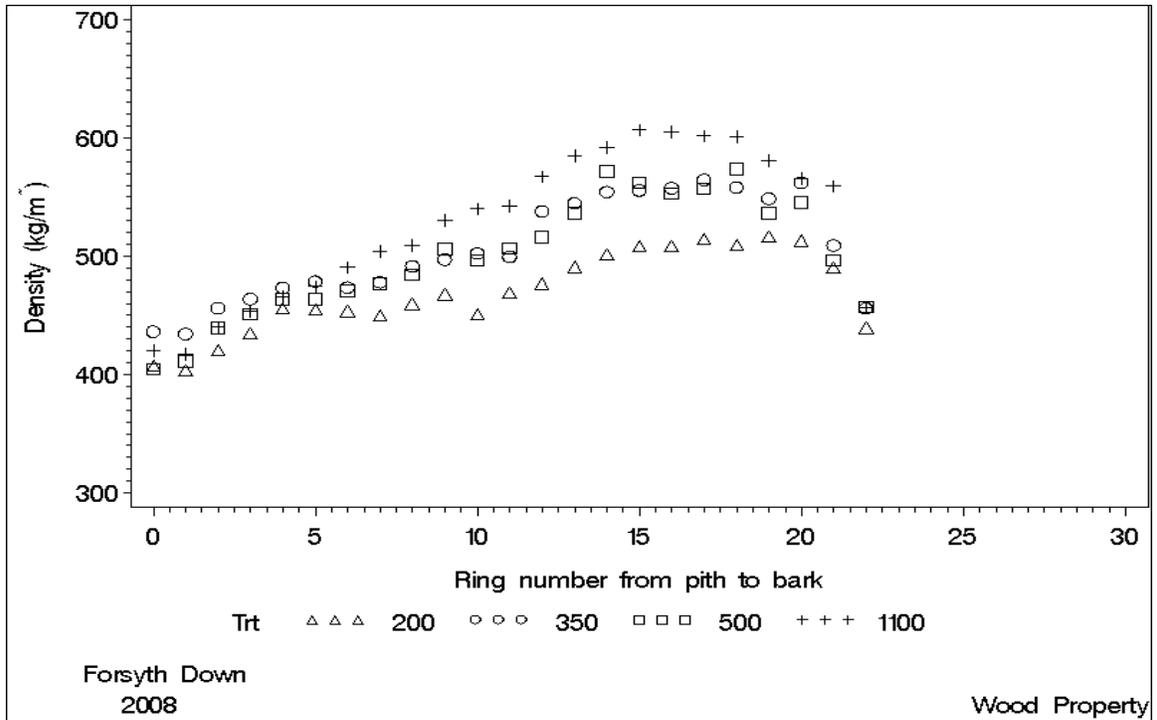


Fig. 3.6. Relationship between density and ring number, by stocking

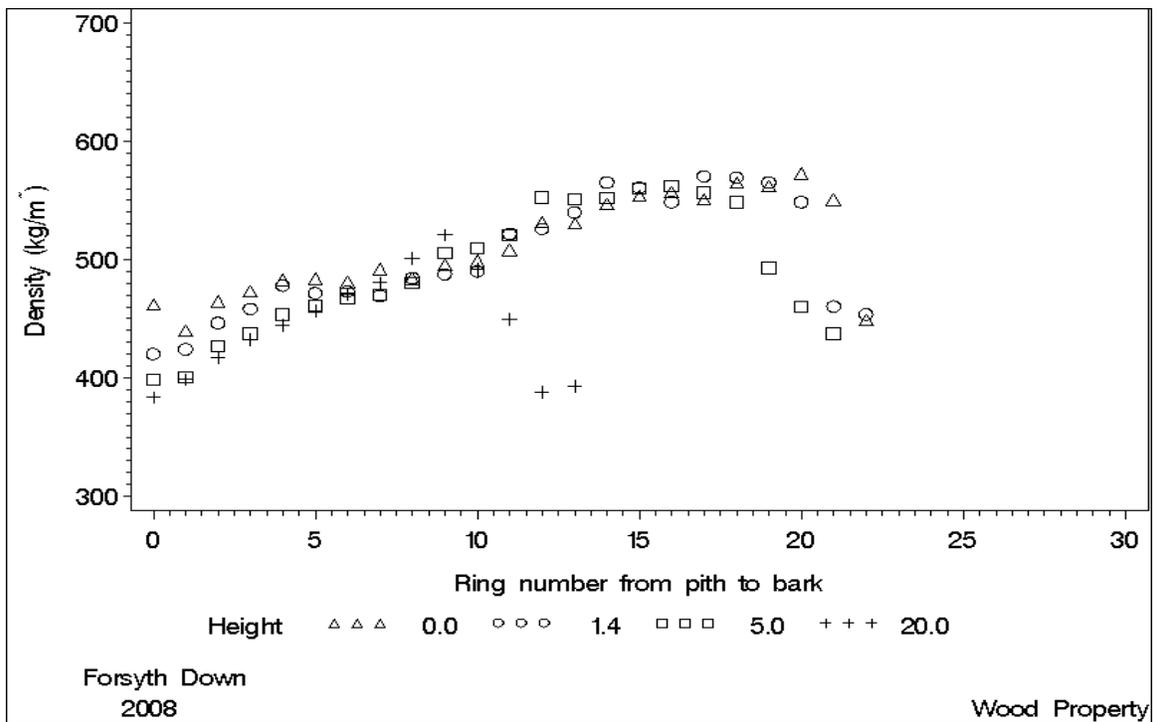


Fig. 3.7. Relationship between density and ring number, by height

Microfibril angle (MFA)

Stocking, height and ring number significantly affected MFA (Fig. 3.8, 3.9 and 3.10). With the exception of the three-way interaction, all interactions significantly affected MFA (Table 3.3).

Table 3.3. Analysis of variance table describing the main and interactive effects of stand density, height, and ring number on MFA.

Effect	F Value	Pr > F
Stocking	6.03	0.0305
Height	1146.13	<.0001
Ring Number	544.84	<.0001
Stocking x Height	10.36	<.0001
Stocking x Ring Number	4.82	<.0001
Height x Ring Number	13.29	<.0001
Stocking x Height x Ring Number	0.81	0.9574

MFA decreased from pith to bark, reaching a minimum of 19° at approximately rings 17-19 and increased to 21° at ring 22 (Fig. 3.10). MFA exhibited a linear decline with tree height (Fig. 3.9) from 27° at heights 0 m to 21° at a height of 20 m. There was a significant decrease in MFA with stocking (Fig. 3.8).

The significant interaction between ring number and stand stocking was due to divergence in MFA, between high and low stocking treatments that occurred after the thinning (Fig. 3.12). The significant interaction between ring number and height was due to convergence in MFA between heights with increasing ring number (Fig. 3.13). The significant interaction between height and stocking (Fig. 3.11) was attributable to rank changes in MFA between stockings at a given height.

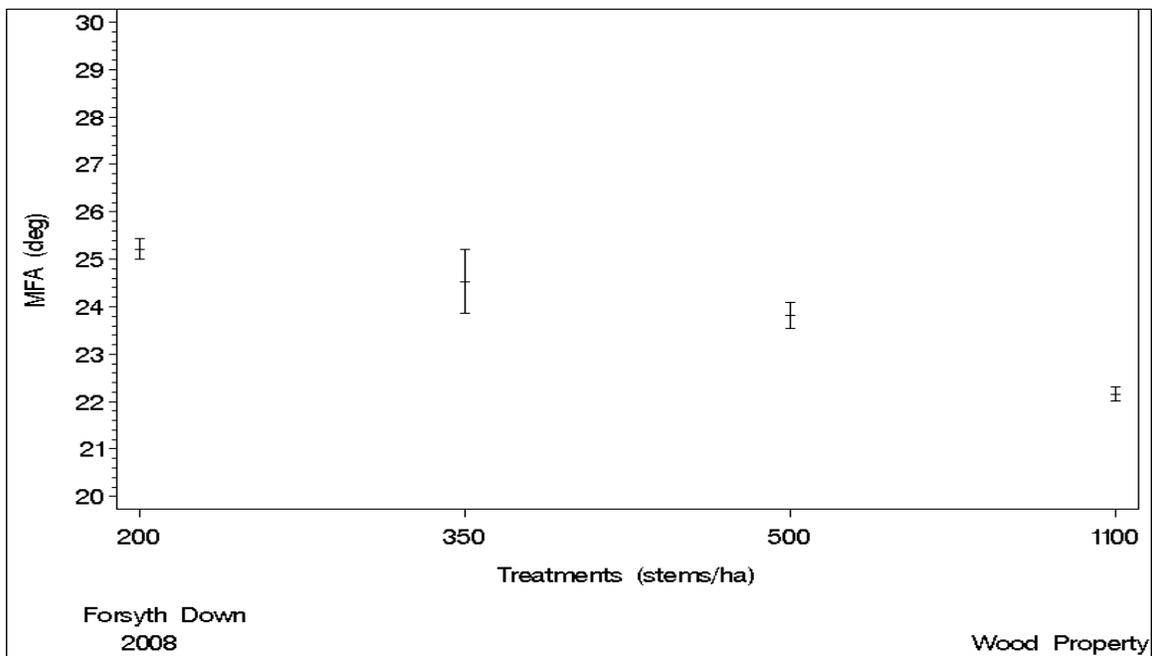


Fig. 3.8. Relationship between MFA and stocking. Each value shows the mean \pm the standard error, from 10 trees.

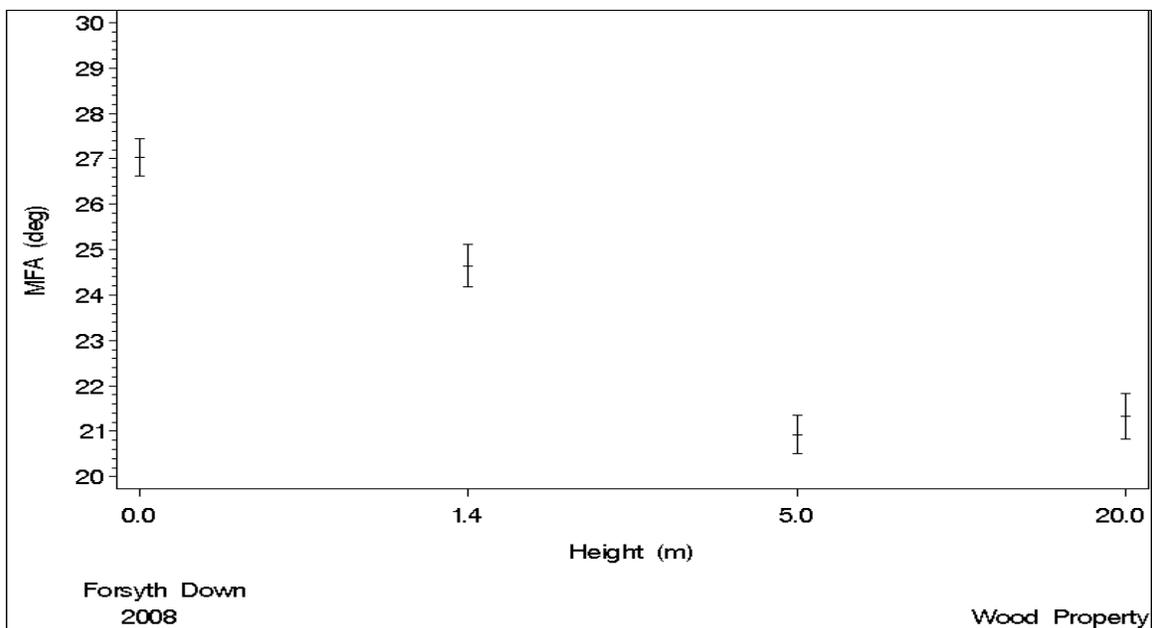


Fig. 3.9. Relationship between MFA and tree height. Each value shows the mean \pm the standard error from 40 trees.

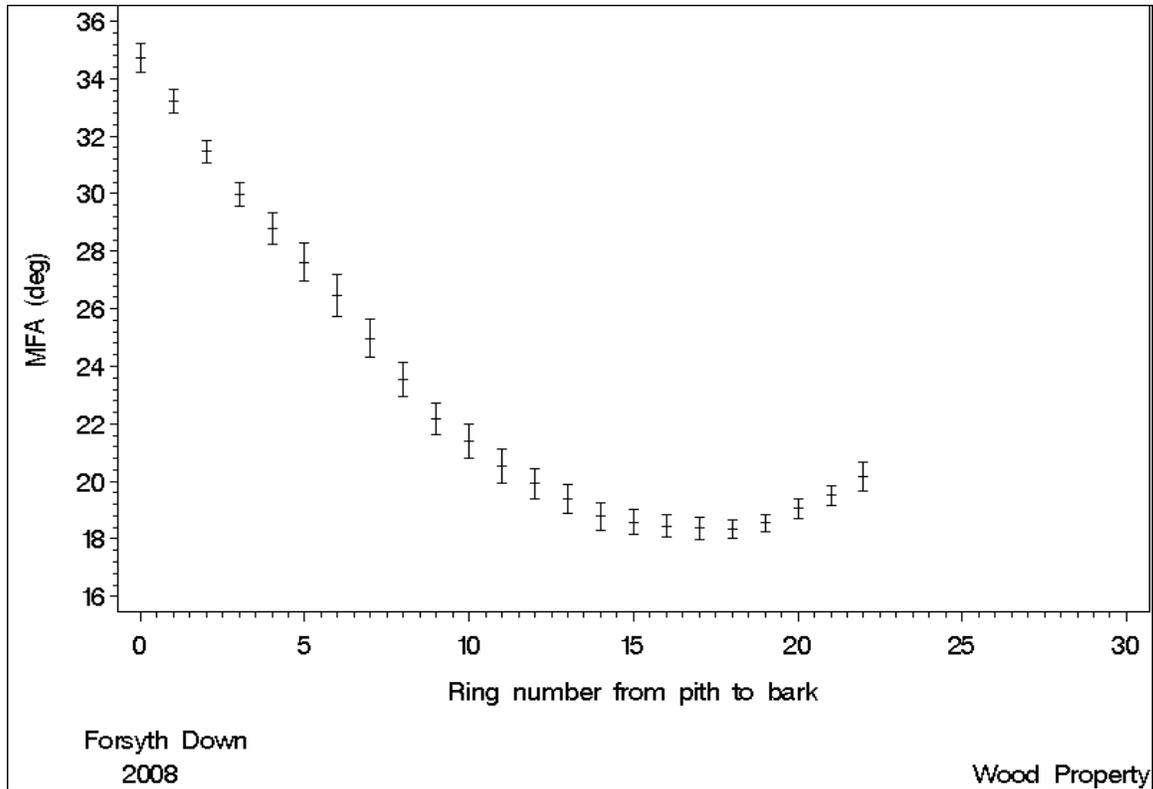


Fig. 3.10. Relationship between MFA and ring number. Each value shows the mean \pm the standard error from 40 trees.

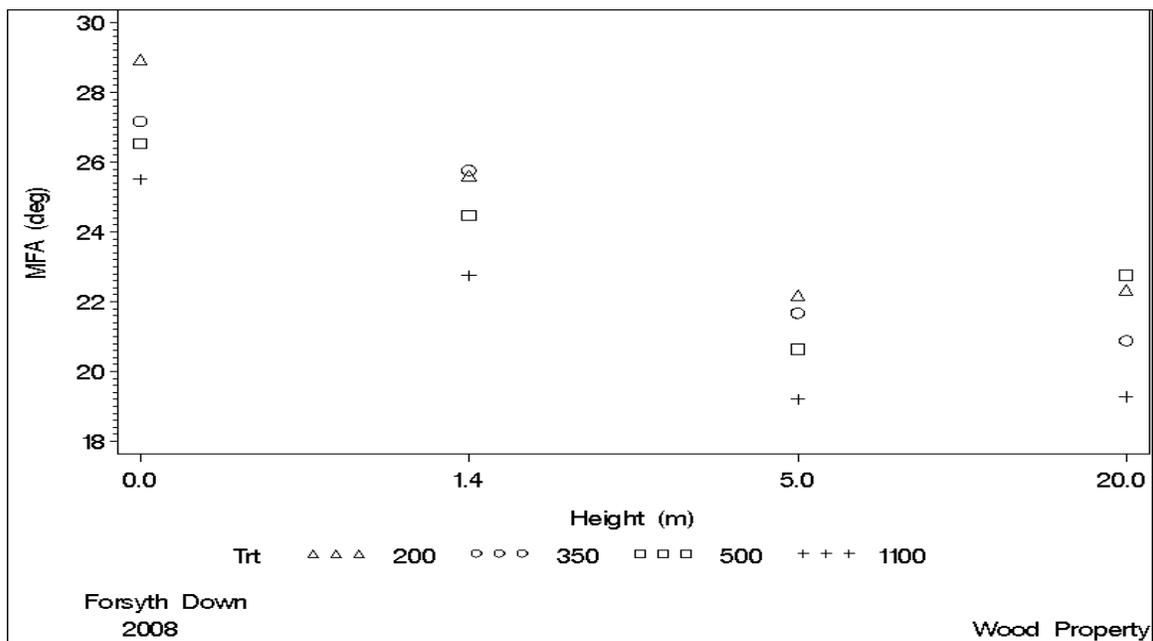


Fig. 3.11. Relationship between MFA and height, by stocking.

