The influence of weed control, clone, and stem dimensions on wood quality of 17 year old stems of *Pinus radiata* which has been grown on the Canterbury Plains

A dissertation submitted by

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ABSTRACT

This study determined whether variation in clone, weed control treatment, or stem dimensions, could have an impact upon outerwood stiffness in 17 year old *Pinus radiata* stems. An experiment located south west of the Dunsandel township in Canterbury, New Zealand, was used to collect measures of acoustic velocity (windward and downward sides) from each of the 278 trees. Diameter at breast height, tree height, and height to live crown were also recorded for each tree. Findings from this research were compared with previous research carried out when the trees were ages eight and eleven.

Assuming a green density of 1,000 kg/m^3, Young's Modulus equation was used to convert acoustic velocity to wood stiffness, or, Modulus of Elasticity (MOE). The effect of wind direction upon mean wood stiffness was not significant ($\alpha = 0.05$). Consequently, one measure of wood stiffness was calculated per tree.

Mean stem slenderness and mean wood stiffness values were calculated by block, weed control treatment, and clone. Weed control treatments had a significant impact upon mean wood stiffness in comparison to the control treatment (0.03 m^2 area of weed control). Significant differences did not exist between different levels of weed control, ie., 0.75 m^2, 3.14 m^2 and 9 m^2 chemical spot spray area.

Clonal variation and stem slenderness significantly affected mean wood stiffness measures. Stem slenderness appeared to be correlated with clonal variation (interaction between clone and slenderness was not significant), however, according to Dr. Euan Mason, this finding is not corroborated by findings from other research on the wood quality of clones in Canterbury (personal communication, September 16, 2013). An analysis of covariance (ANCOVA) determined that mean height to the live crown was not a significant predictor of wood stiffness. Comparison with earlier research showed no change in the ranking of wood stiffness values by clone or treatment.

KEY WORDS: Wood stiffness, Modulus of Elasticity, clone, weed control, stem slenderness

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Introduction

Structural grade differentiation of logs and lumber is no longer solely based on the visibility of external wood quality features such as knots and sweep. Instead, grading systems are increasingly recognising the value of intrinsic wood quality for lumber destined for structural applications. The effect that different growing conditions or silvicultural regimes can have upon the intrinsic wood quality of *Pinus radiata* (D.Don) is not well understood. Consequently there is a need to evaluate how different silvicultural treatments can be used to improve intrinsic wood quality. The study described here evaluated the effects of different levels of weed control, clonal variation and stem slenderness upon wood stiffness in 17 year old *Pinus radiata* stems. This research is essential in order to improve current knowledge about the impacts of early silvicultural treatments upon wood stiffness in rotation age stems. An improvement in such knowledge could enable changes to be made by forest managers in order to yield a greater proportion of high value structural grade timber at harvest.

The regions of wood across the diameter of a stem are commonly referred to as either corewood or outerwood. Corewood comprises the inner cylindrical centre of the tree surrounding the pith, whereas, outerwood is present outside of this region, towards the cambium. In comparison to outerwood, Macdonald and Hubert (2002) state that corewood "is generally characterised by low density, thin cell walls, short tracheids with large lumens, high grain angle and high microfibril angle" (Macdonald & Hubert, 2002).

The term intrinsic wood quality primarily relates to two wood properties, namely, wood stiffness and wood stability (Wielinga, Raymond, James, & Matheson, 2009). These wood properties are relatively poor in *Pinus radiata* lumber, however, they are of utmost importance for commercial applications of *Pinus radiata* timber such as in structural components of buildings (Renard, 2008). Wood stiffness provides a measure of the extent to which timber can withstand heavy loads without strain or deformation.

The research reported here used TreeTap, a Time of Flight (TOF) tool which collects measures of acoustic velocity from the outer 20 mm from the cambium. This is an appropriate measure to collect when evaluating the effects of different silvicultural regimes upon wood stiffness because, Chauhan and Walker (2006) state that acoustics “are an effective surrogate measure of stiffness” (Chauhan & Walker, 2006). In terms of defining what drives changes in wood stiffness measures within a stem, Robert and Jugo (2001) made the conclusion that microfibril angle (MFA) “is a major determinant of specific” (Robert & Jugo, 2001) longitudinal MOE. Variation in MFA is pronounced in the corewood, however, this variation is much less in the outerwood. Consequently, variation between outerwood measures of acoustic velocity is likely due to variation in wood basic density, although, it must be noted that Macdonald and Hubert (2002) refer to the contribution of basic density to changes in wood stiffness as “underwhelming” (Macdonald & Hubert, 2002). Basic density, or wood density as it is referred to in this report, refers to a measure of the amount of cell wall material present in a given volume of timber.

Research by Lasserre, Mason, and Watt (2008) concerning eleven year old stems at an experiment near Dalethorpe, Canterbury, revealed that an increase in between tree competition gave rise to improved intrinsic wood quality. A surprising finding by Mason (2006), was that this was not corroborated at an experiment near Dunsandel, Canterbury, where young stems were exposed to increased competition from weeds. In fact, measures of wood stiffness collected from stems at both ages eight and eleven, revealed that stems growing with competition in the control plots (presence of weed competition) had the worst wood quality when compared to weed free treatments.

These surprising and contradictory findings suggest that further research is required in order to improve understanding about the effects upon wood quality resulting from early (first five years since establishment) weed control treatments. This research provides an opportunity to evaluate the effects upon outerwood quality. Consequently, comparisons can be made with earlier research at the Dunsandel site which most likely examined the quality of corewood quality because of the young ages of the stems (ages eight and eleven) and the fact that TreeTap only measures the very outer region of a stem.

Definition of Objectives

The following null hypotheses were proposed for this research:

- No significant relationships exist between the following pairs of variables: weed control treatments and mean wood stiffness measures, clonal variation and mean wood stiffness measures, stem dimensions and wood stiffness measures.

