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Calculating the Potential Increase in Pinus radiata Stem Value Through Selection for Higher Stiffness

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1. Summary

New Zealand grown *Pinus radiata* is limited in its application for structural purposes by its stiffness deficiencies. This dissertation aims to estimate potential improvements in stem value through selection for improved stiffness. A new method to model and value volumes of structural wood grades within a stem was used to calculate these value improvements. Data for each stem from a stand in Kaingaroa Forest bred for improved wood quality was used to perform this analysis. This data was from a stand bred for improved wood quality and included information on the stiffness, density and width of each growth ring for each stem. The data was in the form of cores. Height and volume data was not recorded and therefore needed to be modelled. The volumes of MSG8, MSG11 and MSG13 wood were estimated by modelling the stem volume at the age when wood is produced that is stiff enough to qualify for each grade.

The majority of stems had merchantable volumes between 1-2.5m^3 with the largest stems containing 3.6m^3. Average stiffness ranged between 5.2GPa and 11.3GPa with the stand average being 8.4GPa. There was no relationship between average stiffness and merchantable volume. Stem values were found to range between \$60-\$131/m^3 with the stand average being \$91/m^3. The 10 most valuable stems had a total stem value (\$318) twice that of the stand average (\$157). The most valuable stem (\$411) showed a 160% increase in stem value from the average. The increases in value/m^3 were caused by large increases in the proportion of MSG11 and MSG13 wood held within the merchantable volume. These potential gains in stem value could help tree breeders assign an accurate economic weighting to stiffness improvements. Forest managers wanting to justify using a more expensive, improved stiffness seedlot may also find these results valuable.

Key words: *Pinus radiata,* stiffness, value, selection, structural purposes, volume and New Zealand.

2. Acknowledgements

I hereby acknowledge Luis Apiolaza, Richard Wollons, John Walker, Andrew Van Houtte and Mike Vernon for their help with this dissertation. I would like to thank David Evison for his guidance, motivation and support throughout this dissertation. I would also like to thank my mother and father, David and Wendy Ferguson, for their support over this project.

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3. Introduction

Pinus radiata is multipurpose softwood that is used for solid wood, pulp and paper products and wood based panels. Its use in structural applications is limited by its stiffness, as measured by Modulus of Elasticity (MOE). Stiffness of wood is determined by both genetic and environmental factors. New Zealand tree breeders are now measuring for higher stiffness. Tree breeders need to be able to allocate an economic value for an increase in stiffness.

4. Problem Statement

The low stiffness of New Zealand grown *P. radiata* is a limiting factor for its use as a structural timber. A limited proportion of *P. radiata* meets the stiffness requirements for the higher value structural grades. Due to the fast growth rates of *P. radiata,* corewood represents a large proportion of the merchantable volume, but this corewood is of a low structural quality. Nelson Pine Ltd, which manufactures LVL in the South Island at Nelson, currently uses field methods to screen logs on the skid site to identify logs that meet their stiffness requirements.

If the volume of high stiffness wood produced by each stem can be increased then these logs will qualify for the higher strength structural grades. If this is able to be achieved, new market opportunities will become available to New Zealand growers such as, laminated veneer lumber (LVL) and the Australian structural timber market.

5. Research Questions

1. How much does stiffness vary between stems bred for improved wood quality?
2. What is the increase in the volume of wood that has a modulus of elasticity of 8GPa, 11GPa and 13GPa that can be produced by selection for wood stiffness?
3. What is the potential increase in stem value due to selection for increased wood stiffness?

6. Literature Review

New Zealand grown radiata pine is fast growing and able to tolerate a range of conditions (Madgwick, 1994). These characteristics have led to *P. radiata* being the dominant species for commercial forestry in New Zealand*,* currently comprising 90% of the commercial forestry estate (New Zealand Forest Owners Association, 2013). New Zealand currently exports the majority of its forest resource (New Zealand Forest Owners Association, 2013), and the inherent lack of stiffness limits the end uses of radiata pine in export markets. Currently a significant proportion is sold into relatively low value uses such as packaging and concrete boxing (Weir, 2013). With such a large proportion of the national forestry estate covered in one species there are potentially large benefits that could arise by increasing the quality of the resource.

The low stiffness of New Zealand grown *P. radiata* has been described as one of its biggest limitations (Walford, 1991). Even with over $1 billion spent on *P. radiata* research over the past 50 years, the stiffness deficiency problem is still to be solved (Walker, 2007). Structural timber in New Zealand is graded into machine stress grades (MSG). The wood is mechanically tested to measure stiffness as a non-destructive way to infer strength (Standards Australia International Limited & Standards New Zealand, 2006). Higher strength grades require wood with greater stiffness values. The number within the MSG13 grade name, for example, MSG8, MSG11 and MSG13, represents the stiffness of the wood measured in gigapascals (GPa) (Wood Solutions, 2013). Therefore, the strength of each structural grade increases with the number within their name. Due to its lack of stiffness, *P. radiata* does not qualify for the higher value structural grades such as MSG13. Higher stiffness wood is produced as the tree ages but due to the large proportion of low stiffness corewood present in *P. radiata* logs, these logs are not suited for structural log markets. If the volume of high stiffness wood produced by each stem can be increased then these logs will qualify for the MSG11 and MSG13 grades.