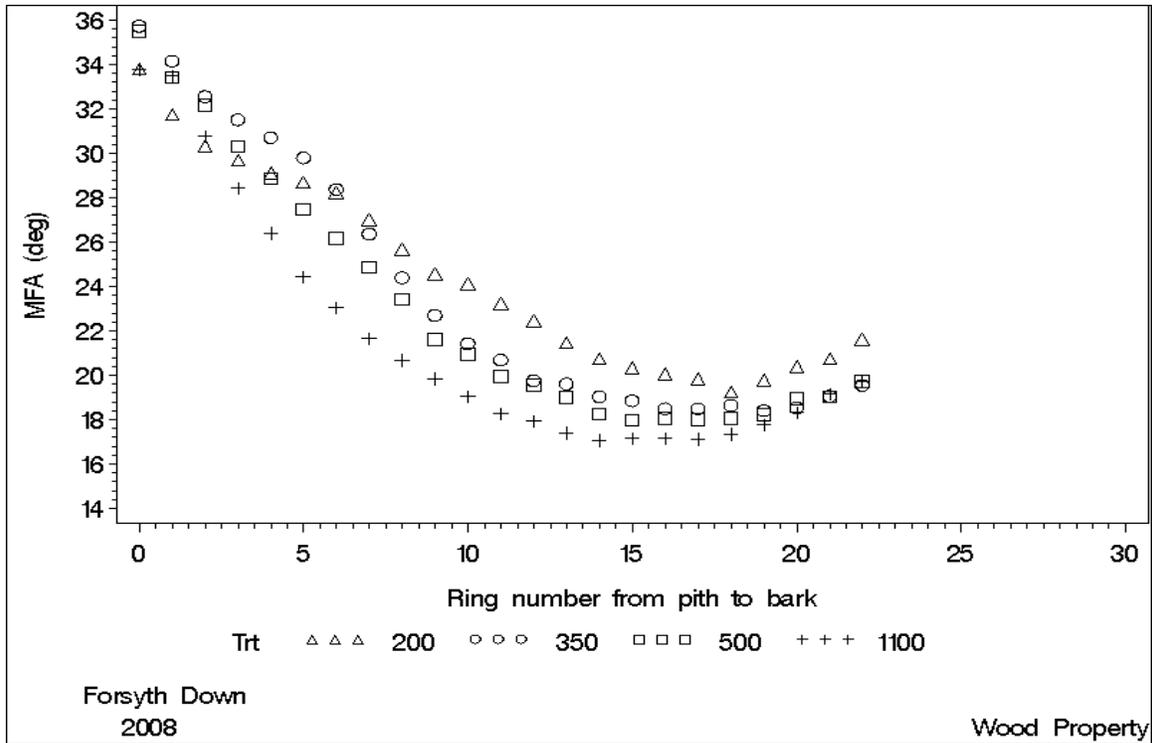


Fig. 3.12. Relationship between MFA and ring number, by stocking

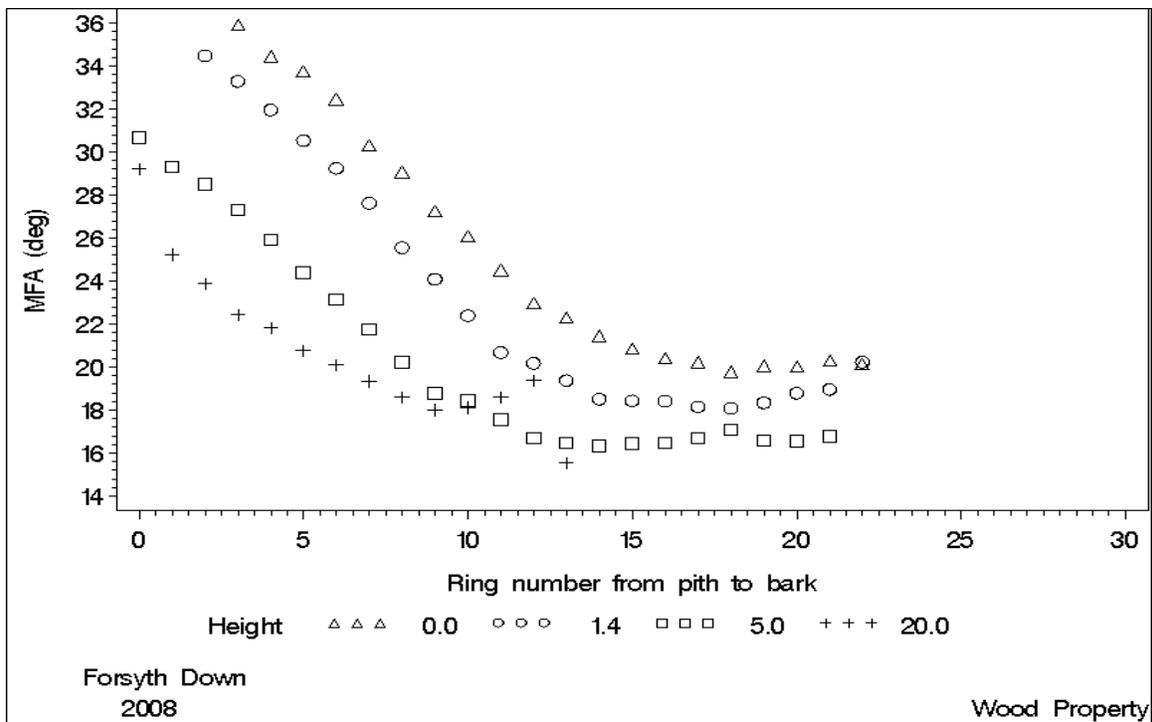


Fig. 3.13. Relationship between MFA and ring number, by height

Modulus of elasticity (MOE)

Ring number, stocking and height had a significant effect on MOE (Fig. 3.14, 3.15 and 3.16). With the exception of the three-way interaction, all interactions significantly affected MOE (Table 3.4).

Table 3.4. Analysis of variance table describing the main and interactive effects of stocking, height, and ring number on MOE.

Effect	F Value	Pr > F
Stocking	14.95	0.0034
Height	514.12	<.0001
Ring Number	593.21	<.0001
Stocking x Height	7.68	<.0001
Stocking x Ring Number	7.15	<.0001
Height x Ring Number	4.32	<.0001
Stocking x Height x Ring Number	0.59	1.0000

Radial variation in MOE was highly significant ($P < 0.0001$) with MOE increasing from the pith to reach a maximum of 15 GPa at rings 17-19 after which it declined to 13.5 GPa at ring 22 (Fig. 3.16). Longitudinal variation in MOE was also highly significant ($P < 0.0001$). MOE increased with increases in tree height from 9 GPa at the stem base, to a maximum of 12 GPa at 5 m and then steadily declined over the remainder of the stem to 10 GPa at 20 m (Fig. 3.15, Appendix 1). There was a significant 28% increase in MOE with stocking (Fig. 3.14) from 8.76 GPa at 200 stems/ha to 12.22 GPa at 1,100 stems/ha.

The significant interaction between ring number and stand stocking was due to divergence in MOE, between high and low stocking treatments that occurred after the thinning (Fig. 3.18). The significant interaction between ring number and height was due to convergence of MOE between height positions with increasing ring number (Fig. 3.19). The significant interaction between height and stocking was attributable to rank changes in MOE between stockings at a given height (Fig. 3.17). MOE had very steep

increase from the base of the tree to 5 m at any stocking that was wholly attributable to a rapid decrease of MFA by height as density also declined from the base to 5 m (Fig. 3.5, 3.11 and 3.17).

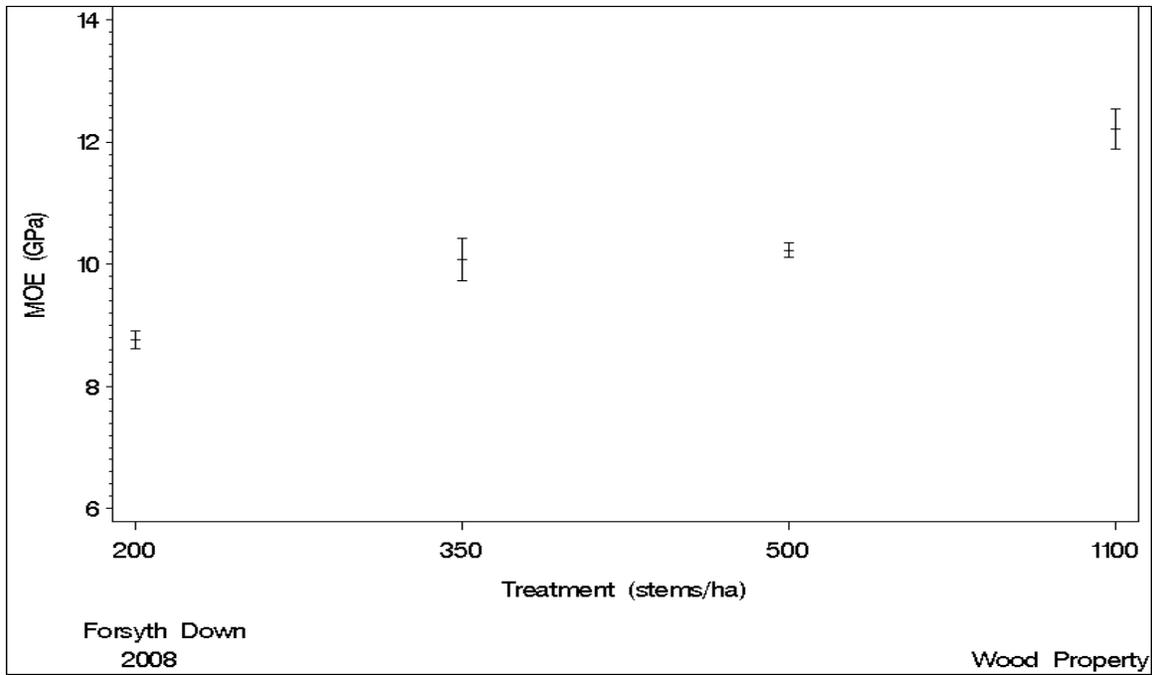


Fig. 3.14. Relationship between MOE and stocking. Each value shows the mean \pm the standard error, from 10 trees.

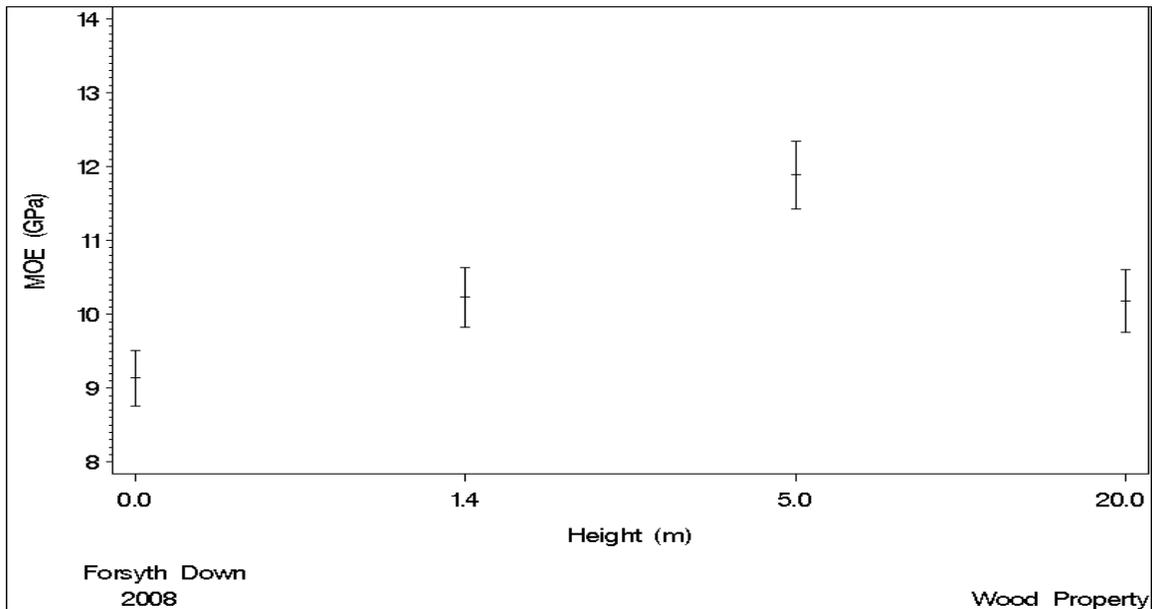


Fig. 3.15. Relationship between MOE and tree height. Each value shows the mean \pm the standard error, from 10 trees.

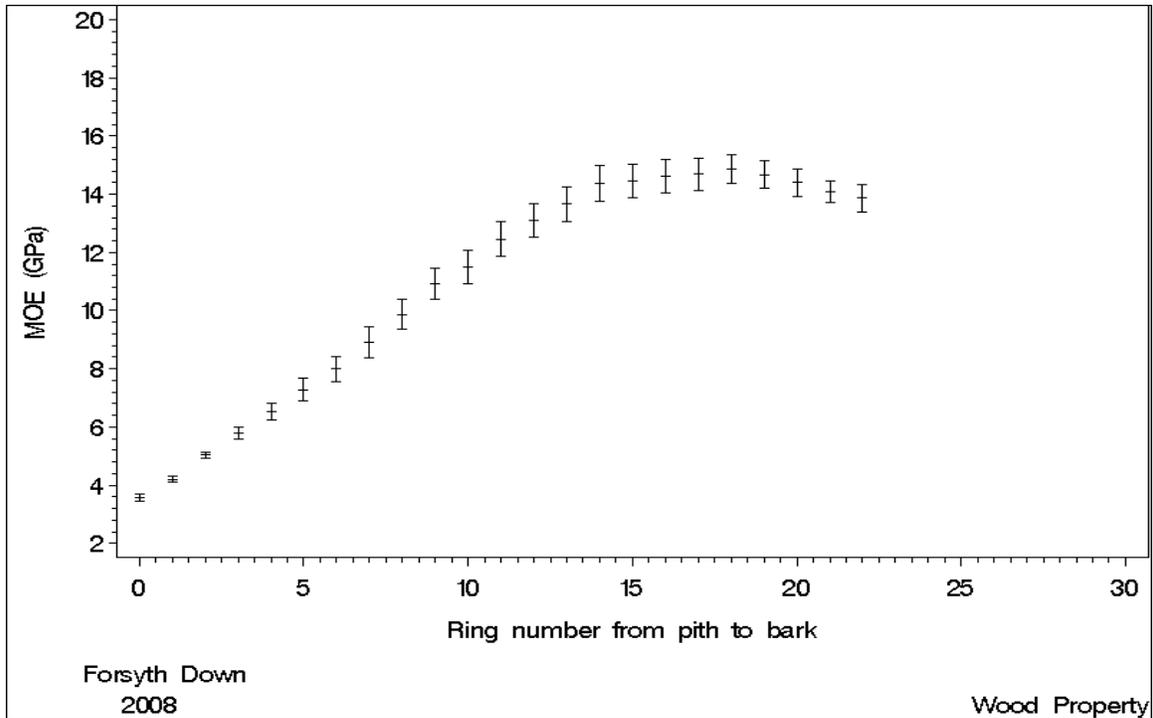


Fig. 3.16. Relationship between MOE and ring number. Each value shows the mean \pm the standard error, from 10 trees.