- No significant differences exist between the results returned at ages eight and eleven, and those from age 17.

- Variations in weed control, clonal choice, and stem dimensions do not have the potential to improve wood stiffness in the outerwood of 17 year old stems.

- The inclusion of a measure of mean height to the live crown will not significantly improve predictions of wood stiffness.

The ultimate aim of this experiment was to evaluate the effects of clonal variation, different levels of weed control, and stem dimensions upon outerwood intrinsic wood quality, specifically, wood stiffness. Previous studies had been carried out using the trees comprising the Dunsandel experiment at ages eight and eleven. As a result, the research described here provided stand level insight about how previous results have manifested themselves in 17 year old stems approaching rotation age.

Literature Review

The implementation of weed control during the early stages of a rotation can improve tree growth by reducing competition for limiting resources such as water, light, and soil nutrients (Mason and Kirongo 1999**).** The long term effects that such weed control treatments can have upon intrinsic wood quality are not well understood. Wood stiffness is a key intrinsic wood quality characteristic that should be considered when managing a plantation of *Pinus radiata* stems in a structural silvicultural regime. The stiffness of the wood affects grade recovery and product revenues and unfortunately, *Pinus radiata* has inherently low wood stiffness (Wielinga et al., 2009). This literature review provides further information about wood stiffness and how it can be measured using the TreeTap TOF tool. Furthermore, information is provided concerning the influence of clone, weed control, and stem dimensions upon wood stiffness.

Wood stiffness

Wood stiffness can be defined as the ability of an elastic body to resist deflection or deformation when these stresses are induced by an applied force. Wood stiffness is expressed as modulus of elasticity (MOE) which is measured in GigaPascals (GPa). Previous studies have evaluated measures of wood stiffness collected from *Pinus radiata* stems and lumber. Wood density relates to the mass of a piece of wood per unit volume and outerwood density has been found to explain some of the variation in outerwood stiffness. Outerwood density increases with increasing stand age. Using the Fakopp TOF tool, Chauhan and Walker (2006) found that despite an overall poor association between outerwood density and acoustic velocity measures, when only considering only the data from the 25-year-old stand, a correlation coefficient of 0.42 existed between basic density and acoustic velocity (Chauhan & Walker, 2006).

Within tree variations in wood density and cellulose MFAs in the S2 layer of tracheid cell walls occur across the radius of the stem. The corewood region within the centre of a mature stem is characterised by low density material and high MFAs. In comparison, the outerwood region of a mature stem is comprised of sapwood which is involved in the translocation of water and sap. Wood quality in the outerwood is more uniform than corewood and of inherently better wood quality characteristics, such as smaller MFAs which are more aligned with the vertical axis of the stem.

Between tree variation in wood stiffness, MFA and wood density measures are driven by a range of exogenous factors. According to Grabianowski (2004), even the wind direction upon a standing tree can cause noticeable differences in acoustic velocity measures by either side of the stem. Furthermore, weed control treatments, clone, and variations in stem slenderness due to different stocking levels can also drive between tree variations in wood stiffness. These contributing factors are further explained below.

Tree Tap

In order to collect information about wood stiffness, several tools have been developed which measure the time taken for a sonic wave to travel through a section of a tree stem. The transit time can be related to MFA and consequently wood stiffness, where the distance between the start and stop probe, divided by the transit time, provides a measure of acoustic velocity. According to Grabianowski, Manley, and Walker (2006), a faster acoustic velocity measure is related to a greater wood stiffness when compared to alternative slower velocities. This is likely the case because better quality wood, such as the outerwood, has MFAs more aligned to the stem axis and allows the sonic wave to travel a more direct route between probes than would be possible with large MFAs. Resonance tools such as Woodspec (Grabianowski et al., 2006) estimate an average MOE for the entire stem section, however, to carry out such a measurement, the stem must firstly be felled. By contrast, TOF tools, such as TreeTap, developed by Dr. Michael Hayes at the University of Canterbury, can be used on standing trees (Lasserre, Mason, & Watt, 2007).

TreeTap measures the time taken for an induced sonic wave to travel between a start and stop. The sonic wave is thought to travel the fastest pathway between probes (Mason, 2006). Consequently, unlike resonance techniques, TOF measures can only be used to measure the stiffness of the outer section of the stem which has inherently of superior wood quality in mature stems. For this reason, TOF measures of wood stiffness tend to be higher than those estimated by resonance techniques (Lasserre et al., 2007). Clearly, this occurs because measures of wood stiffness by TreeTap do not take into account the corewood region which comprises wood of poor wood stiffness due to characteristics such as high microfibril angle and spiral grain.

It has been reported that the resonance method is superior to the TOF method because measures of overall stem MOE were highly reliable and easily repeatable (Lasserre et al., 2007). Despite this conclusion, it must be noted that estimates of stem MOE collected using resonance techniques can be significantly affected by the presence of branches and bark. Lasserre et al. (2007) evaluated the extent to which such sources of error could affect whole stem estimates of MOE in their study of a range of genotypes grown across a range of stand densities. In this study, Lasserre et al. (2007) found that adjustments to MOE measures derived from resonance techniques would need to be made in order to account for the presence of branching, or bark. This is required in order to maintain accuracy because resonance techniques provide a volume based estimate of wood stiffness. Evidently, the presence of branches and bark would contribute to this volume. Adjustments are not required for measures collected using TreeTap because the TOF measure of wood stiffness can only relate to the outer 20 mm from the cambium over a set distance.