Stiffness is also affected by silviculture. Lasserre *et al.* (2005) found that stiffness is significantly affected by planting density and genetics. Gains in stiffness through genetics averaged 0.8GPa or 15%. Improvements in stiffness through increasing planting density were even higher, with an average increase in stiffness of 1.7GPa or 34%. Lasserre *et al.*

(2004) also found that the influence of genotype on stiffness was less than the influence of planting density. For this dissertation, it was decided to focus on the potential gains in stiffness through selection as an impressive dataset was available that suited this type of analysis. Lasserre *et al.* (2004) also found that tree diameter at breast height had a strong negative relationship with stiffness. This suggests that this dissertation may find there is a trade-off in stiffness that occurs when selecting solely for volume growth. Lasserre *et al.* (2007) stated that removing branches and bark increased the overall stiffness of the log by 5.4% and 8.3% respectively.

In addition to the low stiffness of *P. radiata,* shorter rotations that have been in favour with forest managers have led to even lower stiffness levels in logs (Young, 2004). The recent trend with forest managers attempting to increase the stiffness of their resource has been to lengthen rotations (Walker, 2007). However, lengthening rotations is merely a short term solution that will only mask the underlying problem of low quality corewood (Walker, 2007). In order to create a long term solution to the stiffness deficiency of *P. radiata* logs the corewood of these logs must be improved (Walker, 2007). Walker (2007) suggests that improvements in stiffness created through breeding may be difficult to realise if low stockings are used. It is therefore important to complement an improved seedlot with appropriate initial stand densities.

Stiffness is strongly influenced by microfibril angle (MFA) (Downes, *et al*., 2002). MFA is a variable and heritable trait which makes it suited to improvement through breeding (Apiolaza, 2012). By selecting individuals with a low MFA, a seedlot with improved stiffness can be created. If this is able to be achieved, new market opportunities will become available to New Zealand growers such as LVL and structural sawn timber. Apiolaza (2012) explained how basic density correlates strongly with stiffness but due to the low coefficient of variation for density it would be difficult to improve basic density through selection. Harris (1981) proposed that because many of the traits that influence stiffness are under genetic control, large improvements in corewood properties could be achieved through breeding. Tsehaye *et al.* (2000) suggests that the stiffest trees can be 80-85% more stiff than the least stiff stems. This same study also stated that through selection, average stiffness could be increased by one stress grade.

The low stiffness of New Zealand grown radiata pine is largely due to the amount of corewood present in each stem. Corewood is defined by Lasserre *et al.* (2004) as the first 10 growth rings of the stem. For this study, low stiffness wood will be defined as wood with an MOE less than 11GPa. This low stiffness wood will therefore include corewood. This corewood has many traits which do not complement structural use such as: low density, high MFA, low strength , low stiffness and dimensional instability (Lasserre *et al.*, 2004). Due to the fast growth of *P. radiata* in New Zealand, this low quality corewood occupies a large proportion of the full stem volume (Cown , 1992). Cown (1992) stated that corewood can occupy 50% of the stem volume of 25 year old, thinned *P. radiata.* Shorter rotations have led to this corewood occupying a larger proportion of the stem volume as the trees are not grown long enough to generate sufficient latewood (Sorensson *et al.*, 1997). Sorensson *et al.* (1997) suggested that in coming decades, rotation lengths may decrease to 20 years due to improved growth seedlings being deployed. These shorter rotations will only enhance the stiffness deficiencies of the logs as the corewood will represent an even larger proportion of the log. It has been shown that density, MFA and shrinkage (longitudinal, radial and tangential) can be improved if stiffness (MOE) is increased (Ivković *et al.*, 2009).

It is possible that value can be added to the resource if stiffness can be increased to where the resource will qualify for higher value structural grades, such as MSG11. MSG11 is the minimum structural grade acceptable for structural use in the Australian timber market (Wood Products Victoria, 2009). Sorensson *et al.* (2002) stated that the national stiffness average for radiata pine is 8.2GPa. At this stiffness level, logs would qualify for the MSG8 structural grade. In 2008, New Zealand grown *P. radiata* comprised 92% of the residential framing market (Page, 2009). This large market share in the residential framing market does not translate to the non-residential construction market where in 2012, New Zealand grown *P. radiata* timber represented 20% of the market (Moore, 2012). In order to increase this market share, the needs of the consumer must be taken into account (Moore, 2012). Engineers use characteristic values in their design calculations (Moore, 2012). These characteristic values include stiffness (modulus of elasticity), bending, compression and tensile strength (Moore, 2012). If the industry is to increase the market share of wood for construction purposes, these characteristic values must be improved.