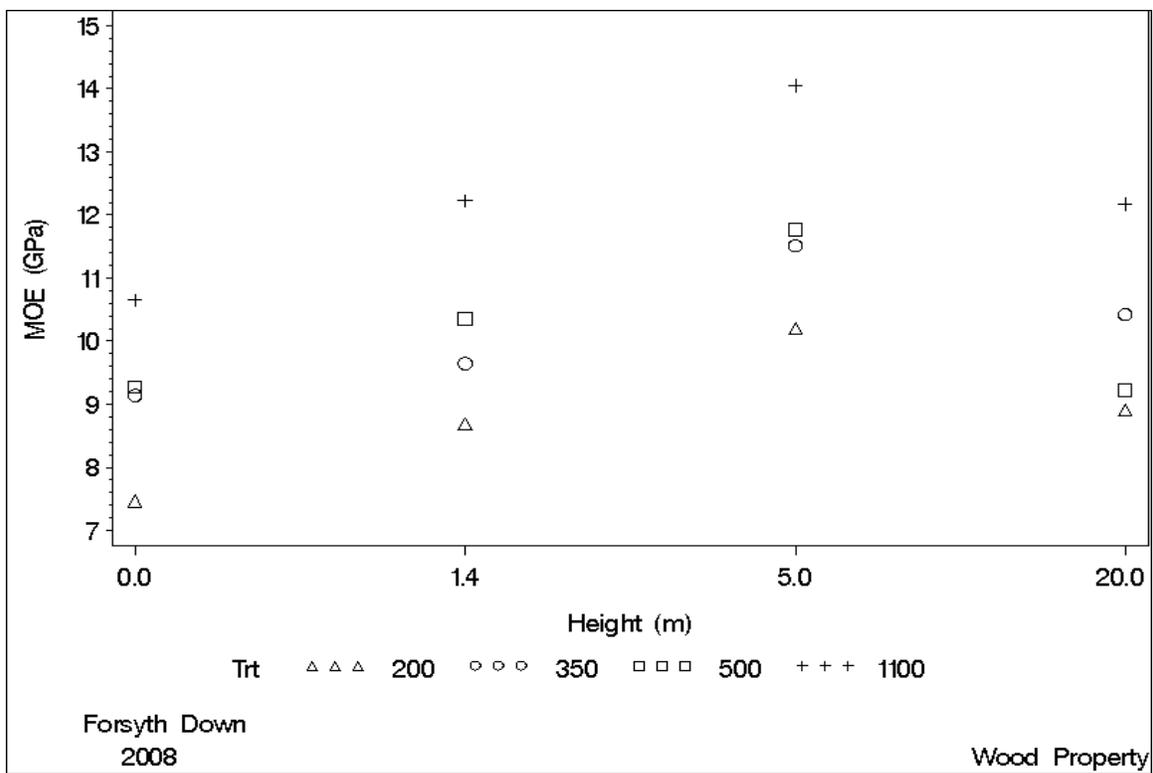


Fig. 3.17. Relationship between MOE and height, by stocking

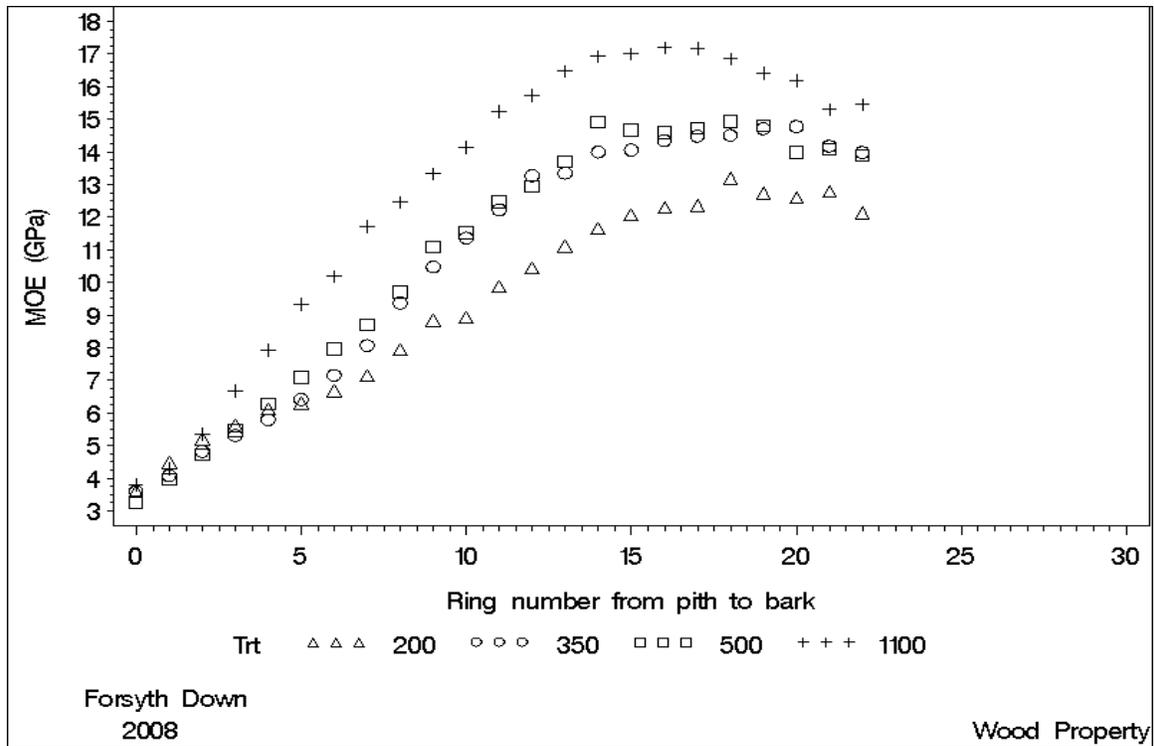


Fig. 3.18. Relationship between MOE and ring number, by stocking.

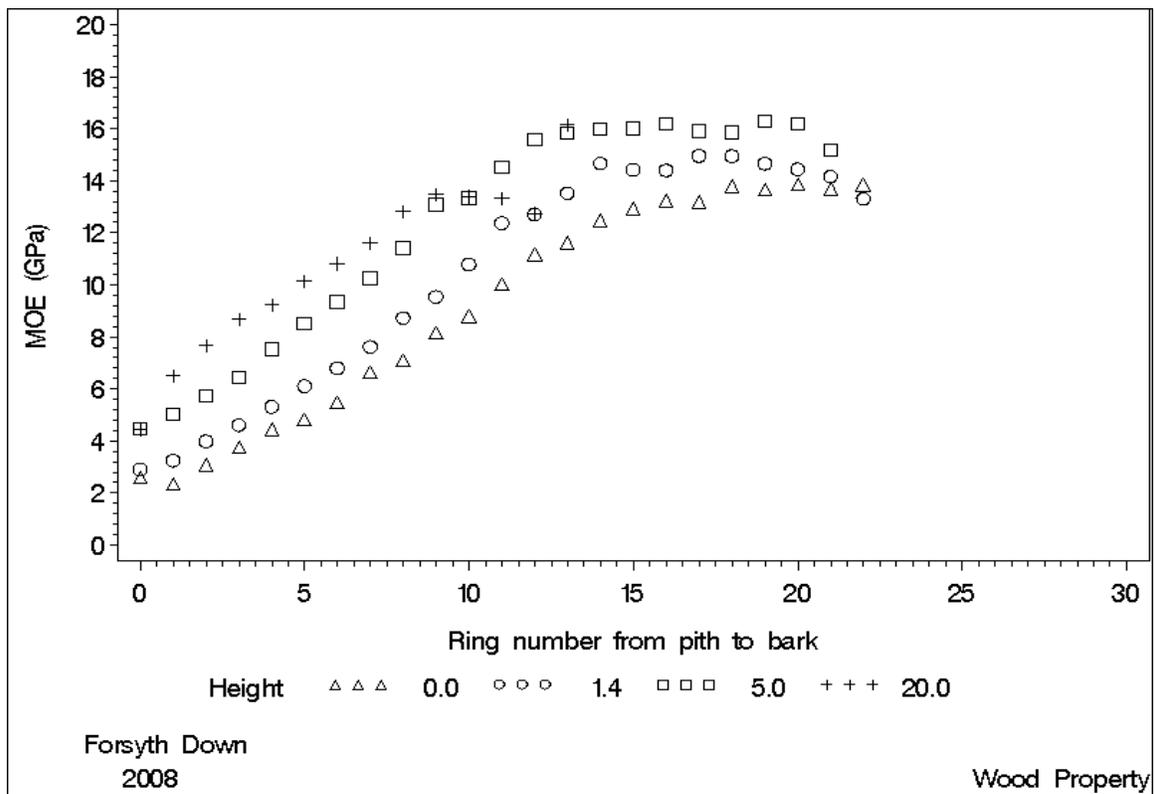


Fig. 3.19. Relationship between MOE and ring number, by height.

3.4 Discussion

Although not significant, the relationship between density and stocking found here is consistent with a number of previous studies (Lasserre *et al.*, 2005; Clark and Saucier, 1989; Lei *et al.*, 1997; Watson *et al.*, 2003; McConchie *et al.*, 1990 and McKinley *et al.*, 2000), where wood density tends to decline with decreases in stocking. Density exhibited a linear decline with tree height (Fig. 3.3), which is consistent with previous research (McKinley *et al.*, 2000; Tsheaye *et al.*, 1995; Burdon *et al.*, 2003). This pattern clearly demonstrates that increases in MOE with stem height noted here and previously (Waghorn *et al.*, 2007; Lasserre *et al.*, 2005), were not at all attributable to density, but rather caused by the rapid reduction in MFA from the stem base to 5 m. By accepting a technical definition of the wood density (Cown 1992b) where a structural wood was defined as wood over 400 kg/m³, all four treatments produced wood far over the threshold value (Fig. 3.5 and 3.6). Due to the interaction between ring number and height (Fig 3.7) there were two rings (12 and 13) at 20 m height with density less than this threshold value, recording 390 and 395 kg/m³ respectively.

Stocking significantly affected MFA. This was consistent with results from previous studies (Lasserre *et al.*, 2005; Lindström *et al.*, 1998; Downes *et al.*, 2002; Barnett and Bonham, 2004; Lundgren, 2004; Watt *et al.*, 2005). The negative relationship between MFA and stocking exhibited a 12% or 3.0° decrease in MFA from 25.2° at 200 stems/ha to 22.2° at 1,100 stems/ha. The mean radial MFA decrease from the pith is also consistent with previous studies (Xu *et al.*, 2004; Donaldson, 1992; Cave and Walker, 1994; Walker and Butterfield, 1996; Butterfield, 1998). Donaldson (1992) assumed that MFA of 30° would be the cut-off point between structurally acceptable and unacceptable wood quality, largely depending on the wood density. All four stockings produced acceptable MFA (over the cut off point) after year 5 (Fig. 3.12).

Vertical variation in MFA for given ring number from the pith has been examined by Walker (2001), Xu and Walker (2004) and Donaldson (1992). As found here in all of these studies it was noted that wood of *P. radiata* from near ground level has low stiffness. Walker and Butterfield (1996) also found poor stiffness caused by high MFA at the base of the tree.

A positive relationship was found between MOE and stocking which demonstrated 28% or 3.5 GPa increase in MOE from 8.76 GPa at 200 stems/ha to 12.22 GPa at 1,100 stems/ha. Gains in MOE with increasing stocking were consistent with previous findings in *P. radiata* (Lasserre *et al.*, 2005, Waghorn *et al.*, 2007) and other species such as *Cryptomeria japonica* (Wang and Ko, 1998; Chuang and Wang, 2001), *Tsuga heterophylla*, *Picea sitchensis* (Wang *et al.*, 2001), *Pinus taeda* (Biblis *et al.*, 1995) and *Picea mariana* (Zhang *et al.*, 2002).

Previous research has shown that MOE increases with air temperature (Watt *et al.*, 2006). A comparison of results from this study, which was undertaken at one of the warmest forestry sites in New Zealand with previous findings at a cooler Canterbury site reinforces this relationship. Table 3.5 shows a wood property comparison at Canterbury and Northland sites:

Table 3.5. Summary of the variables measured in the sampled trees at breast height at age 5 years for trees growing at 833 stems/ha at Canterbury versus 500 stems/ha at Forsyth Downs.

		<u>Canterbury</u>	<u>Forsyth Downs</u>
		833 stems/ha	500 stems/ha
MFA	(°)	38	28
Basic density	(kg /m ³)	400	450
MOE	(GPa)	3.0	7.0

There were substantial differences between wood properties values on the cold southern site and the warm Northland site. Although the stocking at the Northland site was almost 350 stems/ha lower the wood properties were considerably improved, showing a two-fold gain in MOE.

Vertical variation in MOE noted here is similar to that found previously for *P. radiata*. For a 27 year old unthinned *P. radiata* stand grown at a stocking of 700 stems/ha MOE increased around 2 GPa from the base to 3 m (Xu and Walker, 2004). Waghorn *et al.* 2006 found a similar pattern of MOE increase over the height range for 17 year old *P. radiata* in Canterbury where longitudinal variation in MOE was highly significant and

MOE increased with increases in tree height from 5.1 GPa at the stem base, to 6.7 Gpa at 5 m. In this study MOE increased over 3 GPa from the base to 5m.

CHAPTER FOUR

USE OF RING WIDTH TO ACCOUNT FOR RADIAL AND LONGITUDINAL VARIATION IN WOOD PROPERTIES WITHIN A STOCKING TRIAL

4.1 INTRODUCTION

Forest managers need to know the wood quality attributes and how they relate to site, silviculture, genetics and age. This is important in order to market the logs properly, value the estate correctly and plan the future estate. Given the importance of MFA, MOE and density in determining wood quality, models describing these properties would be of considerable use to managers.

Many studies have used ring width to model density. For *P. radiata* and many other conifers, it is generally assumed that the wider the growth ring, the lower the wood density (Lindstrom 1996, Larson 1969). Frimbong-Mensah (1987) found in *Picea abies* (Norway spruce) a negative correlation between the ring width and density accounted for 67% of the variation in the data. Olesen (1976) found a strong negative correlation between ring width and wood density for the same species in Norway spruce. In contrast, Petty *et al.* (1990) and Blouin *et al.* (1994) in the same species found that density was only weakly correlated with ring width.

For pine species there is often a weak or little correlation between ring width and density (Zobel 1989). Zhu *et al.* (2004) found wood density to increase or was not affected negatively by ring width in fast growing *Pinus resinosa* trees. Kininmonth and Whitehouse (1991) found that ring number was a major driver in variability of wood properties of *P. radiata* and there was an inverse relationship between ring width and wood density.

Much research has concluded that if the size of the ring width in early years increases the MOE declines (Bowyer *et al.*, 2003). Ring width was significantly related to both MOE and MFA in young *P. radiata* (Watt *et al.* 2004) A weak positive correlation between ring width and MFA has also been found in stands of *Pinus taeda* (Megraw,

1985), *Pseudotsuga menziesii* (Erikson and Arima, 1974), *Pinus elliottii* (Hiller, 1964) and *Picea abies* (Lindstrom *et al.*, 1998).

Many studies show that MFA varies with cambial age, growth rate, and height within the stem (Erickson and Arima, 1974; Donaldson, 1992; Cave and Walker, 1994). The inverse of cambial age has been used to explain variation in MFA in *P. abies* (Lindstrom *et al.* 1998). This research found that cambial age of a growth ring number was the most important determinant of MFA. Other variables that reflect growth conditions were also found significant, although they did not add much to the model accuracy (Lindstrom *et al.*, 1998). Lundgren (2004) found a weak correlation between ring width and MFA in Norway spruce trees. In a study on 11 year old *P. radiata* at Canterbury it was found that MFA was significantly correlated with fibre length, ring width, MOE and tree diameter (Lasserre *et al.* 2007). Considerable research has shown that MOE and MFA vary across stand density gradients and are significantly related to ring width. However little research has investigated whether ring width accounts for longitudinal and radial variation in these properties across stocking gradients.

Using ring width to predict MFA and MOE, across a stocking gradient will be the focus of this chapter. These objectives of this chapter were to (i) determine how the continuous variable ring width influences wood properties and (ii) determine whether there are significant treatment effects remaining after accounting for the effect of ring width.