Evidently, TreeTap does not provide the whole stem measure of wood quality that is achieved when using resonance tools. Despite this perceived drawback, Lasserre et al. (2007) found that measures of wood stiffness derived using TreeTap were strongly correlated ($r^2 = 0.94$) with those estimated for the whole stem via resonance techniques. Furthermore, when wood stiffness is measured periodically throughout the rotation of a stand using TreeTap, any changes in wood stiffness can mapped across the radius of the stem. This is because each measurement relates to a different section along the radius of a stem.

Weed control

Reductions in tree height and diameter at breast height were reported by Balneaves and Clinton (1992) for stems growing in competition with weeds. Mason and Milne (1999) explain that weed control can result in a type I response. This means that trees grown in areas where weeds are controlled during the early stages of growth will demonstrate a temporary increase in growth rate, however, this increase will not be sustained. Previous research at the Dunsandel experiment by Mason (2006) which analysed changes in stem dimensions over time, showed a time gain (the time elapsed between the attainment of mean equivalent stem dimensions for trees growing in either weed control plots of control plots) of two to three years. This occurred for those stems growing in plots subjected to any level of weed control during the first two years of growth (1 m spot spray, 2 m spot spray, complete weed control), and slightly increased (although not significantly) for increasing areas of weed control surrounding tree stems.

The experiment evaluated in this research is a continuation of previous research by (Mason, 2006). The experiment of interest is located on the drought-prone Canterbury Plains in the South Island of New Zealand. Michael S. Watt, Whitehead, Mason, Richardson, and Kimberley (2003) found that weed competition at such sites primarily suppresses tree growth by reducing the availability of soil water**.** In addition to the impacts upon available soil water, Kirongo, Mason, and Nugroho (2002) summarise alternative benefits to tree growth that result from effective weed control on the drought prone Canterbury Plains. These are, earlier needle emergence which enables a longer growing season, longer needles with greater leaf areas, and the existence of a crown with a greater proportion of current season foliage (Kirongo et al., 2002).

A study by Flannery (2009) used the Fakopp TOF acoustic velocity tool as a means for measuring wood stiffness. This study compared the acoustic velocity measures derived from stems growing in competition with grasses, with those collected from stems growing in absence of grass competition. The findings determined that stems growing in competition with grasses had lower acoustic velocity measurements, therefore poorer wood stiffness. Comparatively, the study by

M. S. Watt, Clinton, Parfitt, Ross, and Coker (2009) which investigated the influence of site and weed competition upon wood stiffness in six year old *Pinus radiata* revealed that weed competition caused wood stiffness in the relevant stems to increase by 16% on average.

Research by Mason (2006) hypothesised that trees growing in areas that had been subjected to weed control would express increased radial growth rates, thus, leading to poor intrinsic wood quality and therefore, low wood stiffness. As expected, measurements collected from the experiment at age eight proved that weed competition had given rise to stems with the lowest radial growth rates. However, those stems exposed to weed competition had the lowest average wood stiffness (Mason, 2006). Given the findings by Mason (2006), and Flannery (2009)**,** it could be assumed that wood stiffness is detrimentally affected by competing weed vegetation, however, this contradicts the findings mentioned previously by M. S. Watt et al. (2009). Additionally, Michael S. Watt et al. (2005) evaluated the effects of competition from the woody weed broom upon intrinsic wood quality. This study revealed that that stems competing with broom had significantly higher wood stiffness than those growing without competition from broom (Michael S. Watt et al., 2005).

Stem Dimensions

Reductions in height and diameter growth associated with weed competition also results in changes in derived stem dimensions such as slenderness. Stem slenderness is calculated by dividing tree height by the diameter at breast height. It is widely thought by the New Zealand plantation forest industry that with increased *Pinus radiata* stocking levels, the associated increase in between tree competition leads to an increase in stem slenderness. Michael S. Watt et al. (2006) report a strong correlation between stiffness (r^2 = 60) and stem slenderness for their study which calculated slenderness using tree height and ground line diameter. Lasserre, Mason, Watt, and Moore (2009) found that an increase in stocking from 833 to 2,500 stems/ha resulted in an increase in corewood stiffness by 40% (Mason 2006). Similarly, Flannery (2009) identified that increasing stocking levels, specifically from 625 stems/ha to 2,500 stems/ha, returned a significant positive (p-value < 0.01) change in TreeTap acoustic velocity measurements from 1.44 km/s to 1.51 km/s (Flannery 2006). Despite this finding, the effects of stocking upon wood stiffness and stem slenderness were not found to be significant (p value < 0.05) (Flannery 2009).

Mason (2006) and Flannery (2009) suggest that this positive trend between corewood stiffness and increasing stocking level could be driven by the following mechanisms associated with higher stockings; a reduction in radial growth rate, a reduction in the degree of tree sway, a more rapidly rising height to base of green canopy, and, the fact that stem diameters are more slender at any given age. When considering the logic behind stiffness and stem slenderness it makes sense that a slender tree may have to be stiffer to prevent stem buckling**.**

Clone

Findings presented by Sharma, Mason, and Sorensson (2008) from research carried out at the Dalethorpe experiment in Canterbury, strongly suggests that some clones are better suited to growing with increased competition. Sharma, Mason et al. (2008) reported that such findings were observed from as early as ages 7 or 8. It is believed that competitive ability is likely under genetic control. Research carried out by Mason (2006) at the Dunsandel experiment found that variation in wood stiffness between different clones was highly significant (p-value < 0.001). The collation of data from all plots in order to model wood stiffness gave rise to the finding that clone could be used to account for 32% of the variation in wood stiffness (Mason, 2006).

As previously mentioned, MFA and density are the key determinants of corewood stiffness, and because MFA is relatively uniform in outerwood, basic density is a key determinant of variation in wood stiffness. Tree breeding involves the study of the heritability of particular traits. It is reported by Renard (2008) that the trait for wood density is heritable, and, the heritability of this trait is well understood. Consequently, there is potential to selectively breed for improved wood density, however, according to Renard (2008) “it was found that growth rate was negatively correlated with all wood quality traits” (Renard, 2008)**.** This issue emphasises the difficulty in selecting traits to give rise to optimum tree growth, whilst also selecting for superior intrinsic wood quality.