LVL is an engineered wood product which randomises wood defects and can be used in the construction of multi-storey buildings (Domone & Illston, 2010). LVL manufacturers require logs that are stress graded to at least MSG11, in order to meet the New Zealand standard AS/NZS 4357.0 : 2005 (Standards New Zealand, 2005).

It is possible to create stiffness improvements in corewood through selection (Dungey *et al.,*2006). Dungey *et al.* (2006) suggests that selecting for stiffness would be most effective at rings 4-8 as this is where the corewood is located and stiffness increases with ring number. This dissertation will quantify the improvements in corewood stiffness and assign a value to the achieved level of improvement. It was also suggested in Dungey *et al.* (2006) that selecting for stiffness (MOE) could also bring improvements in MFA, density and dimensional stability. Stiffness heritability for the stems used in this study by Dungey *et al.* (2006) was very high at ring number four (0.9) and remained above 0.5 from ring 3–11. For these same trees it was found that possible gains in stiffness could be achieved from ring 3-25 with the greatest possible gains occurring between rings 4-10. This strengthens the suggestion that large improvements can be made in corewood stiffness.

If the stiffness levels of *P. radiata* can be improved by one stress grade, as was suggested is possible by Tsehaye *et al.* (2000), then the average log will qualify for the more lucrative MSG11 structural grade. It has been assumed that if the resource can be improved to where it qualifies for MSG11 that a large increase in value will occur. There is a lack of knowledge surrounding the actual increase in value that is brought about by an increase in stiffness. It would be of benefit for tree breeders and forest managers to understand how much value is added when stiffness is above 11GPa. Tree breeders would use the information for the economic weighting of stiffness in their breeding equations. Forest managers may be able to justify the added cost of deploying an improved stiffness seedling stock if the additional value these seedlings create is substantial.

7. Methods of Analysis

7.1 Data

Data from a stand of trees in Kaingaroa Forest in the Central North Island was used for the analyses (Dungey *et al.*, 2006). The stand was planted at 3m x 3m spacing and was thinned three times, once at age 7, again at age 12 and then again at age 18. This data was from a stand of 350 stems harvested at age 31 and was in the form of cores collected at breast height. Up to nine individuals from each of the 50 open-pollinated families were selected for the data sample. Cores were collected from each tree and for each growth ring MFA, density, stiffness and ring width was recorded. Silviscan was used to measure the Modulus of Elasticity (MOE) for each growth ring. Silviscan provides non-destructive estimates of wood quality as explained in Dungey *et al.* (2006). Only data up to ring number 28 was used for the analyses as data in later years was inconsistent.

Diameter at breast height (DBH) at age 28 for each stem in the sample is shown in Figure 1. DBH has a fairly normal distribution. The majority of stems at age 28 had a DBH between 40cm - 45cm and the largest DBH at age 28 was 58cm.

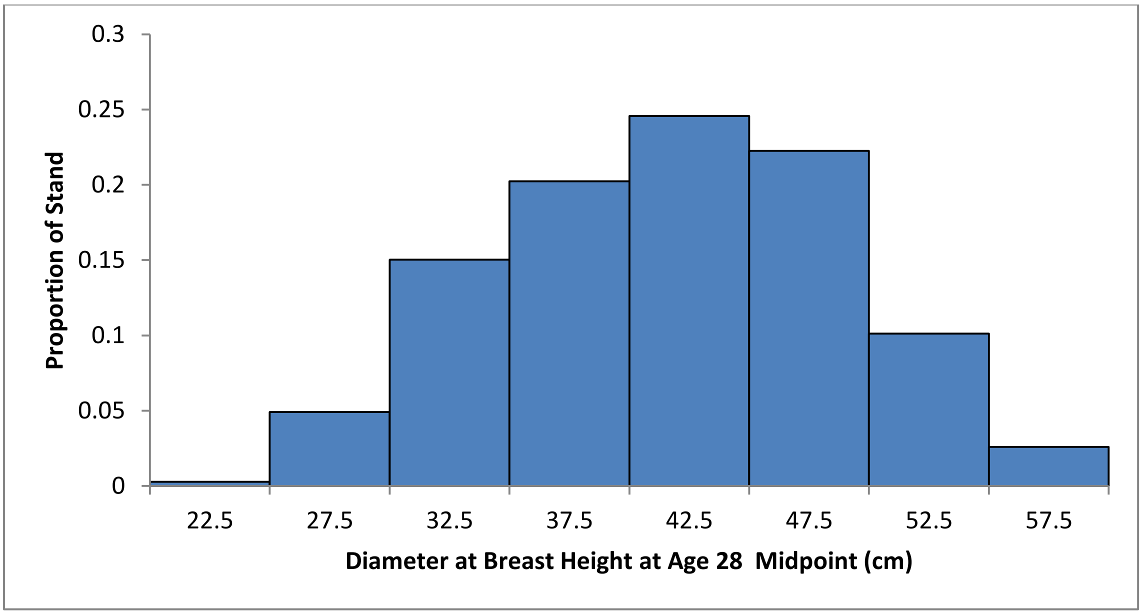

Figure 1: Diameter at breast height (cm) at age 28 for all trees in the stand.