4.2 METHODS

Site and experiment treatments

This study was carried out on data from an experiment established by the ex-Carter Holt Harvey Forests. The thinning trial was situated at Forsyth Downs, Mangakahia District of ex Carter Holt Harvey Forests Ltd. in the Northland region. The experimental site was located on a north east aspect at an elevation ranging from 350 to 385 m and slope between 5° and 15°. The site was on Waimatenui clay soils of moderate

to high fertility with an average rainfall of 1,180mm per year, with most rainfall occurring during winter (42.5 % of the annual rainfall occurs between May and August).

The Forsyth Downs trial was established as a randomized block design, with 4 treatments and 4 replicates that included a total 16 plots with an inner measurement area of 0.1 hectare per plot.

The area was planted in winter 1982 at an initial stocking of 1,667 stems/ha and spacing of 2 × 3 m with *P. radiata* seedlings from GF 7 stock and thinned in 1987 to 200, 350, 500 and 1,100 stems/ha. At age 5, sixteen 0.4 ha plots were overlaid using a randomized block design, with four replicates per spacing treatment. Diameters of all stems were measured at breast height (1.4 m) prior to thinning.

Measurements

Measurements were undertaken on an annual basis until age 16 and four years later at ages 20, 23 and 24 for diameter at breast height and tree height (random sample over the diameter range) for all residual stems in the experimental plots. Data have been stored in the PSP database, maintained by Scion.

Measurements of wood properties using SilviScan were made on 10 stems from each of the four spacing treatments. For each tree a single radius from each of 4 heights (0, 1.4, 5 and 20 m) were analysed using SilviScan.

SilviScan samples were prepared according to established procedures (i.e. soaked in ethanol for several weeks with two changes of ethanol) prior to dispatch to CSIRO, Melbourne.

SilviScan provided three forms of data that included;

- a) X-ray densitometry from pith to bark (air-dry density)
- b) X-ray diffraction from pith to bark (MFA, relative spiral grain)
- c) Estimated stiffness from pith to bark (MOE), using density and MFA

Each SS sample yields a pith-to-bark profile of wood properties. The average wood property value for each core was determined as the simple average of the profile properties. Radial and tangential profiles of density, MFA and estimated MOE were assessed on each disc height at a sampling interval of 50 μm . Radial profiles of ring width were determined for each disc during the Silviscan procedure.

Data analysis

Statistical analysis was undertaken using SAS 9.3 software (SAS Institute, 2000). Analysis of variance was used to examine the main and interactive effects of stand density on ring width.

The analysis compares mixed effects model that include the following three combinations of variables. The first model was a reference model (Equation 4.1) and only included the main and interactive effects of stocking, disc height and ring number. The second model (Equation 4.2) includes ring width in a polynomial formulation. In the third model the main and interactive influence of stocking, height and ring number were examined by adding these to a model with ring width, to determine how much of the treatment variance was captured by ring width (Equation 4.3).

$$Y_{ijk} = \mu + \alpha_k + \beta_i + \gamma_j + (\beta\gamma)_{ij} + (\alpha\beta)_{ki} + (\alpha\gamma)_{kj} + (\alpha\beta\gamma)_{ijk} + e \quad [4.1]$$

$$Y_{ijk} = \mu + rw_{ijk} + rw^2_{ijk} + e \quad [4.2]$$

$$Y_{ijk} = \mu + rw_{ijk} + rw^2_{ijk} + \alpha_k + \beta_i + \gamma_j + (\beta\gamma)_{ij} + (\alpha\beta)_{ki} + (\alpha\gamma)_{kj} + (\alpha\beta\gamma)_{ijk} + e \quad [4.3]$$

where Y_{ijk} are MOE, MFA or density at i^{th} stocking, j^{th} disc height, k^{th} ring number, μ the overall mean, rw the ring width, α the stocking, β the disc height, γ the ring number, $(\beta\gamma)$ the interaction between disc height and ring number, $(\alpha\beta)$ the interaction between stocking and disk height, $(\alpha\gamma)$ the interaction between stocking and ring number, $(\alpha\beta\gamma)$ the interaction between stocking, disc height and ring number, and e is the experimental error.

4.3 RESULTS

Ring width (RW)

Ring width was significantly affected ($P < 0.0001$) by stocking, height and ring number. All interactions significantly affected ring width (Table 4.1).

Table 4.1. Analysis of variance table describing the main and interactive effects of stocking, height and ring number on ring width.

Effect	F Value	Pr > F
Stocking	11.61	0.0065
Height	179.53	<.0001
Ring Number	367.79	<.0001
Stocking x Height	4.32	<.0001
Stocking x Ring Number	4.89	<.0001
Height x Ring Number	7.54	<.0001
Stocking x Height x Ring Number	1.52	<.0001

Ring width increased rapidly in the early years reaching a peak at ring 2 -3, after which time ring widths decreased (Fig. 4.3). Ring width exhibited a linear decline with tree height by 11% from 9.8 mm at a height of 0 m to 8.7 mm at a height of 5 m and increased around 4.5% to 9.1 mm at a height of 20 m. There was a significant decrease in ring width with stocking, from 11.2 mm to 7.3 mm (26%) for 200 and 1,100 stems/ha respectively (Fig. 4.1). The ring widths for treatments 350 and 500 stems/ha were almost identical (Fig. 4.1).

While there was a significant interaction between height and stocking this was relatively weak compared to the other interactions (Table 4.1). This interaction was attributable to the rank changes between 350 and 500 stems/ha (Fig. 4.5). The significant interaction between ring number and height was due to a different trajectory in ring width across the cambium for data from 20 m (Fig. 4.6). There was a significant interaction between ring number and stocking that was attributable to the greater reduction in ring

width across the ring number that occurred at higher stocking relative to low stocking during intermediate ages (Fig. 4.4). A weak but significant relationship was evident between stocking, height, ring number and ring width (Table 4.1).

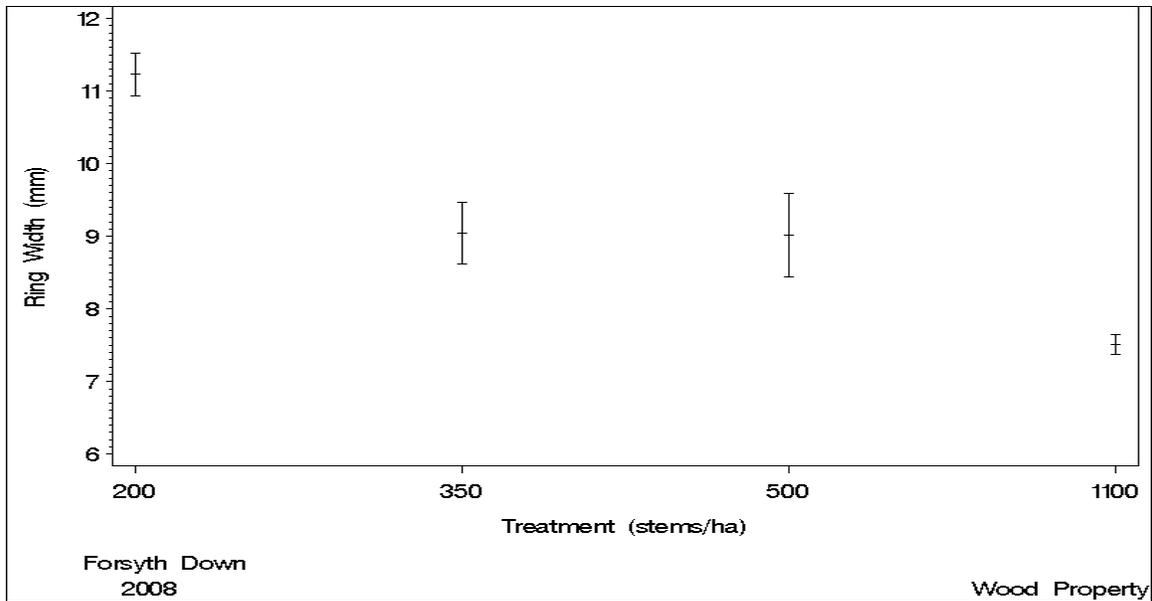


Fig. 4.1. Ring width plotted against stocking (std error bars from 10 trees)

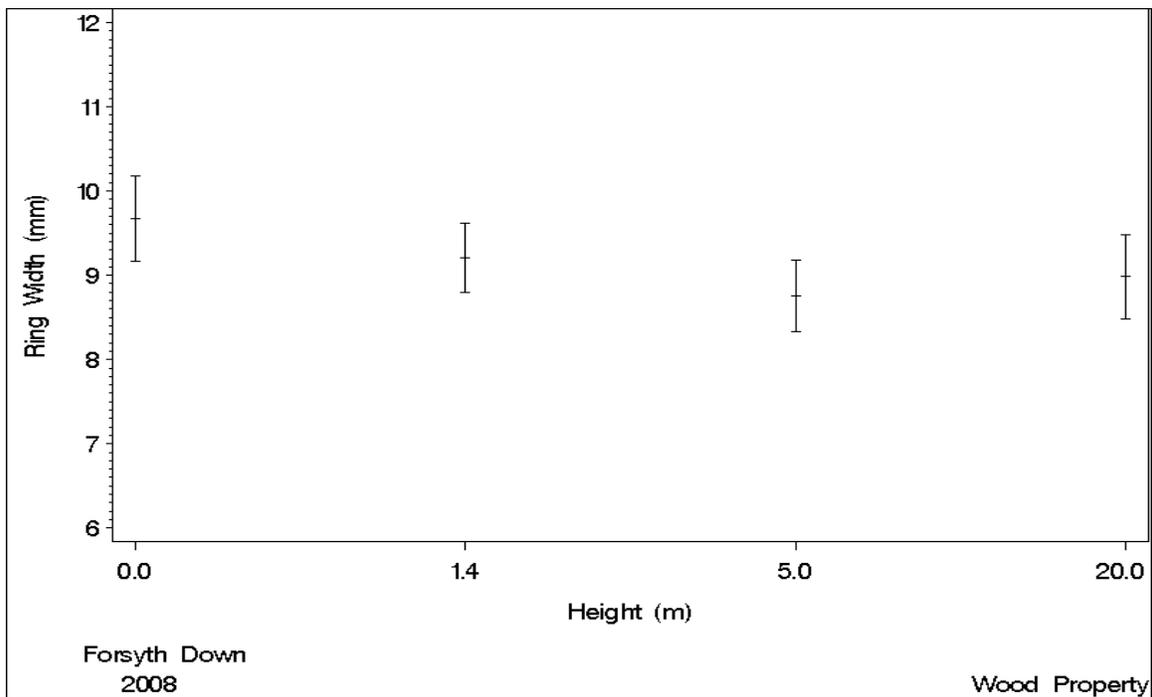


Fig. 4.2. Ring width plotted against height (std error bars from 10 trees).

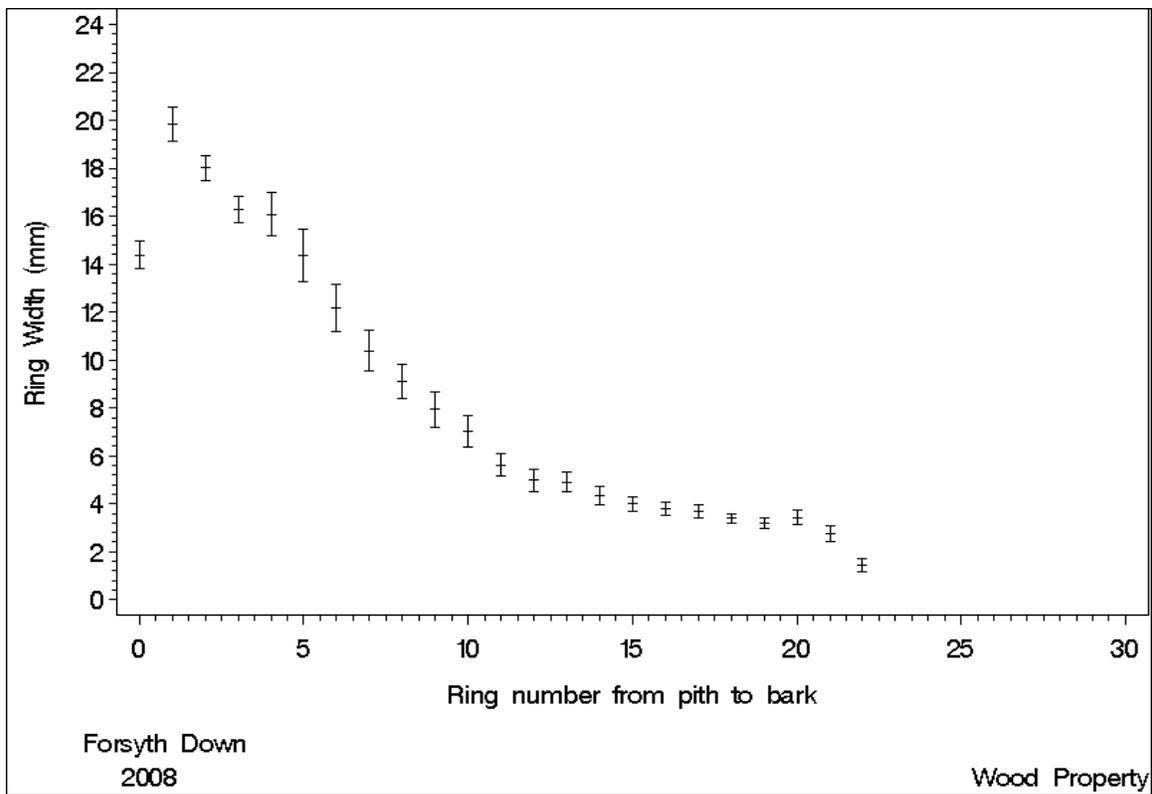


Fig. 4.3. Ring width plotted against ring number (std error bars from 10 trees)