Summary

In conclusion, wood stiffness of *Pinus radiata* lumber is a very important intrinsic wood quality due to the common structural applications of *Pinus radiata* timber. The ability of higher structural grade material to attain premium prices has encouraged research concerning how wood stiffness can be improved. A strong association between MFA, wood density and wood stiffness, combined with sound knowledge about the heritability of wood density, provides an opportunity for selective breeding for wood stiffness. Unfortunately, this has not been widely implemented due to the negative correlation between wood stiffness and other wood quality traits.

As a result, there is a clear need to evaluate how different silvicultural treatments can be used to improve wood stiffness in rotation age stems. Previous research concerning weed control has shown contradictory findings, with some researchers reporting improvements in wood stiffness where stems have grown in competition with weedy vegetation (Michael S. Watt et al., 2005). Comparatively, others have found the opposite to be true for *Pinus radiata* stems at ages eight and eleven (Mason 2006). Stem dimensions can be affected by a range of factors such as stocking, clone, and weed control treatment. Positive relationships have been reported to exist between stem slenderness and wood stiffness, however, the impacts of these trends have not been significant.

Background

Study area

The experimental site of interest in this research is located south-west of the town of Dunsandel in Canterbury (172.05°E, 43.65°S). The site is flat, has an approximate annual rainfall of 600 mm to 700 mm (Mason, 2006)**,** and summer droughts commonly occur. According to Kirongo et al. (2002), at the time this experiment was established in September 1996, the grasses on site included “a mixture of Italian ryegrass (*Lolium perenne* L.), white clover (*Trifolium repens* L.), and sorrel (*Rumex acetosella* L.)” and the soils were Lismore stony silt loams (Kirongo et al., 2002).

The layout of the experiment is a randomised complete block split plot design, with three complete blocks, each comprising four different levels of weed control treatments (Figure 1). Herbicidal weed control treatments were applied three weeks after planting, and at various times over the subsequent five years. At the time of planting, each plot included a line of 10 trees of each clone at a planting spacing of 3 m × 3 m, however, due to thinning treatments and now that the trees are 17 years old, three to four clones exist for each clone within each plot. Each complete block is a rectangular area 36 m × 27 m, and contains one of each of the four levels of weed control.

The four levels of herbicidal weed control are: complete weed control equivalent to a 9 m^2 spot spray per tree, 3.14 m^2 (2 m diameter) circular spot spray, 0.75 m^2 (1 m diameter) circular spot spray, and the control plot where a 0.03 m^2 area was cleared of weeds only at the time of planting. Weed control by way of spot spraying was achieved using circular shelters of 1 m and 2 m diameter for the respective 3.14 m^2 and 0.75 m^2 treatments to ensure accurate application of 7.5 kg (all amounts are in units of active ingredients) or terbuthylazine mixed with 300 g of haloxyfop and 900 g of clopyralid in 250 L of water per treated hectare (Kirongo et al., 2002). These weed control treatments were carried out three weeks after planting. A follow up spray was carried out during the first summer to control the sorrel because this grass was not completely controlled during the previous spray. The follow up spray involved the "addition of 3.75 g of tribenuron methyl and 36 g of oxyfluorfen per treated hectare" (Mason, 2006) to the original mix. This mix was subsequently used to actively control the weed free areas (exclusion of 0.03 m^2 areas) for 5 years.

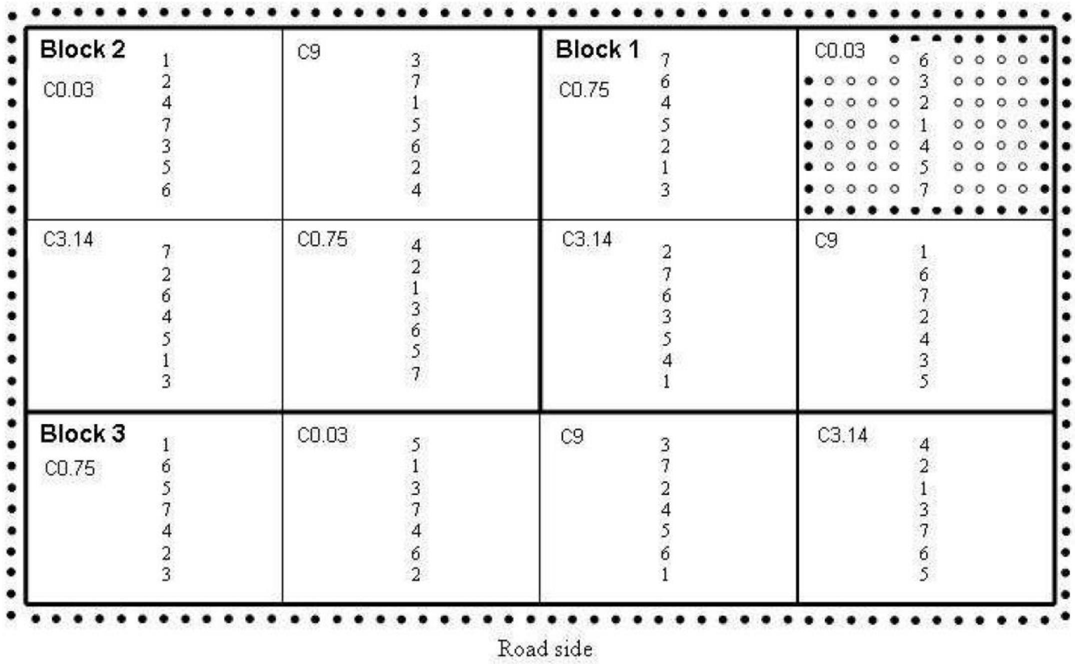

Figure 1: Layout of the Dunsandel experiment

Methodology

Data collection

The height and diameter at breast height (DBH) of all trees analysed in this study were collected in early June, 2013. A vertex was used to collect height measurements and a DBH tape was used to measure diameters. In June, four days were spent collecting acoustic velocity measures using the TreeTap machine, followed by another two days in August to re-measure some plots where trees were missed during the initial measurements. Two people were involved in the data collection using TreeTap in order to minimise the chance of causing damage to the probes. Furthermore, the combination of two people using the TreeTap machine ensured that the results obtained were carefully reviewed during data collection so that any outlying values could be deleted and re-measured.