No height or volume data was taken when the data was recorded. Height, taper and volume equations were therefore required to model the dimensions of each tree. The height equation shown below was developed by Richard Woollons (Woollons, 2003) and is suited to the Central North Island, where the data was sourced from. The volume and taper equations shown below were developed by The New Zealand Forest Research Institute and are compatible with one another (Katz *et al.*, 1984). Microsoft Excel was used to run the necessary functions to model the shape of the trees in the sample.

Height = exp(4.8583 - 4.3384/sqrt(diam) - 20.0550/time + 28.6820/(sqrt(diam)*time))

Tree volume = diam^1.8264 * (Height^2/(Height - 1.4))^1.12869 * exp(-10.385)

Taper (diameter at predicted height) = function (D, H, predicted height)

The modelled heights to the critical diameter (20cm) at age 28 for each tree in the sample are shown in Figure 2 below. Around 45% of the sample reached the critical diameter at 21-25m. Only 15% of the sample reached the critical diameter at a height greater than 25m. The higher a stem reached this critical diameter, the greater the merchantable volume, given the DBH is also above average.

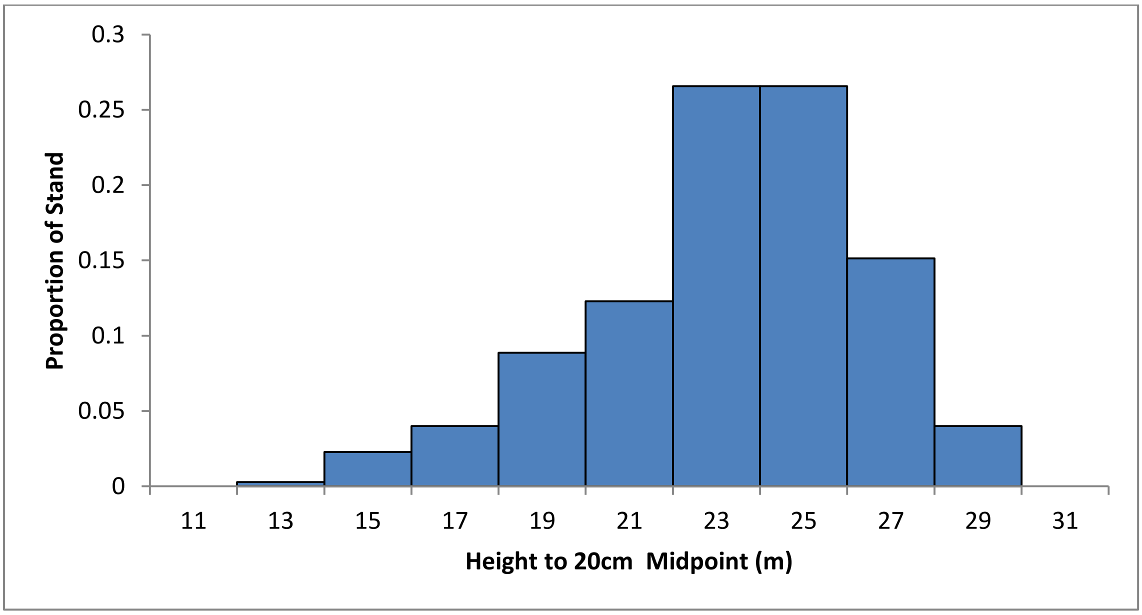

Figure 2: Heights to a 20cm diameter top for all trees in sample.

7.2 Methods

The MOE values produced through Silviscan are integral to this analysis. By knowing the age at which different trees reach set stiffness thresholds, trees were organised by how early they begin to start producing structural grade timber.

The merchantable volume of the stem was assumed to have a frustum shape. The equation for the volume of a frustum is shown below (Equation 2). Height for this equation was calculated using the taper equation to estimate the height up the stem where 20cm is reached. This minimum small end diameter (SED) was used as it is the minimum SED for an LVL log (Andrew Van Houtte, personal communication, 18 August 2014). These heights were calculated at age 28 for each stem. The radius at the bottom of the frustum was assumed to be equal to the radius at breast height, the height where the cores were taken. The radius at the top of the stem was equal to half the LVL log minimum SED. The excess wood at the top of the merchantable volume that is unable to be cut into an LVL log was included in the economic analysis as it was assumed the entire merchantable volume can be sold for LVL purposes.