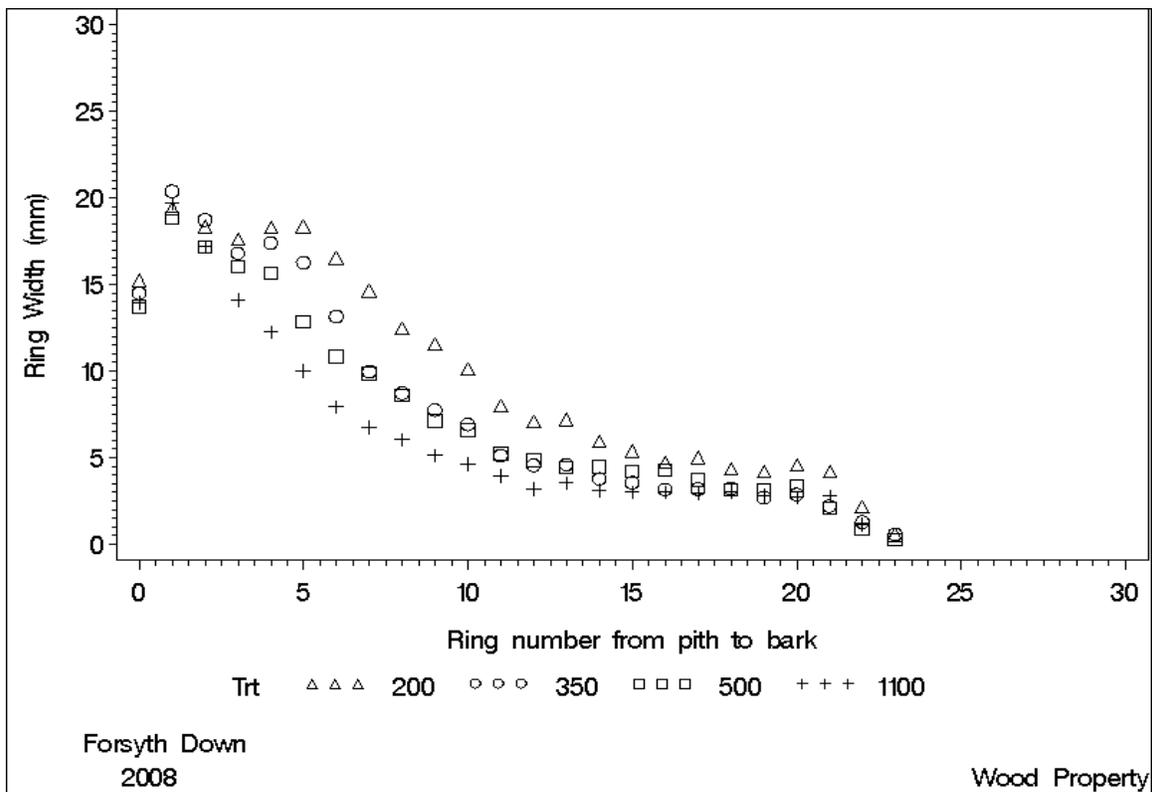


Fig. 4.4. Relationship between ring width and ring number, by stocking

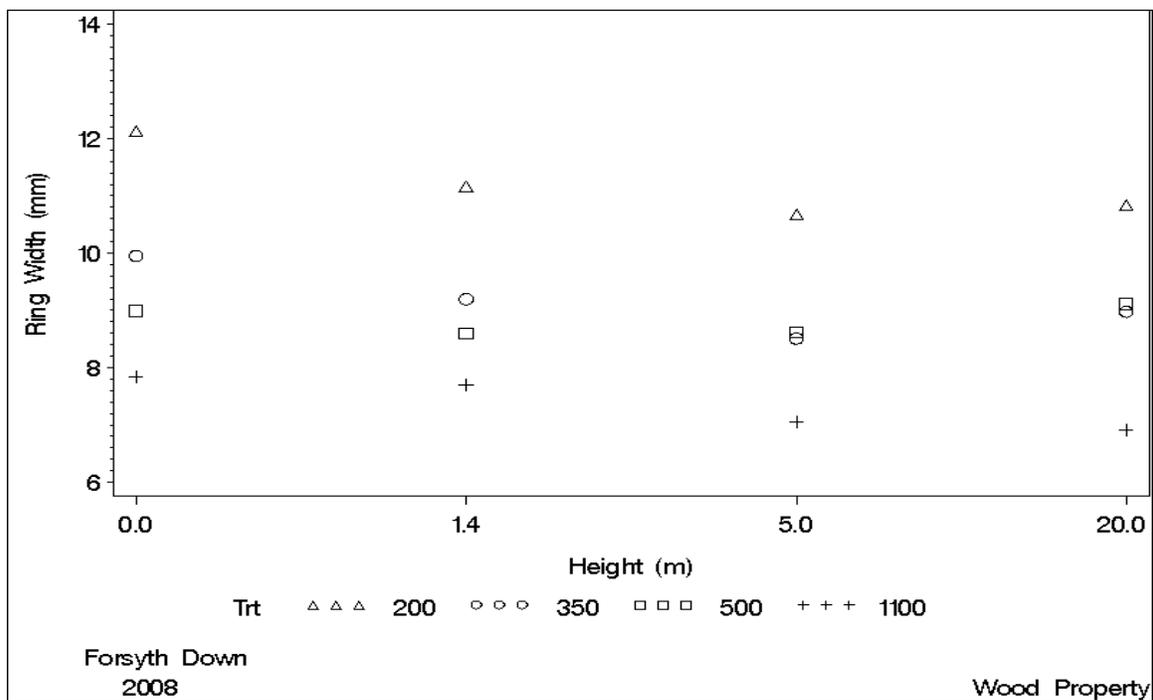


Fig. 4.5. Relationship between ring width and height, by stocking

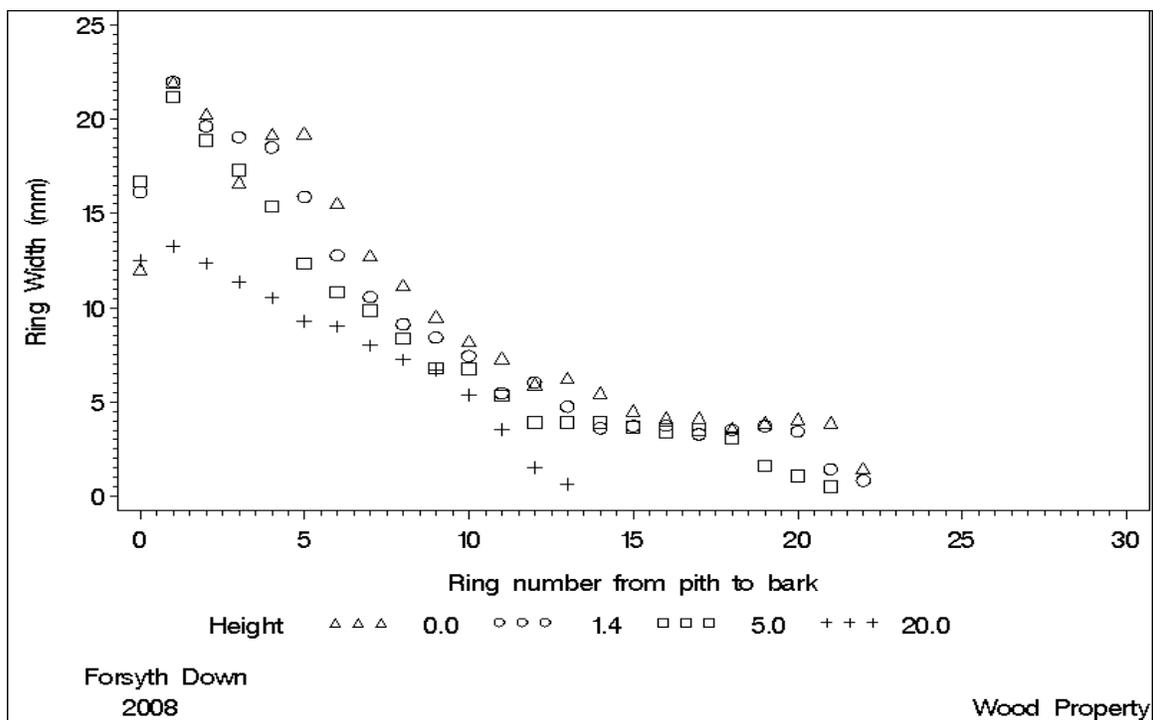


Fig. 4.6. Relationship between ring width and ring number, by height

Density and ring width

Density increased rapidly at smaller ring widths reaching a peak of over 700 kg/m³ at 3-5 mm ring width before decreasing (Fig. 4.7).

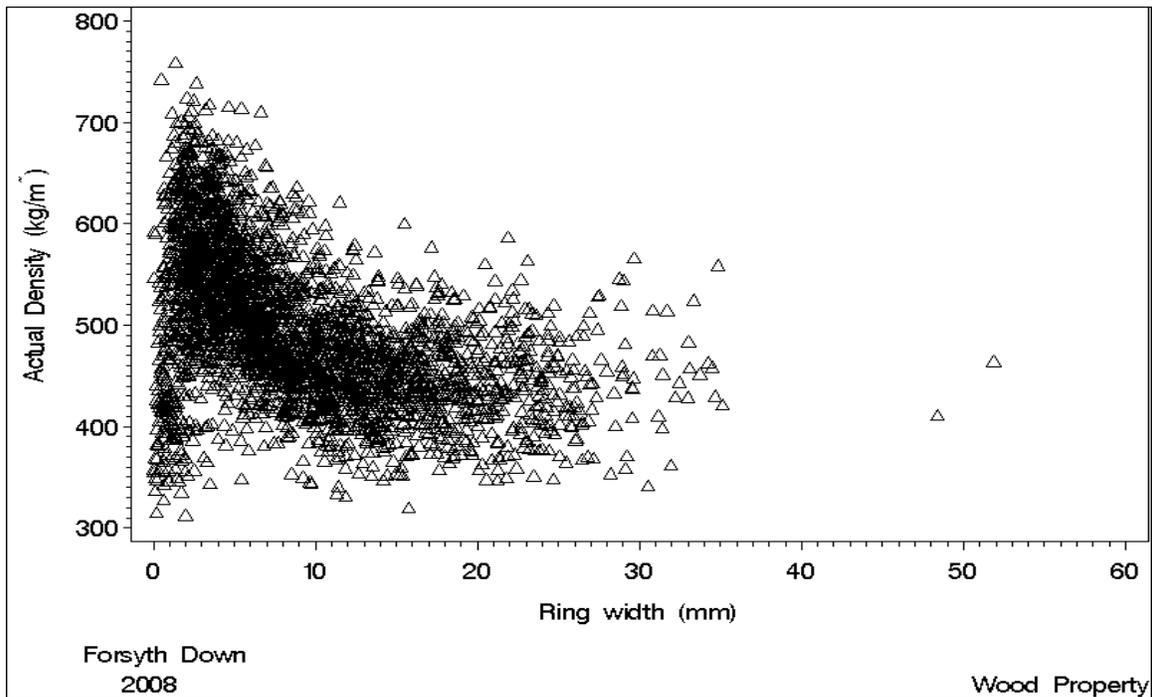


Fig. 4.7. Actual density plotted against ring width

Model statistics of the mixed functions fitted to the density data are as follows:

Table 4.2. Model statistics for the mixed functions of density.

<i>Statistics</i>	<i>Mixed (4.1)</i>	<i>Mixed (4.2)</i>	<i>Mixed (4.3)</i>
Std deviation	38.89	57.24	38.88
Variance	1512	3276	1512
Std Error Mean	0.71	1.04	0.71
Range	416.3	427.1	415.5
-2RLL	28798.9	33424.8	28805.6
AIC	28806.9	33430.8	28813.6
AICC	28806.9	33430.8	28813.7
BIC	28803.3	33428.1	28810.0

The residuals analysis showed the best fit of the density data by mixed equations [4.1] and [4.3]. The fit of the statistics was lower for equation [4.1] but there was some sign of bias in residuals and the degree of heterogeneity was high, therefore equation [4.3] was used for density model. The residual distribution in equation [4.3] was normal (Fig. 4.8), the range of the residuals was relatively low, standard error mean was reasonably low (Table 4.2) and there was little bias in relation to predictions (Fig. 4.9). As a result we could confidently use the mixed equation [4.3] for the density prediction.

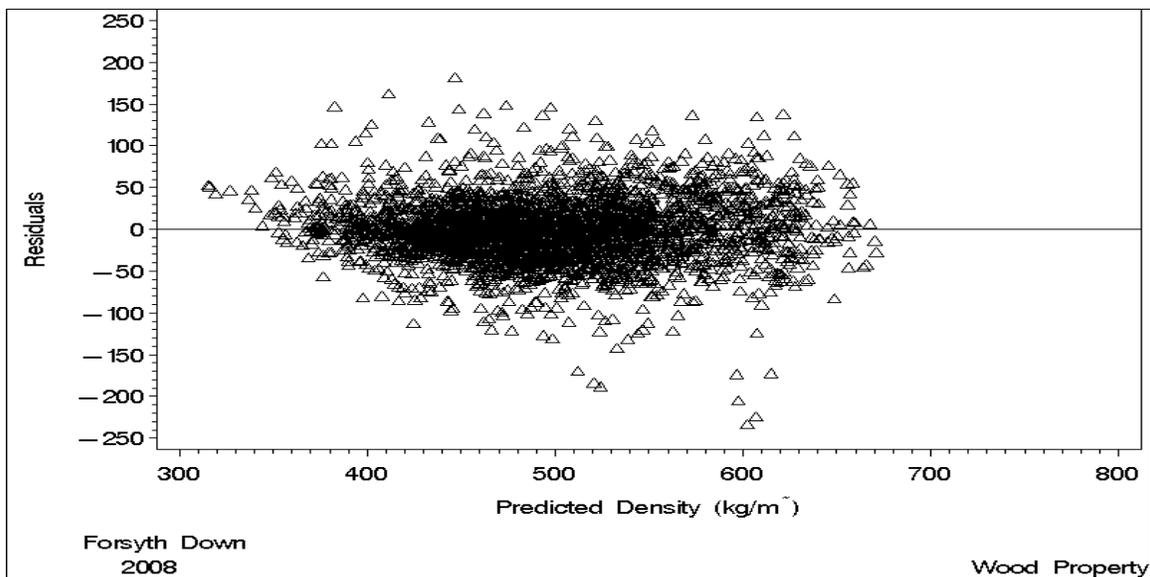


Fig. 4.8. Density residuals of mixed function showed fairly randomly scattered data about the zero residual line

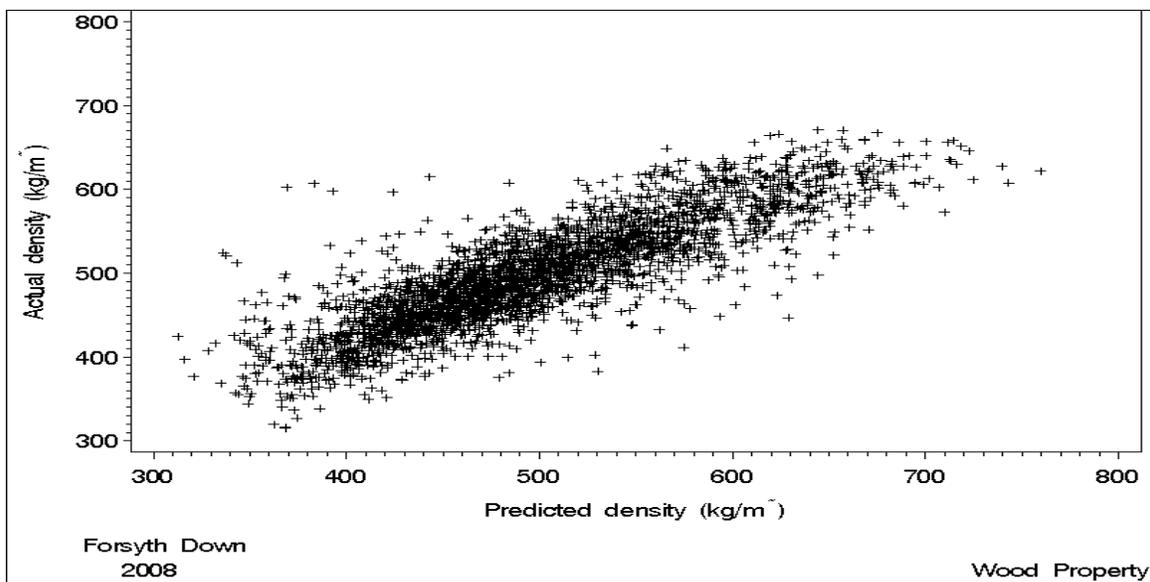


Fig. 4.9. Measured density plotted against predicted density

Using equation 4.3 the model was significantly affected by height and ring number in the tree but not by stocking (Table 4.3). With the exception of the three-way interaction, all interactions significantly affected density. Equations [4.1] and [4.3] had very similar model statistics as there was no effect of the ring width on the density.

Table 4.3. Analysis of variance table of the mixed model describing the main and interactive effects of ring width, stocking, height and ring number on density

Effect	F Value	Pr > F
Ring width	0.63	0.4287
Ring width x Ring width	0.42	0.5188
Stocking	3.66	0.0828
Height	76.70	<.0001
Ring number	47.60	<.0001
Stocking x Ring number	4.74	<.0001
Height x Ring number	8.99	<.0001
Stocking x Height x Ring number	0.81	0.9642

Ring width by itself was significant as a predictor of density, but when it was combined with other variables it was insignificant. This suggests it does not account for treatment effects, and it did not add anything to a model with only class effects.

To determine why ring width was insignificant in the model, the ring number was included as a polynomial effect in the model with ring width (equation 4.4) and compared to a polynomial formulation of the ring width model (equation 4.5) and to a polynomial formulation of the ring number model (equation 4.6), described as,

$$Y = \mu + rw + rw^2 + rn + rn^2 + e \quad [4.4]$$

$$Y = \mu + rw + rw^2 + e \quad [4.5]$$

$$Y = \mu + rn + rn^2 + e \quad [4.6]$$

where rw and rn are ring width and ring number respectively.

The F and P values and fit statistics for all models (4.4, 4.5, and 4.6) were assessed and presented in Table 4.4.

Table 4.4. Analysis of variance table of the mixed model describing the effects of ring width and ring number on density with fit statistics.

Model	[4.4]		[4.5]		[4.6]	
Effect	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F
Rwidth	2.35	0.1258	419.28	<.0001		
Rwidth x Rwidth	0.95	0.3301	119.11	<.0001		
Rnumber	783.7	<.0001			842.8	<.0001
Rnumber x Rnumber	334.0	<.0001			297.6	<.0001
Fit Statistics						
-2RLL	32499.7		33424.8		32528.2	
AIC	32505.7		33430.8		32534.2	
AICC	32505.7		33430.8		32534.2	
BIC	32503.0		33428.1		32531.5	

There was significant impact on density by ring number while ring width was insignificant in equation 4.4. Fit of the statistics was lowest for equation 4.4, followed by 4.6. A comparison of ring width to ring number indicated that when only a single variable was included ring number had a greater influence on density than ring width, but did still not account for the main or interactive effects of stocking or height on density (data not shown).