Green dynamic acoustic velocity was measured using the TreeTap tool in combination with a range of ancillary gear. In order to collect measures of acoustic velocity, the probes were gently hammered into the outerwood using a hammer with a plastic attachment. The first probe was hammered into the tree at approximately 1.9 m above the ground. Following this, the second probe was hammered into the stem at a distance of 1.3 m below the initial probe. Both probes were hammered into the tree in the downward facing direction until the sound indicated that solid wood had been penetrated. Care was taken to ensure the angle of the probe to the tree stem was less than 45°. Thirdly, a chisel was hammered into the stem 30 cm below the bottom probe. Again, care was taken to ensure this was located at an angle of 45° or less from the tree stem, however, the chisel is hammered upward into the tree stem.

A lightweight hammer was used to exert a force onto the bottom chisel which released a sonic wave into the stem. This sonic wave travelled between the two probes and the TreeTap machine calculated the transit time and recorded the acoustic velocity. The process of releasing sound waves into the stem to be measured was repeated six times on each side (upwind and downward directions) of every stem.

Data analysis

Stem slenderness was calculated for each tree in the experiment by dividing tree height by the corresponding diameter at breast height. Acoustic velocity values were averaged by each of the two sides measured for every tree in the experiment. Subsequently, Young's Modulus equation was used to calculate mean wood stiffness, expressed as dynamic MOE for the windward and downward side of each tree.

- Young's Modulus equation: $\text{MOE} = \rho V^2$

Where:

- ρ is the green density of the material and assumed to be a constant value of 1,000 kg/m^3
- V is the velocity of the sonic wave in km/s.

The statistical software program, R, was used to carry out statistical analyses and a significance level of $p < 0.05$ was assumed for all analyses. Firstly, the dataset comprising wood stiffness by side was summarised by calculating mean wood stiffness values by block, weed control treatment, and clone. Exploratory data analysis was carried out using the statistical software, R-commander in order to detect any unusual measurements or outliers. A split plot design ANOVA evaluated the effect of wind direction upon mean wood stiffness by side. The values of wood stiffness by side of the tree were averaged to generate one measure of wood stiffness per tree. Split plot ANOVA was used to test for the significance of block, weed control treatment, clone and stem slenderness upon measures of wood stiffness. All split plot ANOVA calculations used the Linear Mixed Effects (lme) command in R because this this command accounts for the unbalanced design of the Dunsandel experiment with different numbers of trees per weed control treatment.

The Tukey Honest Significant Difference (Tukey HSD) test was used to calculate whether or not significant differences existed between mean wood stiffness by block, weed control treatment, and clone. After using R to calculate the mean height to live crown by block, weed control treatment and clone, ANCOVA was used to determine whether this variable had a significant effect upon predictions of wood stiffness.

Results

THE EFFECT OF WIND DIRECTION UPON MEAN WOOD STIFFNESS

The results of a split plot ANOVA using the lme command (Table 1) found that the direction of wind, referred to as “Side” in Table 1, does not have a significant effect upon wood stiffness on different sides of the tree (p-value = 0.33).

Table 1: The effect of wind direction upon mean wood stiffness measures

Source	**numDF**	**denDF**	**F-value**	**p-value**
(Intercept)	1	519	3193.9	<0.001
Weed control	3	6	5.9	0.03
Clone	6	519	66.2	<0.001
Side	1	519	1.0	0.33
Weed control : Clone	18	519	2.0	0.01

*df: degree of freedom
*numDF: degrees of freedom in the numerator
*denDF: degrees of freedom in the denominator

SPLIT PLOT DESIGN ANALYSIS OF VARAINCE

A split plot design ANOVA using the lme command in R was carried out to determine the effects of block, weed control treatment and clone upon wood stiffness. The results of this analysis (Table 2) revealed that weed control treatment causes a marginally significant effect upon wood stiffness in 17 year old stems, with a p-value of 0.048 (Table 2). Mean wood stiffness values are also found to be strongly affected by clonal variation (p-value < 0.001), however, the interaction between weed control and clone is not significant (p-value = 0.65) (Table 2).

Table 2: Split plot ANOVA of wood stiffness

Source	numDF	denDF	F-value	p-value
(Intercept)	1	48	3459.4	<0.001
Weed control	3	6	5.4	0.048
Clone	6	48	21.3	<0.001
Weed control:Clone	18	48	0.8	0.65

MEAN WOOD STIFFNESS BY WEED CONTROL TREATMENT

A Tukey HSD test revealed that the lack of weed control (only a 0.03 m^2 area cleared around the base of the stem at the time of planting) resulted in a mean wood stiffness value which differed significantly from the three alternative weed control treatments with p-values of 0.02, 0.01 and < 0.001 for differences with the 1 m spot spray, 2 m spot spray and complete weed control respectively (Table 3). No significant differences existed between mean wood stiffness measures from the three different levels of weed control (0.75 m^2 area, 3.14 m^2 area and 9 m^2 area) (Table 3, Figure 2).