The volume of wood in each strength grade was calculated by using Equation 1. The volumes of lower strength wood were calculated under the assumption that these volumes were cylindrical in shape. This assumption is illustrated in Figure 3. Wood was organised into the four strength grades shown in Table 1 according to the MOE value of the growth ring.

Table 1: The four strength grades used in the analysis.

	<MSG8	**MSG8**	**MSG11**	**MSG13**
MOE	< 8 GPa	>=8GPa and <11GPa	>=11GPa and < 13GPa	>= 13GPa

The less than MSG8 grade also contained an 80mm peeler core which is wood that is unable to be peeled on the LVL lathe. The diameter of each cylinder was estimated as the diameter of the stem when wood above each stiffness threshold is consistently produced. It was also assumed that the stiffness values measured at breast height do not change up the stem. In some stems, earlier growth rings would exceed the stiffness threshold but in later growth rings stiffness would regress to below the thresholds. When this occurred the diameter of the cylinder of low stiffness wood was extended up until the ring when high stiffness wood was consistently produced. This ensured that the volumes of higher stiffness wood only contained wood that was above the stiffness threshold.

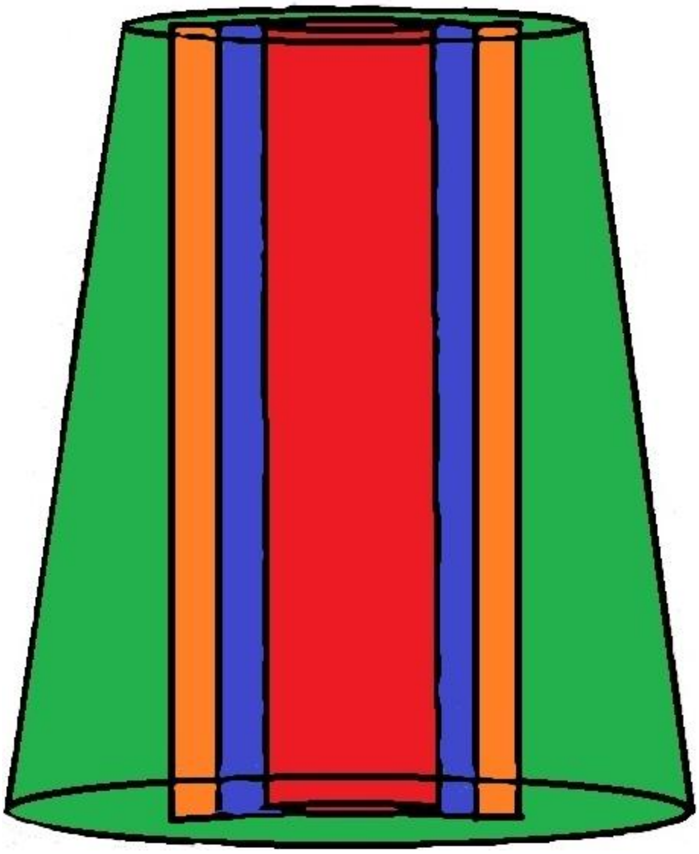

Figure 3: Diagram of frustum and cylindrical assumptions for high stiffness and low stiffness wood. Red = 80mm peeler core and/or <8GPa wood, blue = MSG8 wood, orange = MSG11 wood and green = MSG13 wood.

$$\textbf{Volume of wood in strength grade} = \textbf{Merchantable volume} - \textbf{Total volume of other grades}$$

Equation 1: Volume of wood in each strength grade

$$\mathbf{V} = \frac{\mathbf{1}}{\mathbf{3}} * \boldsymbol{\pi} * \mathbf{h} * \left(\mathbf{r1}^{\mathbf{2}} + \mathbf{r2}^{\mathbf{2}} + (\mathbf{r1} * \mathbf{r2})\right)$$

Where: h = height r1 = radius of bottom of frustum r2 = radius of top of frustum

Equation 2: Frustum volume equation.

Total stem value was calculated by applying volume based values to each strength grade. The cubic metre values of each grade were calculated by gathering prices for each grade of LVL at Placemakers. Prices were quoted for lengths of MSG8, MSG11 and MSG13 LVL. The dimensions and prices of the quoted LVL lengths are shown in Table 2. The consumer price premiums for each grade were then applied to an average MSG11 LVL log value of \$120/m^3. This average MSG11 log value was provided by Andrew Van Houtte, an LVL producer (Andrew Van Houtte, personal communication, 18 August 2014). The resulting per cubic metre values for each grade are shown in Table 3 below.

Table 2: Quoted prices/m^3 and associated consumer price premiums for MSG 8, MSG 11 and MSG 13 LVL, sourced from Placemakers.

	Dimensions	Volume (m^3)	Price/m^3	Price Premiums
MSG8	90mm x 45mm x 4.8m	0.02	228.91	1.00
MSG11	200mm x 50mm x 4.8m	0.05	452.50	1.98
MSG13	200mm x 50mm x 4.8m	0.05	556.25	2.43

Table 3: The volume based values for MSG8, MSG11 and MSG13 wood.