MFA and ring width

MFA was positive correlated to the ring width (Figure 4.10) at any position of the stem, ranging from 13° to 50°.

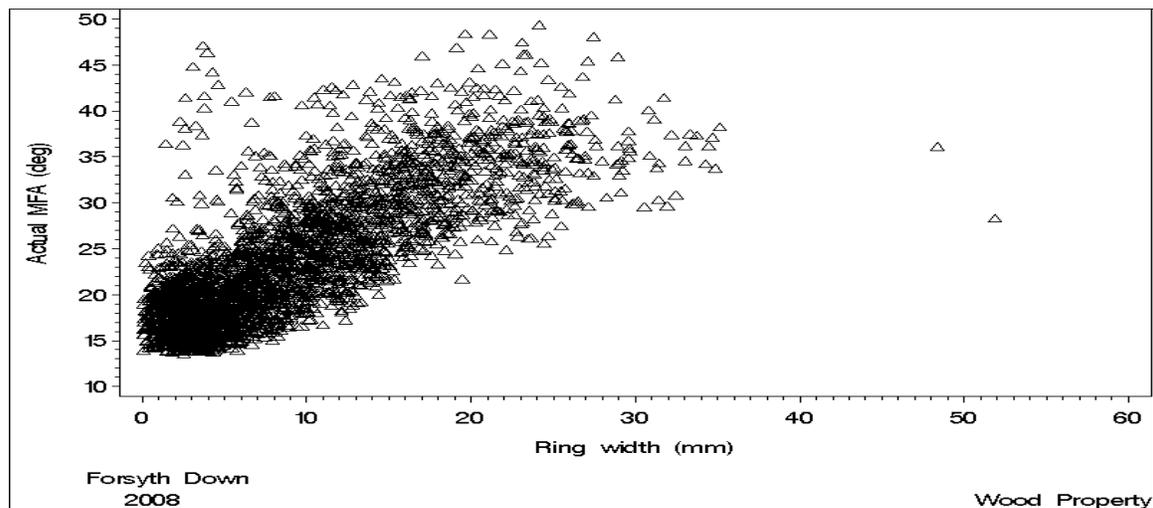


Fig. 4.10. Actual MFA plotted against ring width

Table 4.5. Model statistics for the mixed functions of MFA.

<i>Statistics</i>	<i>Mixed (4.1)</i>	<i>Mixed (4.2)</i>	<i>Mixed (4.3)</i>
Std deviation	2.45	4.29	2.31
Variance	5.99	18.37	5.33
St Error Mean	0.044	0.077	0.042
Range	29.1	40.4	32.6
Fit Statistics			
-2RLL	13754.6	17646.5	13454.3
AIC	13760.6	17652.5	13460.3
AICC	13760.7	17652.5	13460.3
BIC	13757.9	17649.8	13457.5

Results of the analysis showed the best fit of the data by mixed equation [4.3]. The residual distribution was normal (Fig. 4.11), the range of the residuals was relative low, standard error of the mean was relatively low and no bias in relation to predictions,

consequently we could use confidently the mixed equation [4.3] for the MFA prediction. The likelihood-based statistics of AIC, AICC and BIC showed that equation [4.3] provided the best fit to the data (Table 4.5).

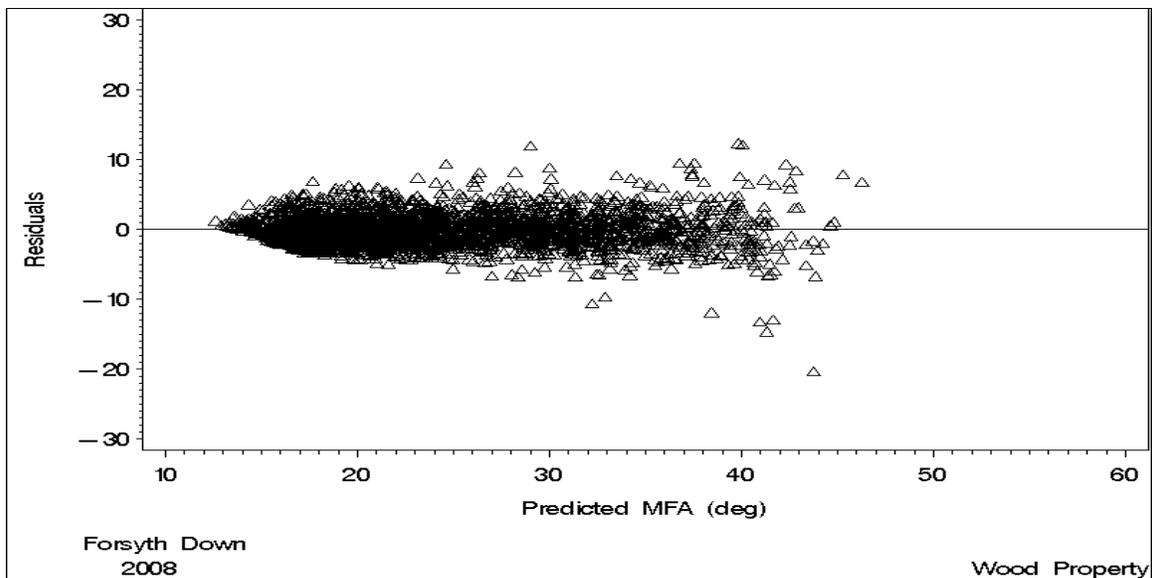


Fig. 4.11. MFA residuals of mixed function showed fairly randomly scattered data about the zero residual line (horizontal lines show the bias - difference between actual value and predicted values).

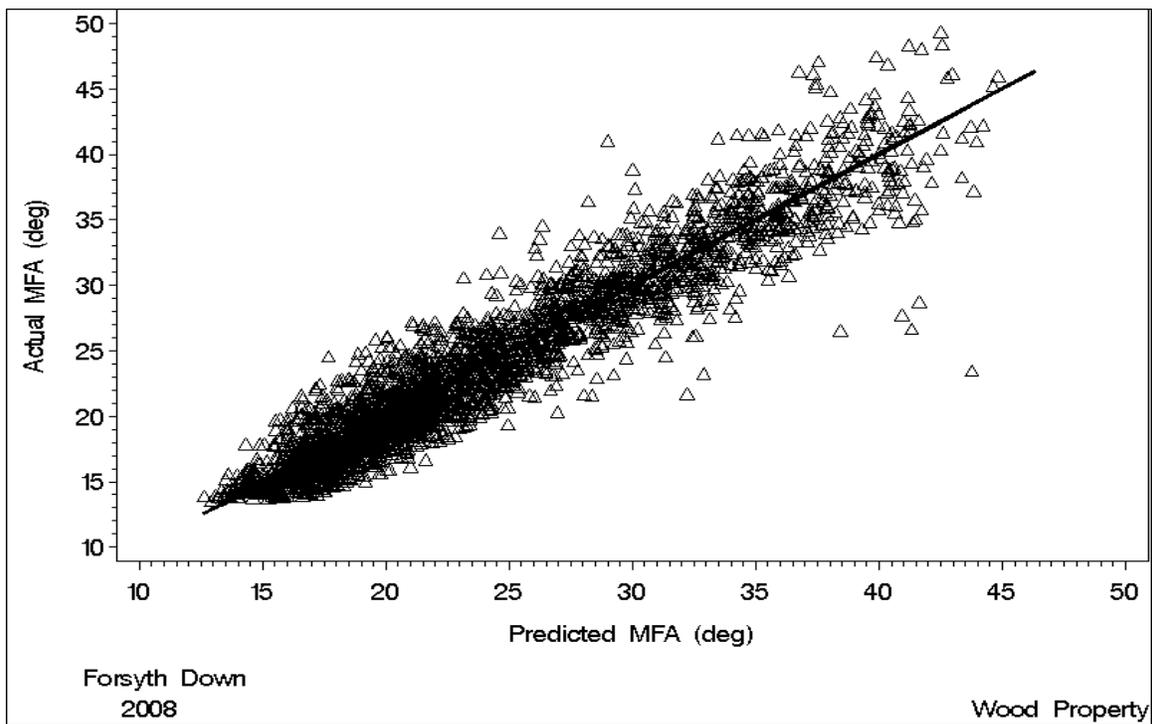


Fig. 4.12. MFA measured plotted against predicted MFA

Plotting residuals over predicted values indicated little apparent bias (Fig. 4.11). This is confirmed by the standard error mean that is very near zero. Both actual and predicted values ranged from 12° to 45° with no sign of diverging distribution. (Fig. 4.12). There was no sign of any systematic error in the model. There appear to be no patterns of residuals when plotted against ring width (not shown).

The model was significantly affected by ring width, height and ring number in the tree but not by stocking. With the exception of the three-way interaction, all interactions significantly affected MFA (Table 4.6). Ring width was significant in MFA model both by itself and when it was combined with other variables. Ring width accounted for the stocking effect.

Table 4.6. Analysis of variance table of the mixed model describing the main and interactive effects of ring width, stocking, height and ring number on MFA

Effect	F Value	Pr > F
Ring width	215.88	<.0001
Ring width x Ring width	69.10	<.0001
Stocking	3.55	0.0875
Height	831.23	<.0001
Ring number	104.71	<.0001
Stocking x Ring number	2.64	<.0001
Height x Ring number	13.43	<.0001
Stocking x Height x Ring number	1.19	0.0501

Means were calculated for MFA (equation 4.3) before and after (using the LSmeans function) the addition of ring width and plotted against height and ring number as they had a key effect on these class level variables in the model.

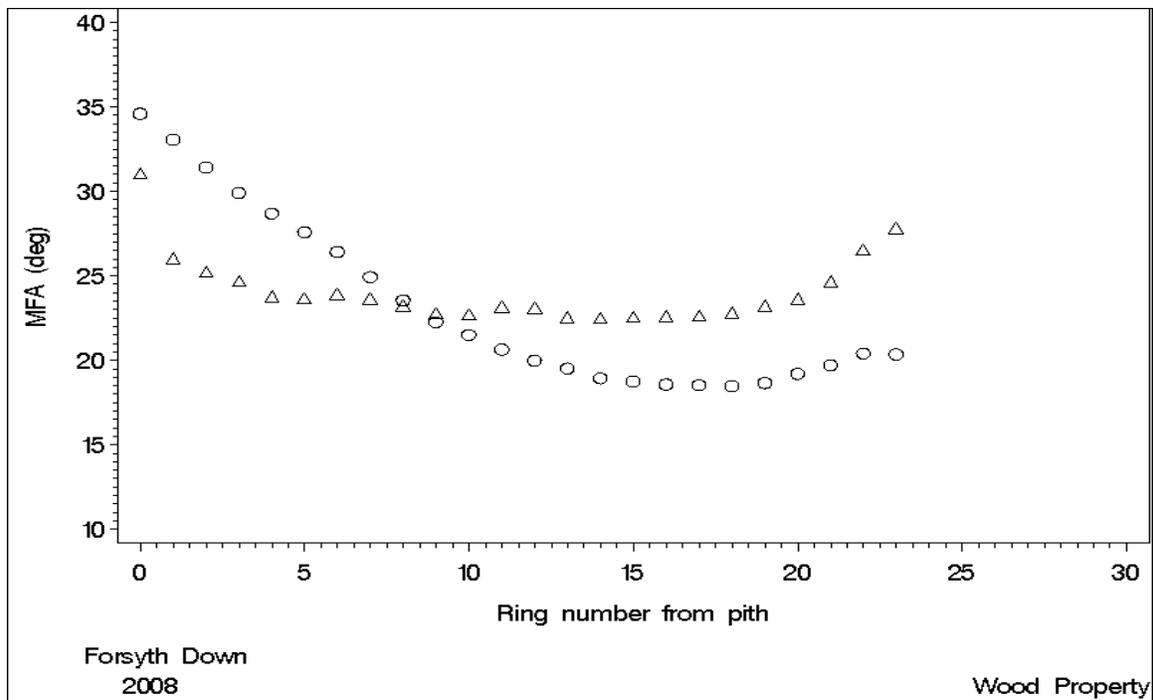


Fig. 4.13. MFA adjusted for ring width (triangles) and unadjusted (circles) plotted against ring number.

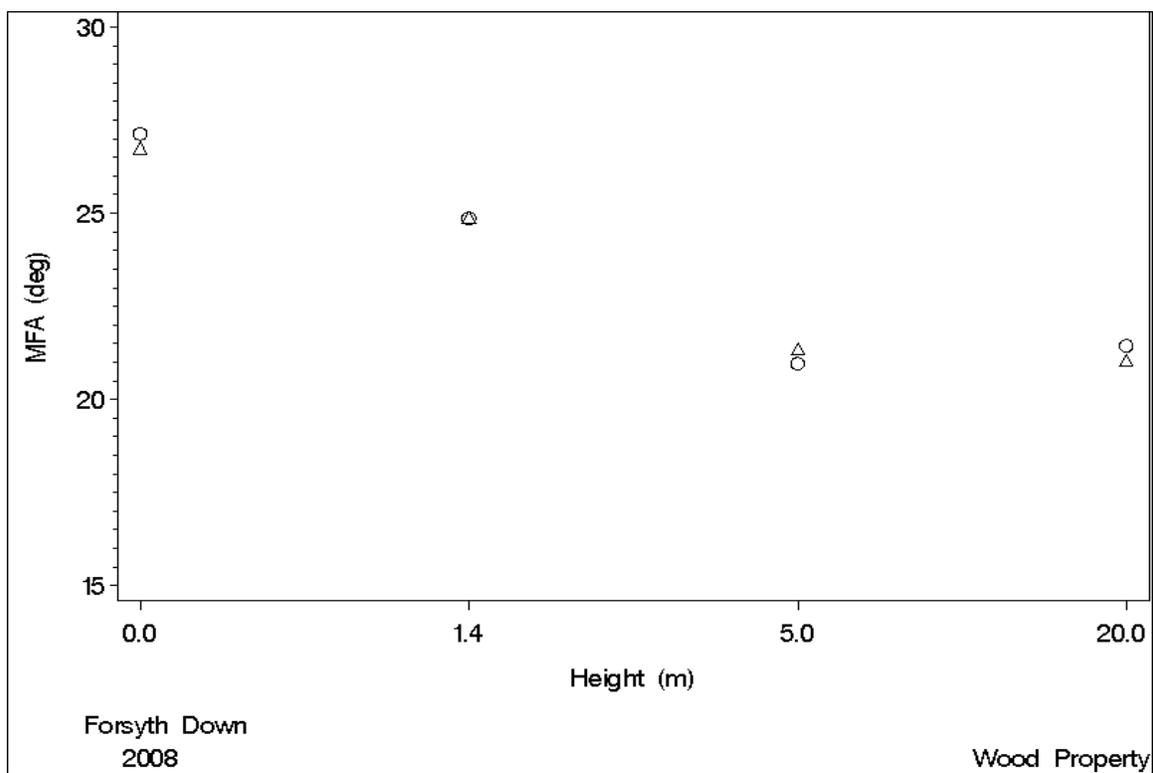


Fig. 4.14. MFA adjusted for ring width (triangles) and unadjusted (circles) plotted against height.

Adjusted MFA by ring width is almost identical to unadjusted in the vertical direction, there is no almost any additional residual effects on MFA (Fig 4.14). In the radial direction ring width reduced the magnitude of the ring number effect on MFA, and the residual response only occurred at very low and high ring numbers.

MOE and ring width

MOE was negatively correlated to ring width (Fig. 4.15).