Table 3: Tukey HSD for wood stiffness by weed control treatment

Weed Control Treated area (m2)	Difference	Lower	Upper	p-value adjusted
0.75-0.03	1.04	0.12	1.96	0.02
3.14-0.03	1.09	0.17	2.01	0.01
9-0.03	1.57	0.65	2.49	<0.001
3.14-0.75	0.05	-0.87	0.97	1.00
9-0.75	0.53	-0.39	1.45	0.44
9-3.14	0.48	-0.44	1.4	0.52

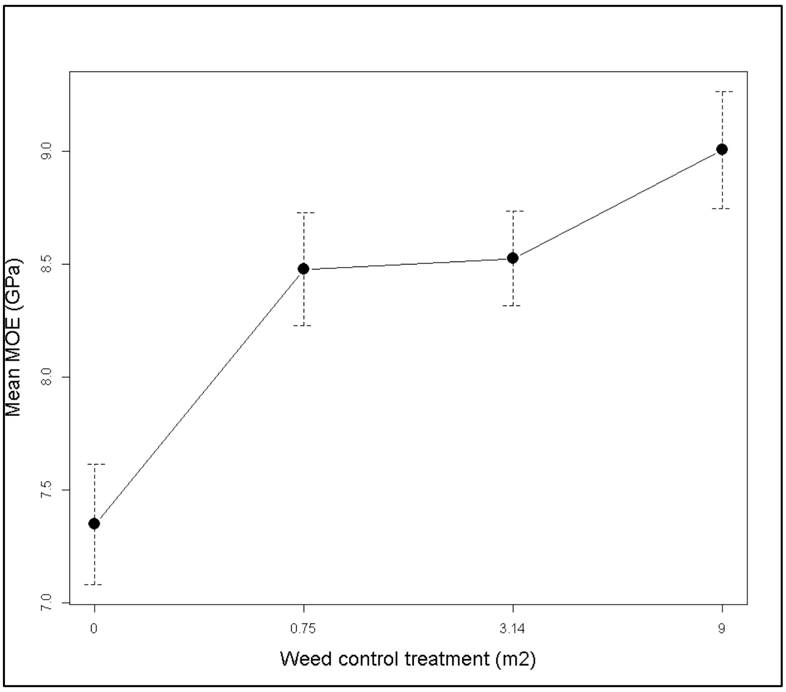

Figure 2: Mean wood stiffness by weed control treatment with 95% confidence intervals

Although significant differences in wood stiffness of age 17 stems were not evident between different levels of weed control, the 9 m^2 chemical spot spray treatment resulted in the highest mean wood stiffness of 9.0 GPa (Figure 3). The mean wood stiffness values for the 0.75 m^2 and 3.14 m^2 spot spray weed control treatments were both less than the 9 m^2 treatment with MOE values of 8.5 GPa (Figure 3). It is evident in Figure 3 that the same ranking in mean wood stiffness values by weed control treatment is maintained across all measurement ages.

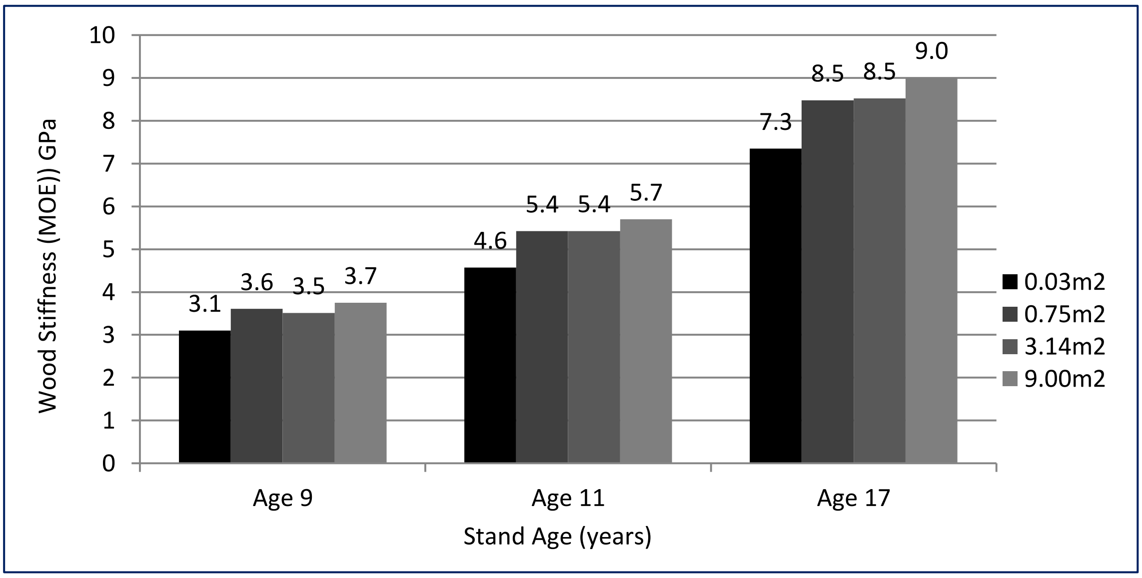

Figure 3: Mean wood stiffness by weed control treatment against tree age

MEAN WOOD STIFFNESS BY CLONE

A Tukey HSD range analysis of mean wood stiffness by clone, revealed that significant differences in wood stiffness occurred between some of the seven clones evaluated in this research. Figure 4 shows the mean wood stiffness arranged by clone at each of the tree ages that were measured throughout the rotation at the Dunsandel experiment. As was shown by the ranking in weed control treatment (Figure 3), the ranking of clones in terms of the highest mean wood stiffness was also maintained throughout the rotation (Figure 4). Clones one and six were the best performing clones, whereas, clones three and four returned the lowest mean wood stiffness values (Figure 4).