< MSG 8	MSG 8	MSG11	MSG13
\$60.00	\$60.71	\$120.00	\$147.51

8.0 Results

8.1 Intrinsic Wood Properties

8.1.1 Merchantable Volume

The volume of merchantable wood in each stem was fairly normally distributed (Figure 4). Merchantable volumes ranged from 0.44-3.5m^3. The majority of stems had merchantable volumes between 1-2.5m^3. The average for the stand was 1.75m^3. Around 13% of the sample had a merchantable volume greater than 2.5m^3. Only two stems had merchantable volumes greater than 3.5m^3 and both of these were just over 3.76m^3.

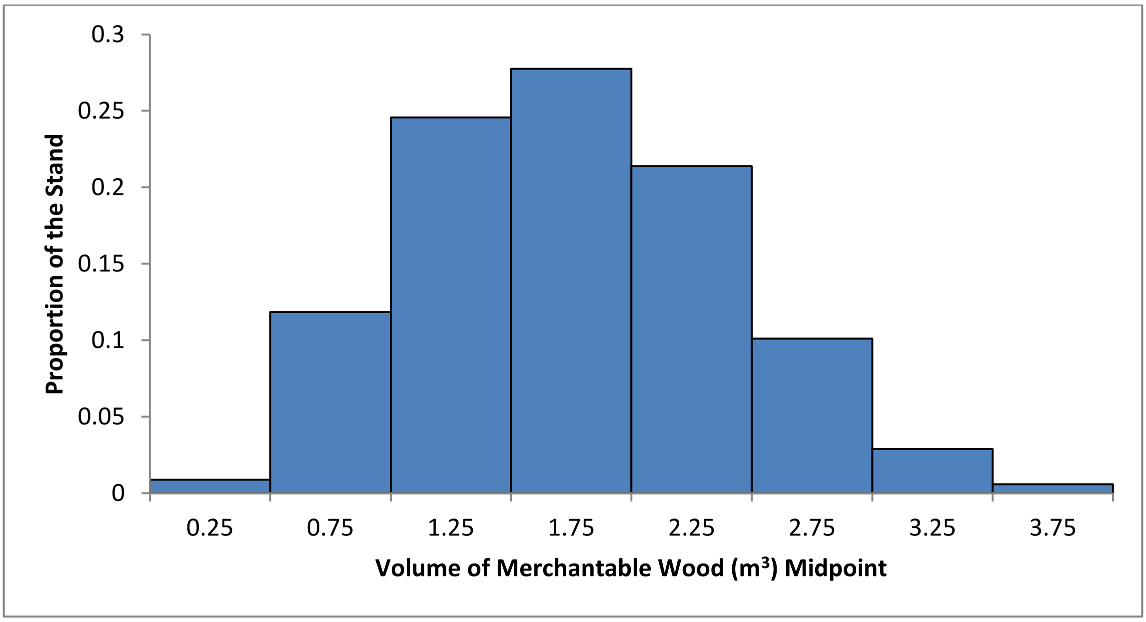

Figure 4: Volume of merchantable wood (m^3).

8.1.2 Stiffness

There was a large range of volumes of MSG11 and MSG13 wood in the stand (Figure 5). Twenty five stems did not contain wood stiff enough to qualify for MSG11 or MSG13. One stem contained 2.6m^3 of this higher stiffness wood. Six stems were found to contain over 2m^3 of this higher stiffness wood while on average, stems in this stand contained 0.72m^3.