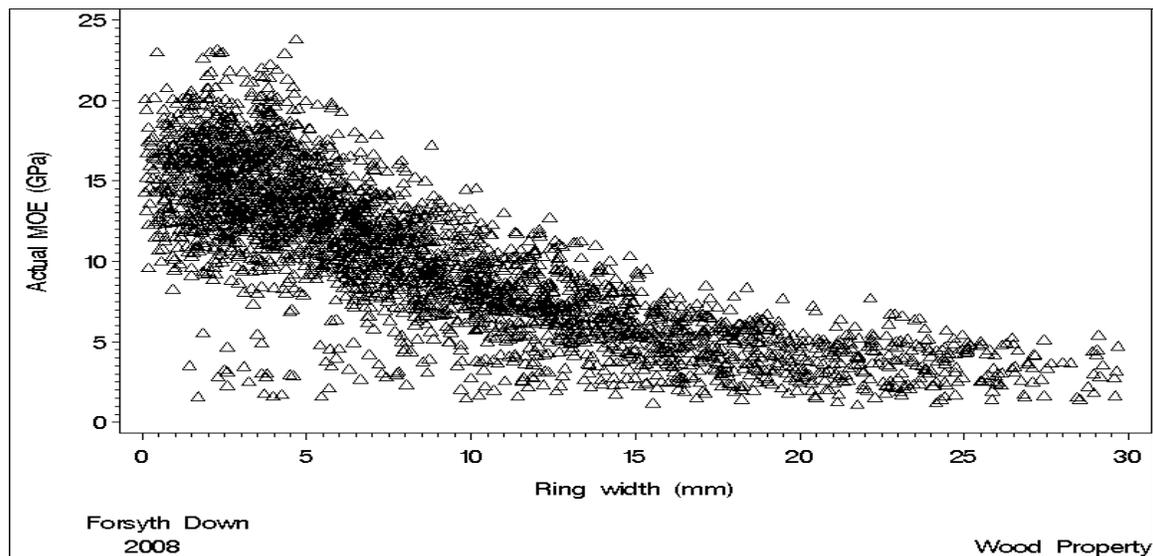


Fig. 4.15. Actual MOE plotted against ring width

Table 4.7. Model statistics for the mixed functions of MOE.

<i>Statistics</i>	<i>Mixed (4.1)</i>	<i>Mixed (4.2)</i>	<i>Mixed (4.3)</i>
Std deviation	1.62	2.49	1.54
Variance	2.64	6.18	2.36
Std Error Mean	0.029	0.045	0.028
Range	14.1	22.7	13.4
Fit Statistics			
-2RLL	11536.6	14352.8	11254.5
AIC	11540.6	14358.8	11258.5
AICC	11540.6	14358.8	11258.5
BIC	11538.8	14356.1	11256.7

Model statistics showed that Equation 4.3 fitted the data best. The residual distribution was normal, the range of the residuals was relative low, standard error of the mean was relatively low and little bias was found in relation to predictions, so we could use confidently the mixed equation [4.3] for the MOE prediction.

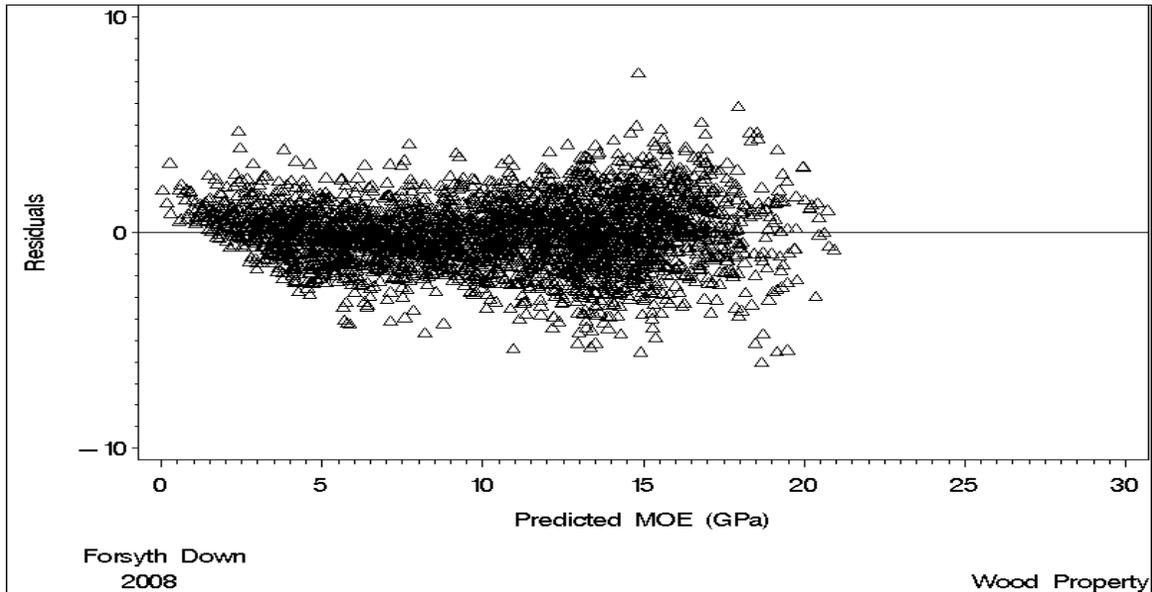


Fig. 4.16. MOE residuals of mixed function showed fairly randomly scattered data about the zero residual line

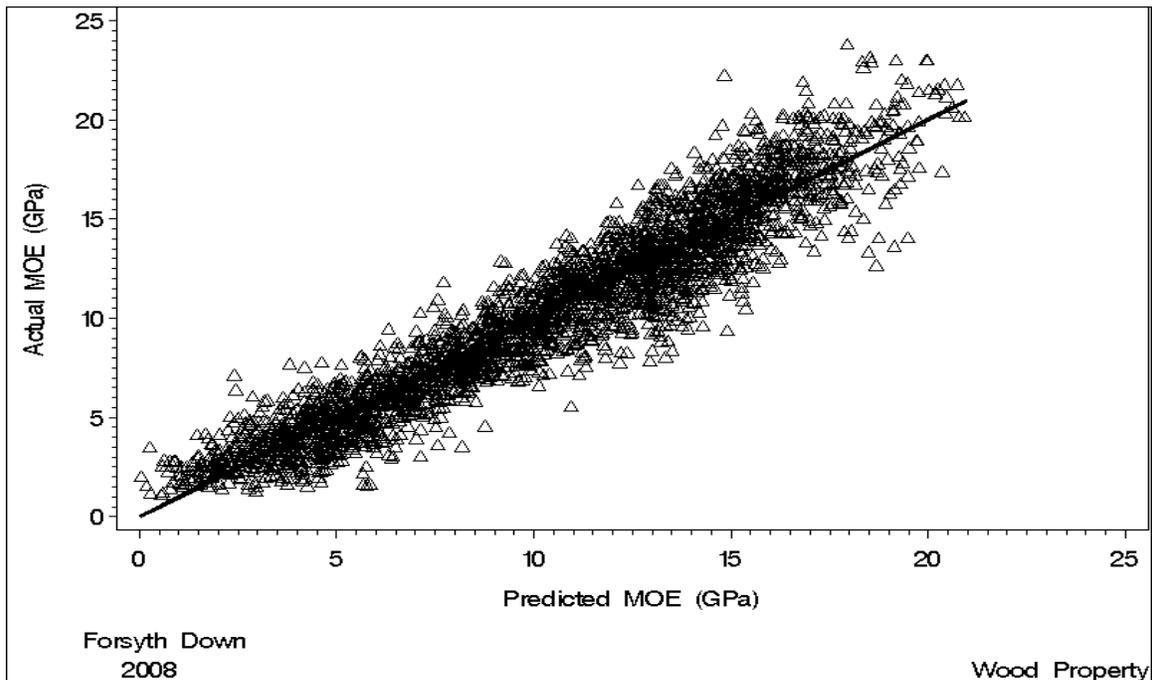


Fig. 4.17. Measured MOE plotted against predicted MOE

Actual and predicted values of MOE were plotted as an XY plot and are shown in (Fig 4.17). Both, actual and predicted values ranged from 1 GPa to 22 GPa. There was no sign of any systematic error in the model (Fig. 4.16) and the model produced unbiased errors.

Ring width, height, ring number and stocking significantly affected MOE. With the exception of the three-way interaction, all interactions significantly affected MOE (Table 4.8).

Table 4.8. Analysis of variance table of the mixed model describing the main and interactive effects of ring width, stocking, height and ring number on MOE

Effect	F Value	Pr > F
Ring width	280.37	<.0001
Ring width x Ring width	150.45	<.0001
Stocking	11.83	0.0063
Height	345.35	<.0001
Ring number	101.24	<.0001
Stocking x Ring number	5.82	<.0001
Height x Ring number	4.17	<.0001
Stocking x Height x Ring number	0.95	0.6678

MOE was highly correlated with height and ring number within the tree. Ring width was significant in the MOE model both by itself and when it was combined with other variables.

Means were calculated for MOE before and after addition of ring width and plotted against height, ring number and stocking as they had a strong effect on the model.

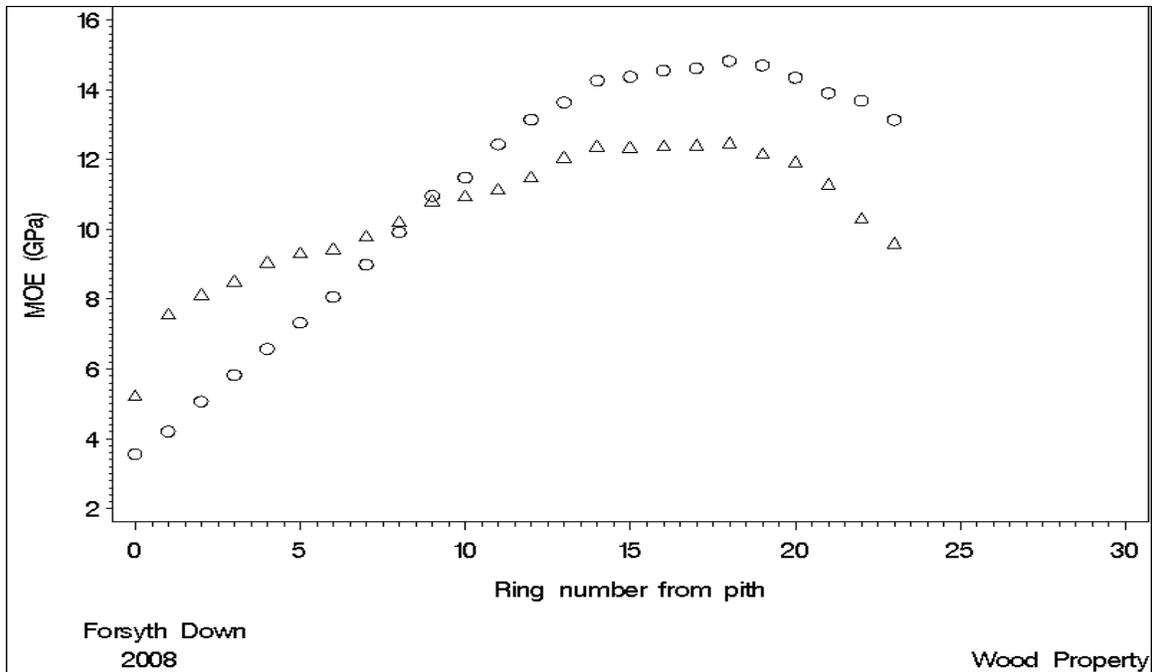


Fig. 4.18. MOE adjusted for ring width (triangles) and unadjusted (circles) plotted against ring number

In the radial directions there was some additional residual effects on MOE after correcting for ring width (Fig 4.18) although the magnitude of this effect was dampened.

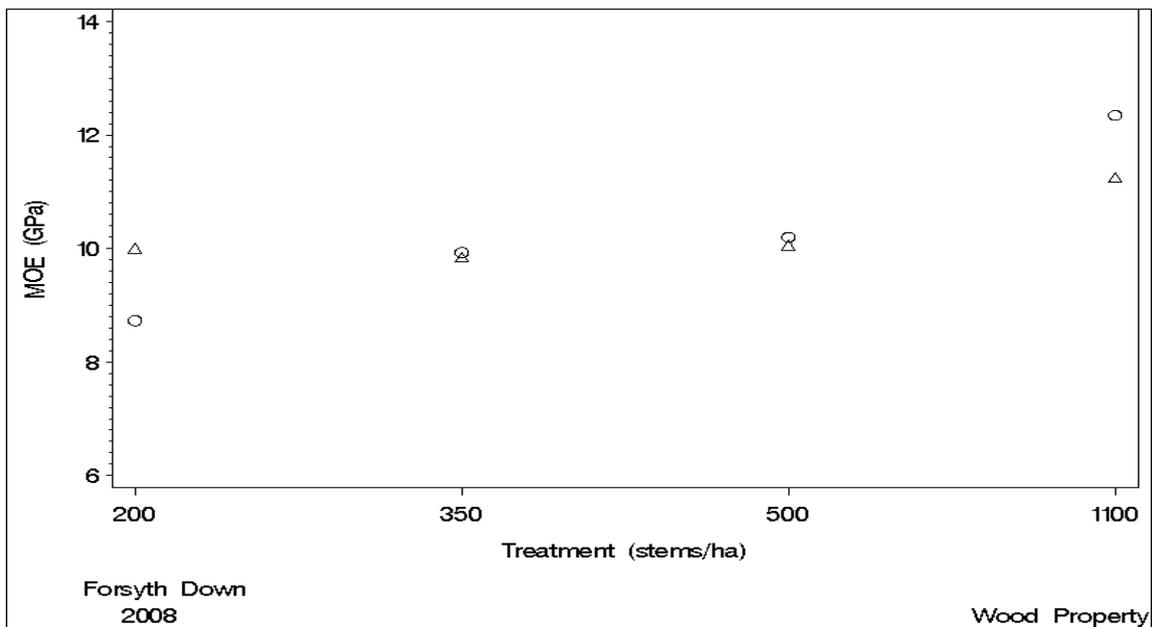


Fig. 4.19. MOE adjusted for the ring width (triangles) and unadjusted (circles) plotted against stocking.

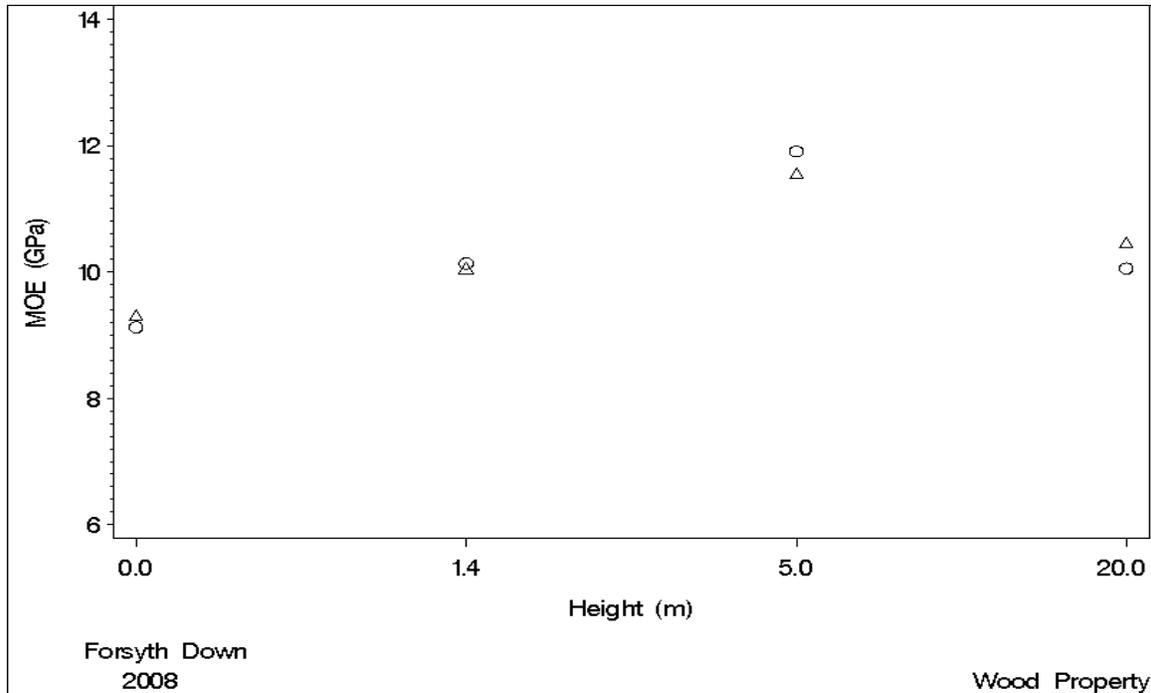


Fig. 4.20. MOE adjusted for the ring width (triangles) and unadjusted (circles) plotted against height.