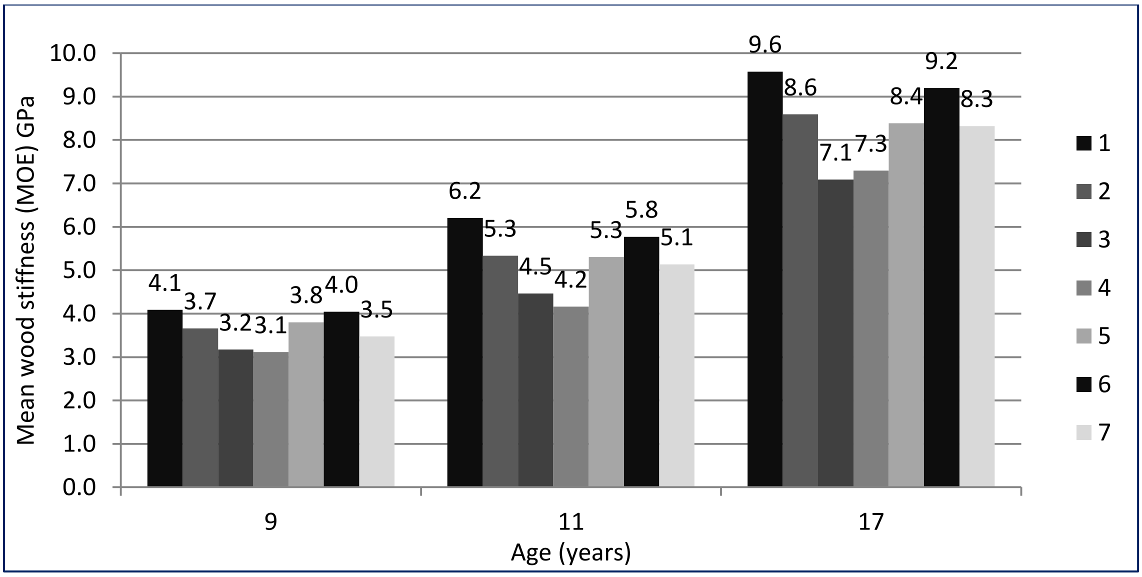

Figure 4: Mean wood stiffness by clone against tree age

MEAN STEM SLENDERNESS

A split plot design ANOVA was also carried out which included mean stem slenderness by block, weed control treatment and clone, into the model. This analysis reported that the weed control treatment was significant (p-value = 0.004), slenderness was significant (p-value = 0.01) and clone was highly significant (p-value < 0.001). None of the interaction terms were significant (Table 4).

Table 4: Split plot ANOVA including stem slenderness to predict wood stiffness

Source	**numDF**	**denDF**	**F-value**	**p-value**
(Intercept)	1	20	9284	<0.001
WeedControl	3	6	14	0.004
Clone	6	20	16	<0.001
Slenderness	1	20	8	0.01
WeedControl:Clone	18	20	1	0.62
WeedControl:Slenderness	3	20	1	0.54
Clone:Slenderness	6	20	0	0.89
WeedControl:Clone:Slenderness	18	20	1	0.80

The Dunsandel experiment has shown a correlation between mean wood stiffness and mean stem slenderness by clone (Figure 5), where clones with higher mean wood stiffness values also have higher mean stem slenderness and vice versa. This relationship was also evident in research carried out at the experiment at ages eight and eleven.

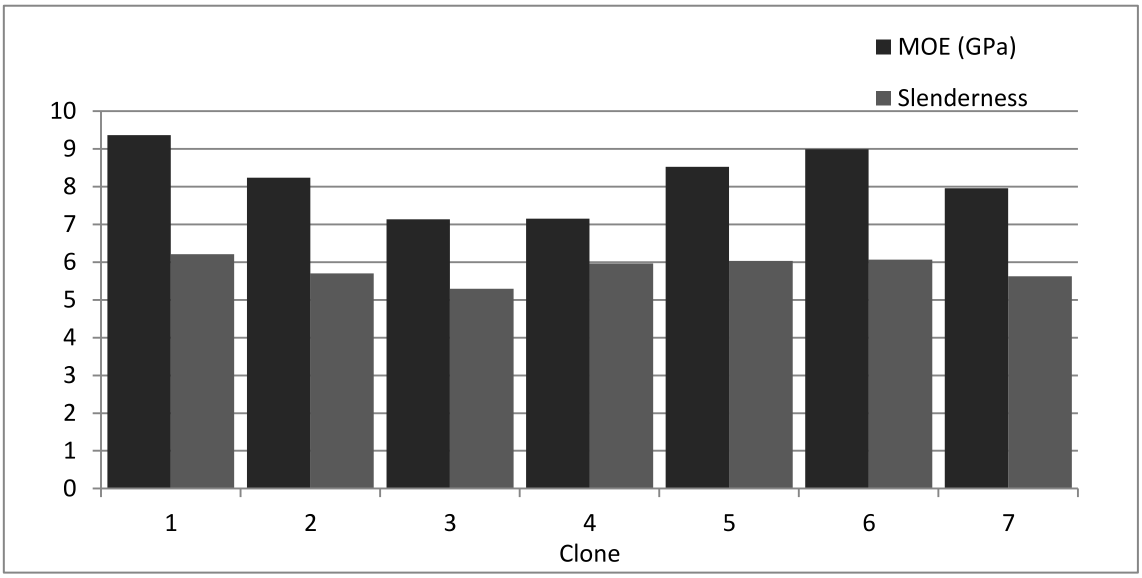

Figure 5 Mean stem slenderness and mean wood stiffness by clone

ANALYSIS OF CO-VARAINCE FOR MEAN HEIGHT TO THE LIVE CROWN

An ANCOVA which included mean height to live crown by block, weed control treatment, and clone, revealed that the mean height to live crown is not significant for predictions of wood stiffness ($\alpha = 0.05$) given a p-value of 0.18 (Table 5).