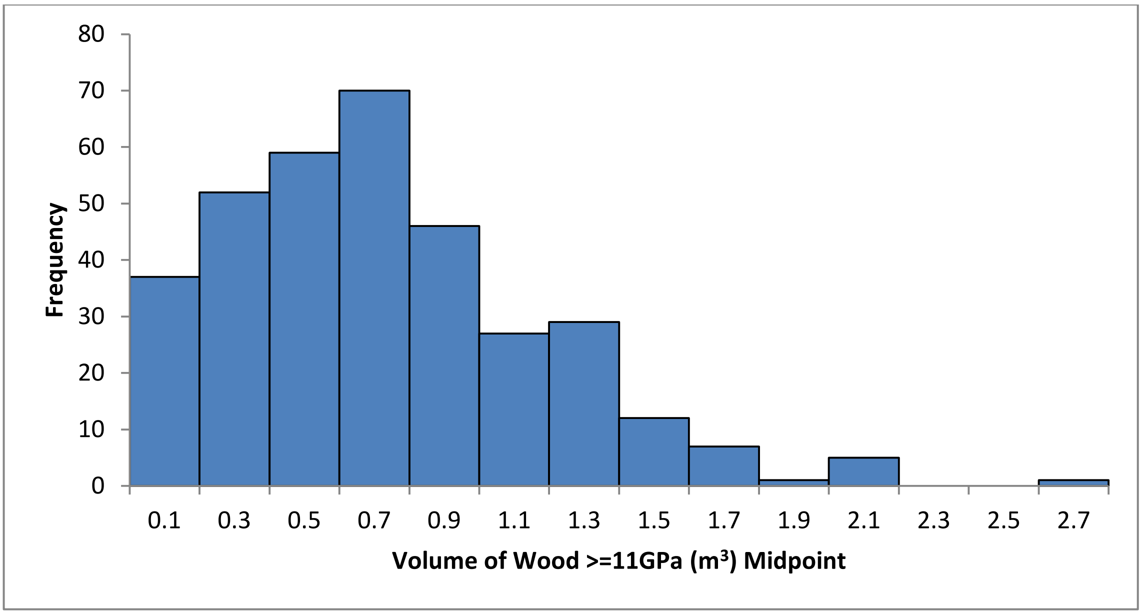

Figure 5: Volume of MSG11 and MSG13 wood in each stem (m^3).

The proportion of high stiffness wood contained within the merchantable for each stem is shown in Figure 6 below. High stiffness wood was deemed to be MSG11 and MSG13 wood. On average, 42% of the merchantable volume was higher stiffness wood while three stems contained 80-83% higher stiffness wood.

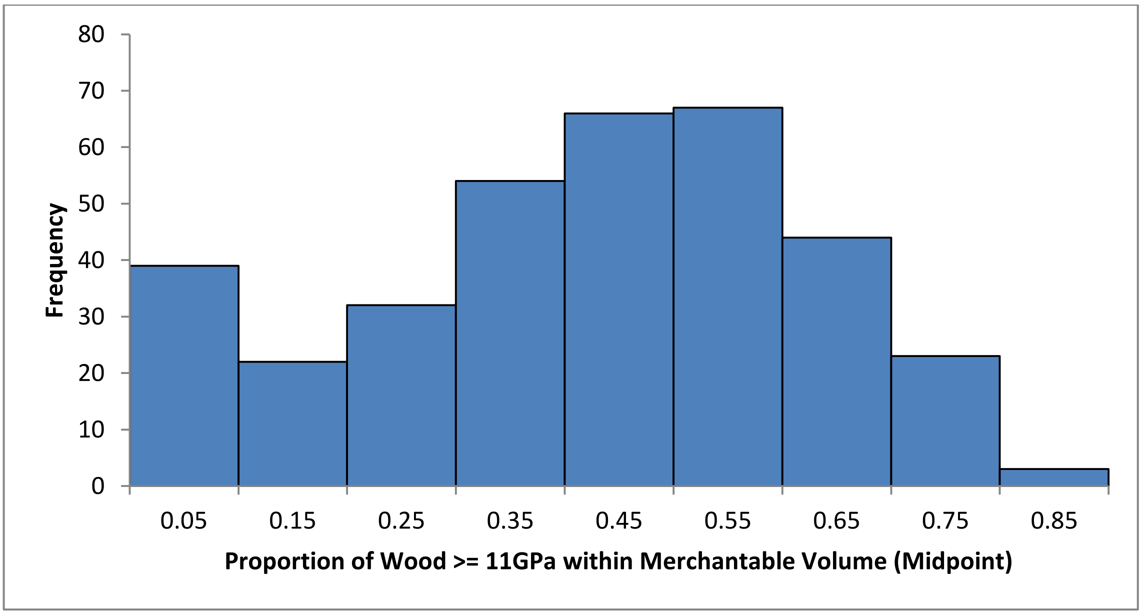

Figure 6: Histogram of the proportion of high stiffness wood (MSG11 and MSG13) to lower stiffness wood (MSG8 and lower grade wood).

The relationship between average stiffness and tree diameter at age 28 is shown in Figure 7 below. There was no relationship found between these two variables but the variation in average stiffness increased greatly with tree diameter. The relationship between merchantable tree volume and average stiffness is shown in Figure 8. There was no relationship between merchantable tree volume and stiffness but variation in average stiffness increased with merchantable tree volume. If stiffness is included in the selection criteria, there are potential gains in stiffness to be had without decreasing merchantable volume. When selecting stems with a large merchantable volume there is the potential to increase average stiffness by 50% or 5GPa with no loss in merchantable volume. The greatest gains in stiffness can be achieved at larger merchantable volumes.