Adjusted MOE by ring width is almost identical to that unadjusted in vertical directions (Fig 4.20). Accounting for ring width removed virtually all of the stocking effect on MOE, apart from that which occurred at high stockings.

4.4 Discussion

Many studies have suggested that growth rate as measured by ring width has an insignificant to weak effect on wood quality for *P. radiata* (Cown, 1973, 1974b; Sutton and Harris, 1974; Cown and McConchie, 1982). We found in this study that ring width by itself was a significant as a predictor of density, but when was combined with other variables it was insignificant (i.e. does not account for treatment effects), and it did not add anything to a model with only class effects. A comparison of ring width to ring number indicated that ring number had a much greater influence on density than ring width. However a model with ring number did not account for the main or interactive effects of stocking and height on density.

The significant correlation between ring width and MFA found in this study was consistent with results from other studies (Lindström *et al.*, 1998; Downes *et al.*, 2002; Barnett and Bonham, 2004; Lundgren, 2004; Watt *et al.*, 2005) but contradicted those of Erickson and Arima (1974) who found a poor relationship between growth rate and MFA. Lasserre *et al.*, 2005, suggested that treatment influences on MFA are at least partially mediated through growth rate and that variation in MFA between initial spacings is not entirely attributable to tree diameter. In this study ring width was significant in MFA model both by itself and when it was combined with other variables. Ring width accounted for the stocking effect. However, analyses showed that the significant decline in MFA with increasing tree height was not accounted for by ring width, as although changes in ring width were significant, values remained relatively constant over the height range.

This study justifies the importance of spacing in regulating MOE and showed the significant improvements in MOE that occurred through increasing final stocking. In this study we found that the ring width, as a continuous variable significantly accounted for stocking variation in MOE. However, as found for MFA, ring width did not account for the significant changes in MOE with height, which increased to a peak at 5 m both before and after inclusion of ring width as a factor.

The aim of the study was to develop a practical wood properties model based on variable that directly relates to the trees growth conditions at the Northland site. The independent variable, ring width is easily accessible through the normal inventory procedures and would be easily translated into a model describing wood properties. However our results show that ring width does not entirely account for radial variation and describes very little of the vertical variation in MFA or MOE. Further research should be undertaken to determine the causal influence of these changes in MOE and MFA with height, so that generally applicable models can be created that can both describe wood properties between sites and within trees.

CHAPTER FIVE

5.1 *CONCLUDING REMARKS*

New Zealand forests include timber with a wide variation in wood quality across regions. This is a manifestation of diverse site conditions that are not likely to change, and represent the climatic and edaphic variability that exists across the country. Within bounds, silviculture can be used to manipulate this resource to produce timber with desired properties. The influence of silvicultural practices on stand growth and wood quality is one of the most important issues in the management of *P. radiata* forests in New Zealand.

MOE is most highly valued in structural grade lumber as the lumber grades for machine stress grading are priced according to the MOE of the lumber. There are significant price differentials for lumber based on MOE, particularly around the threshold values for MOE that distinguish acceptably stiff lumber from lumber that is not stiff (MSG grading system and NZ building standards). A major obstacle for forest owners to achieve timber with acceptable stiffness is the lack of information or models that describe wood properties. Another key area of uncertainty is whether increased stocking can be used to produce corewood timber that meets structural grade standards on warm sites.

This thesis addressed both, the effect of stocking on stand basal area, height, diameter and branch diameter and the effect of stocking on wood properties MFA, MOE and density. Finally we investigated how ring width influences wood properties and whether this variable accounts for treatment effects on these properties.

5.2 *Growth analysis*

The first part of this thesis investigated the effect final crop spacing has on stand basal area, height, diameter, and branch diameter. Basal area increased with stocking while diameter decreased. Compared to the lowest stocking, the highest stocking diameter was reduced by 24 cm or 40%, at age 24. Both the asymptote and growth rate parameters significantly declined with stocking and significantly differed between most stockings. Diverging growth patterns for basal area for the different thinning treatments

occurred early on in the experiment. Compared to the lowest stocking, the highest stocking basal area was increased by $20 \text{ m}^2/\text{ha}$, or 27%, at age 24. Maximum asymptotic yield increased with an increase in stocking while the maximum growth rate decreased.

Compared to the highest stocking the lowest stocking mean top height was reduced by 3.2 m or 10%, by age 24, however this variation was not significant. Mean top height for stockings 200, 350, 500 and 1,100 stems/ha were 30, 32, 34, and 32 metres respectively. Petterson height equation coefficients were calculated for each age of measurement in each plot and used for the mean top height calculation based on the diameter data and then mean top heights were modelled by the Chapman Richards equation. The mean top height asymptote significantly increased with stocking and also significantly differed between most stockings.

Strong positive correlations were found between stem and branch diameter. The lowest stocking had large branches and there were also a large number of trees with poor stem form and forking. The negative relationship between maximum branch diameter and stocking exhibited a 48% or 35 mm decrease in branch diameter from 73 mm at 200 stems/ha to 38 mm at 1,100 stems/ha.

In terms of growth characteristics higher stockings (500 stems/ha) were found to represent an appropriate compromise between site occupancy, stem and branch diameter. This knowledge provided above would assist the decision making process when defining appropriate silvicultural regimes for fertile farm sites in Northland, New Zealand.

5.3 *Wood property analysis*

In the second part of this thesis the main and interactive effects of stocking, ring number and tree height on MFA, MOE and density were determined. Values of density significantly varied between height and ring number in the trees but not between stockings. Density across rings from the pith increased from 400 kg/m^3 to 580 kg/m^3 at 1,100 stems/ha and from 400 kg/m^3 to 480 kg/m^3 at 200 stems/ha. Density was significantly affected by height and it exhibited a linear decline with tree height by 10 % from 510 kg/m^3 at 0 m to 460 kg/m^3 at a height of 20 m. Due to the interaction between ring number and height there were two rings (12 and 13) at 20 m height with density less

than the commonly used threshold value of 400 kg/m³ recording 390 and 395 kg/m³ respectively.

Stocking, height and ring number significantly affected MFA. A negative relationship was found between MFA and stocking which demonstrated 12% or 3.0° decrease in MFA from 25.2° at 200 stems/ha to 22.2° at 1,100 stems/ha. MFA decreased from pith to bark from 34° to 18° at 1,100 stems/ha and from 34° to 20° at 200 stems/ha. MFA exhibited a linear decline with tree height by 22 % from 27° at heights of 0 m to 21° at a height of 20 m.

Stocking, height and ring number significantly affected MOE. A positive relationship was found between MOE and stocking which demonstrated 28% or 3.5 GPa increase in MOE from 8.8 GPa at 200 stems/ha to 12.2 GPa at 1,100 stems/ha. MOE increased from pith to bark from 3.5 GPa to 17 GPa at 1,100 stems/ha and from 3.5 GPa to 12 GPa at 200 stems/ha. MOE exhibited a linear increase with tree height of 25 % from 9.2 GPa at a height of 0 m to 12.2 GPa at a height of 5 m and then a decline by 15% to 10.4 GPa at a height of 20 m.

Stocking, ring number and height significantly influenced MOE and MFA while density was not affected by stocking but it was highly affected by ring number and height. With the exception of the three-way interaction, all interactions significantly affected MOE, MFA and density, but these were of considerably weaker than the main effects.

5.4 *Wood property modelling*

In the third part of this thesis the effect of the continuous variable ring width on MFA, MOE and density was determined.

Stocking, height and ring number and all interactions between these variables significantly affected ring width. Ring width increased rapidly in the early years reaching a peak at ring 2 –3 of 20 mm, after which time ring widths declined. Ring width exhibited a linear decline with tree height by 11% from 9.8 mm at a height of 0 m to 8.7 mm at a height of 5m and then increased around 4.5% to 9.1 mm at heights 20 m. There was a significant decrease in ring width with stocking, from 11.2 mm to 8.3 mm (26%) for 200

and 1,100 stems/ha respectively. The ring widths for treatments 350 and 500 stems/ha were almost identical.

Density and ring width

Ring width by itself was significant as a predictor of density, but when it was combined with other variables it was insignificant (i.e. does not account for treatment effects), and it did not add anything to a model with only class effects. There was a significant impact of ring number on density while ring width was insignificant in the same model. A comparison of ring width to ring number indicated that ring number had a greater influence on density than ring width.

MFA and ring width

MFA was significantly affected by ring width, height and ring number in the tree but not by stocking. Ring width was significant in the MFA model both by itself and when it was combined with other variables. Ring width accounted for the stocking effect. Adjusted MFA by ring width was found to be almost identical to unadjusted MFA in the vertical direction. In the radial direction ring width reduced the magnitude of the ring number effect on MFA, and the residual response only occurred at very low and high ring numbers.

MOE and ring width

The best model of MOE included the class level effects of height and ring number within the tree, and ring width, as a continuous variable. While there was a significant stocking effect this was relatively weak compared to the other main effects. Adjusted MOE by ring width was almost identical to unadjusted in the vertical direction. Although ring number was still significant in the model with ring width, inclusion of ring width dampened the effect of ring number on MOE. Accounting for ring width removed

virtually all of the stocking effect on MOE, apart from that which occurred at high stockings.

5.5 *Implications for management*

Given that there are large differentials between MSG8 and the next most valuable grade, management regimes should focus on cutting a large proportion of wood into this grade. This grade requires branch diameters of less than 6 cm, a target MOE of 8 GPa, and a minimum small end diameter of 30 cm. At 350 stems/ha the maximum branch diameter may average around 6 cm but it is frequently over 6 cm. In contrast, at 500 stems/ha maximum branch diameter does not exceed 6 cm at this Northland site. In terms of MOE, the 500 stems/ha reaches 8 GPa by age 6, but at 350 stems per hectare this threshold is not attained until age 7. Combining the diameter results from this study with information on tree taper (data not shown) indicates that by age 25 years three structural grade logs with a minimum sed of 30 cm could be cut to 18 m at 500 stems/ha. It is likely that timber cut from these trees that is not categorised as MSG8 would be suitable for MSG6, as this grade has a lower small end diameter (200 mm) and MOE target (6 GPa).

This is the first time that a study has shown that under a standard structural regime, a substantial proportion of the corewood can be cut out as high value structural grade timber. As the juvenile core can comprise up to 50% of the recoverable stand volume this is a significant result for forestry managers.

5.6 *Areas for further research*

This research was limited to a particular site, one thinning time and a standard seed source. To obtain a broader insight into how stocking influences longitudinal and radial variation in wood properties it would be advisable to examine MFA, MOE and density resulting from different initial and final crop stockings at different thinning times, across a site gradient, with contrasting genotypes. There are many stocking trials established across New Zealand that would be useful for this kind of analysis. Collation of this type of data will provide a good foundation for the development of national

models sensitive to variation between sites (e.g. climate, edaphic properties), within sites (e.g. intra and interspecific competition), and within trees (tree height, ring position).

Further research should determine the gains possible from using genotypes bred for improved wood properties on both cool and warm sites to identify if use of high MOE clones enable structural grade to be cut further into the pith than year 6 at warm sites or within the corewood on sites with cool temperatures and marginal MOE. This research is likely to be of considerable use as the largest proportion of the forest resource in New Zealand occurs on sites with marginal MOE (Watt *et al.*, 2006) in the central North Island.

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Appendix 1: Module of elasticity (MOE) against ring number, height and stocking

Treatment 200 stems/ha						Treatment 350 stems/ha					
RING	MOE 0m	MOE 1.4m	MOE 5m	MOE 20m	Average	RING	MOE 0m	MOE 1.4m	MOE 5m	MOE 20m	Average
0	3.1	3.0	4.2	4.2	3.6	0	2.3	2.8	4.6	5.2	3.7
1	2.6	3.6	5.2	6.5	4.5	1	2.3	3.0	5.0	6.7	4.2
2	3.3	4.6	5.7	7.2	5.2	2	3.0	3.5	5.7	7.9	5.0
3	3.8	4.9	5.9	7.9	5.6	3	3.8	3.9	5.8	8.7	5.6
4	4.4	5.0	6.4	8.7	6.1	4	3.9	4.5	6.8	9.1	6.1
5	4.1	5.0	6.8	9.3	6.3	5	4.4	4.9	7.7	9.8	6.7
6	4.1	5.4	7.3	9.8	6.7	6	5.0	5.6	8.2	11.2	7.5
7	4.6	5.9	7.9	10.2	7.2	7	5.9	6.4	9.3	12.0	8.4
8	5.2	6.8	9.0	10.8	7.9	8	6.9	8.1	10.8	13.1	9.7
9	6.1	7.5	10.5	11.3	8.8	9	7.9	8.8	12.4	13.9	10.8
10	6.4	7.7	10.4	11.2	8.9	10	9.0	10.3	13.0	14.2	11.6
11	7.4	9.6	12.1	10.4	9.9	11	9.9	11.5	14.3	13.5	12.3
12	8.3	9.8	13.4	9.6	10.3	12	11.4	12.8	15.5	14.3	13.5
13	8.7	11.1	13.6		11.1	13	12.1	12.9	15.1		13.4
14	9.5	11.8	13.7		11.7	14	12.8	13.6	15.6		14.0
15	10.1	11.9	14.3		12.1	15	13.0	13.5	15.7		14.1
16	10.6	11.7	14.7		12.3	16	13.1	13.6	16.4		14.4
17	10.8	12.3	14.0		12.4	17	13.1	14.4	15.9		14.5
18	11.7	13.3	14.5		13.2	18	13.5	14.6	15.5		14.5
19	11.3	13.0	14.8		13.0	19	14.3	14.6	15.7		14.9
20	11.6	13.0	14.6		13.1	20	15.0	14.2	16.9		15.4
21	11.9	13.2	17.3		14.1	21	14.3	14.2	13.0		13.8
22	12.0	12.5			12.3	22	14.3	12.4			13.3
23	12.4				12.4	23	10.0				10.0

Treatment 500 stems/ha						Treatment 1100 stems/ha					
RING	MOE 0m	MOE 1.4m	MOE 5m	MOE 20m	Average	RING	MOE	MOE	MOE	MOE	Average
0	2.5	2.6	4.1	3.8	3.3	0	2.4	3.3	4.9	4.6	3.8
1	2.3	3.0	4.7	5.9	4.0	1	2.2	3.4	5.2	7.0	4.4
2	2.9	3.5	5.6	7.0	4.7	2	3.2	4.3	6.0	8.6	5.5
3	3.6	4.2	6.4	7.8	5.5	3	3.9	5.5	7.7	10.3	6.9
4	4.3	5.1	7.5	8.2	6.3	4	5.2	6.8	9.4	10.8	8.1
5	5.0	5.8	8.6	8.9	7.1	5	5.8	8.7	11.0	12.4	9.5
6	5.7	6.8	9.7	9.7	8.0	6	7.1	9.4	12.1	12.7	10.3
7	7.1	7.7	10.3	9.6	8.7	7	9.0	10.5	13.5	14.5	11.9
8	7.3	8.8	11.6	11.2	9.7	8	9.1	11.2	14.4	16.3	12.8
9	8.6	9.9	13.7	12.1	11.1	9	10.1	12.0	15.7	16.6	13.6
10	9.1	11.3	13.3	12.5	11.5	10	10.7	13.9	16.8	15.7	14.3
11	10.5	12.8	14.1	12.8	12.6	11	12.3	15.6	17.6	15.7	15.3
12	11.4	12.3	15.1	13.5	13.1	12	13.6	16.0	18.3	14.0	15.5
13	11.8	13.4	15.9		13.7	13	13.9	16.7	18.8	16.1	16.4
14	12.7	16.0	16.1		14.9	14	15.0	17.3	18.6		16.9
15	13.3	15.3	15.5		14.7	15	15.3	17.0	18.7		17.0
16	13.6	15.0	15.2		14.6	16	15.8	17.3	18.5		17.2
17	13.3	15.5	15.4		14.7	17	15.6	17.6	18.3		17.2
18	14.1	15.0	15.6		14.9	18	15.9	16.8	17.8		16.8
19	13.6	14.6	16.6		15.0	19	15.4	16.4	17.6		16.5
20	13.5	14.4	15.1		14.3	20	15.3	16.2	18.7		16.8
21	13.5	14.6	15.3		14.5	21	15.1	14.9			15.0
22	13.7	16.7			15.2	22	15.5				15.5
23	17.6				17.6	23					