Table 5: ANCOVA of wood stiffness with height to live crown as a covariate

Source	**numDF**	**denDF**	**F-value**	**p-value**
(Intercept)	1	45	5417.1	<0.001
Weed control	3	6	8.4	0.01
Clone	6	45	22.5	<0.001
Slenderness	1	45	5.4	0.03
Height to live crown	1	45	1.8	0.18
Weed control:clone	18	45	1.0	0.43
Slenderness:Height to live crown	1	45	0.1	0.80

Discussion

This study has found that weed control during the first five years of a rotation can significantly reduce mean wood stiffness in 17 year old stems when compared to the absence of weed competition. There does not appear to be any significant benefit associated with different levels of weed control because no significant differences in mean wood stiffness were calculated between the 0.75 m^2, 3.14 m^2 and 9 m^2 weed control treatments. As a result, based on the findings in this research, it would be recommended that if forest managers were to manage for improved wood stiffness, the most cost effective weed control treatment could be applied. In consideration of this, it must be noted that these findings do not reflect those from all other research concerning the relationship between weed competition and wood stiffness (Michael S. Watt et al., 2005), therefore, the results in this research must be interpreted with caution and may only apply to competition from pasture on dry sites.

Differences in mean wood stiffness at age 17 can also be attributed to variations in clone. The best performing clones in terms of the highest wood stiffness values were clone one and clone six. The relative performance of all seven clones has remained constant across all three measurement periods. This finding shows that an initial improvement in corewood stiffness achieved by different clones at an early age is carried throughout the rotation so that the same improvement in wood stiffness is evident in the outerwood at age 17.

It was surprising to learn of the strong association between mean stem slenderness and variation in mean wood stiffness by each of the seven clones at the Dunsandel experiment (Figure 5). It must be noted that despite this perceived close association, a split plot ANOVA did not return a significant interaction between clone and stem slenderness (Table 4). Based on the findings from this experiment, it could be suggested that increasing stem slenderness, at constant stocking, gives rise to improved wood stiffness, perhaps because more slender stems need to be better able to resist wind-throw and breakage. Despite this speculation, such a conclusion could not be drawn with sufficient confidence due to opposing conclusions drawn from other research that has been carried out on the Canterbury Plains. As a result, it is believed that the relationship shown for slenderness by clone at the Dunsandel experiment could be due to chance and perhaps a type II error has occurred.

Wind direction was not found to have a significant effect upon wood stiffness for measures of mean wood stiffness on the upwind and downward directions (Table 1). Only a limited amount of research has been carried out assessing the how wind can affect wood stiffness. Grabianowski (2004) made the observation that a combination of wind and desiccation due to the drying effects of a prevailing north-west wind could influence wood properties. This study by Grabianowski (2004) did not evaluate wood stiffness at the tree level, rather, an evaluation of “edge effects” was carried out. An explanation as to why no significant difference was found between mean wood stiffness measures taken from each side of the trees at Dunsandel could be because evaluations of this this impact at the tree level is at too fine a scale. Further evaluation could be carried out by creating a subset of the data which reflects trees on the edge on both the upward, and downward directions.

An interesting finding from the Dunsandel experiment is that the type I response of a time gain in terms of tree growth (height and diameter) associated with trees grown in the presence of weed competition. Mason (2006) reported the time gain to be two to three years. This idea of a time gain can be further explained by referring to Figure 3 where, for example, at age 9, trees in the 9 m^2 weed control treatments would be as tall as trees in the 0.03 m^2 weed control treatment if these trees were 2.5 years older (11.5 years). Although wood stiffness data was not collected at age 11.5 years, the data summarised in Figure 3 involves comparisons between ages 9 and 11 can be used as an estimate. It is evident that for a given tree height rather than tree age the 0.03 m^2 treatment, or, lack of weed control, gives rise to improved wood stiffness than the 9 m^2 treatment. This is interesting because, if observing the mean wood stiffness values by stem dimensions rather than tree age, it is possible that slower grown trees due to weed competition, could have improved mean wood stiffness for a given tree size. This is unlikely to be implemented by forest managers because it is common approach to reduce the rotation length in order to maximise the number of rotations over time.

Conclusions

- Wind direction (windward versus downward) did not have a significant impact upon wood stiffness measures collected form each side of the tree (p-value = 0.33).
- Mean wood stiffness was significantly affected by weed control treatment (p-value = 0.048).
- Mean wood stiffness was significantly affected by clonal selection (p-value < 0.001).
- The interaction between weed control treatment and clone was not significant (p-value = 0.65).
- All weed control treatments resulted in significantly improved wood stiffness for a given age when compared to the control treatment (0.03 m^2 weed control) with p-values of 0.02, 0.01 and <0.001 for the respective 0.75 m^2, 3.14 m^2 and 9m^2 weed control treatments.

- The ranking of the different levels of weed control treatments (including the control treatment) in terms of the highest mean wood stiffness value, remained constant across the three ages at which data was collected (ages 9, 11 and 17).
- The rank of clonal performance in terms of the highest mean wood stiffness value by clone also remained constant across the three ages at which data was collected. Clones one and six were the best performing clones, whereas, clone three and clone four consistently returned the lowest mean wood stiffness values.
- Including mean stem slenderness as a covariate into the split plot ANOVA model showed that stem slenderness significantly affected predictions of wood stiffness (p-value < 0.01).
- The interaction of stem slenderness and weed control treatment was not significant (p-value $= 0.54$).
- The interaction of slenderness and clone was also non-significant (p-value $= 0.89$).
- Including mean height to the live crown as a covariate into the split plot ANOVA model showed that mean height to the live crown is not a significant predictor of wood stiffness (p-value $= 0.18$).

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