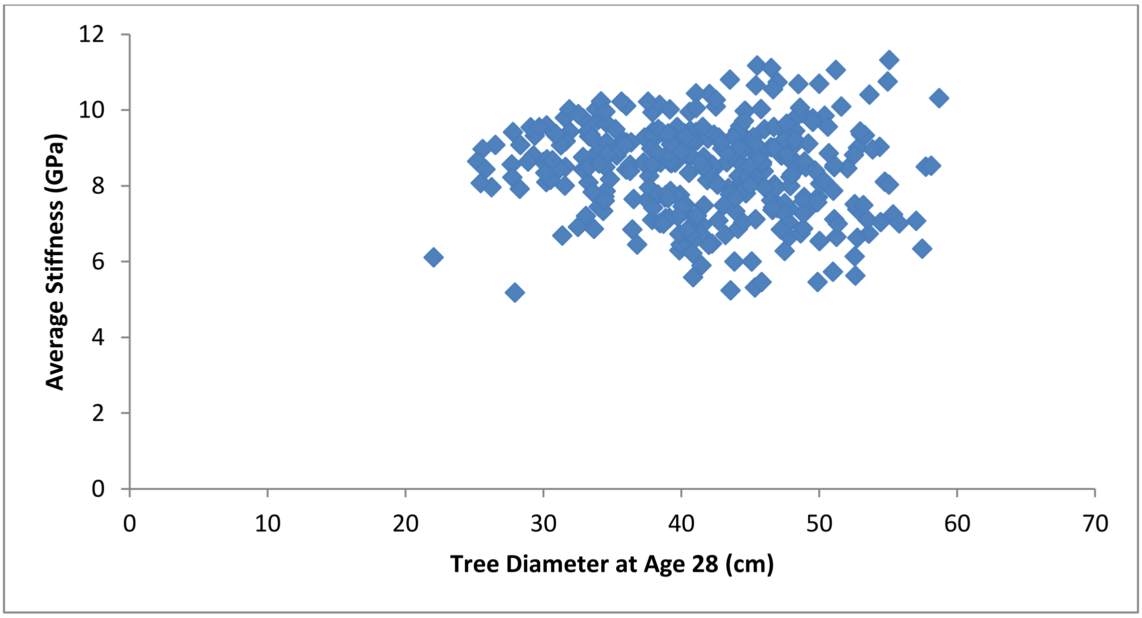

Figure 7: Relationship between average stiffness (GPa) and tree diameter at age 28.

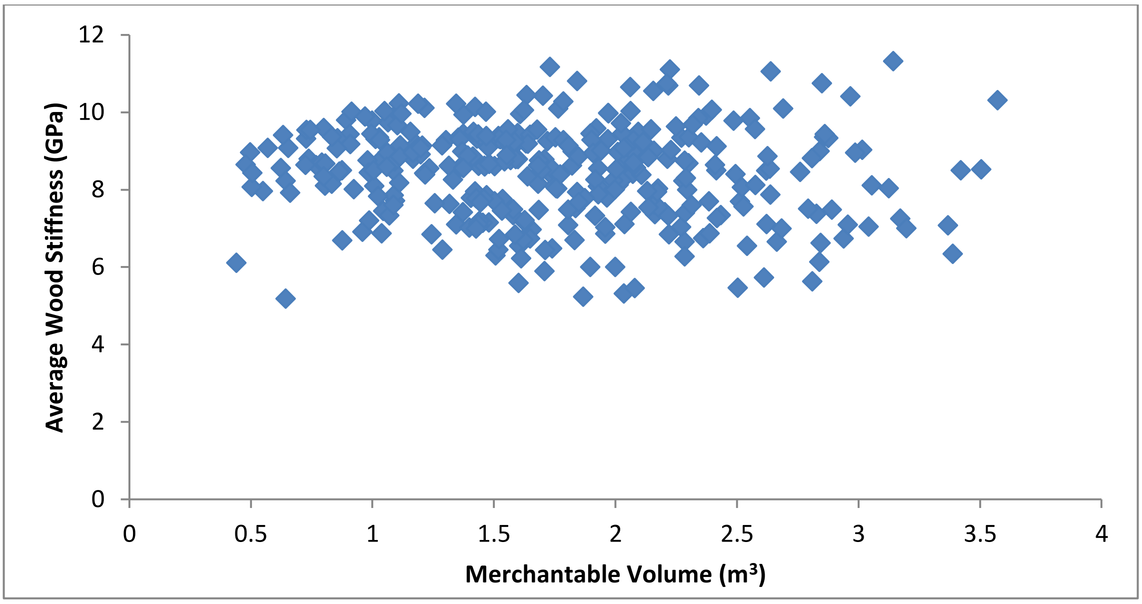

Figure 8: Relationship between merchantable volume (m^3) and the average stiffness of merchantable volume (GPa).

The relationship between average density of a stem and merchantable stem volume is shown in Figure 9. Average density ranged from 430kg/m^3 and 630kg/m^3. There was a weak negative relationship between stem volume and average density. It can be seen that there was large variation in average density at each merchantable volume. Gains in density without sacrificing merchantable volume are able to be achieved but these gains diminish at larger merchantable volumes. These gains were largest between 1-2m^3 merchantable volume. Above 2.5m^3 merchantable volume, it was possible to increase average density by around 100kg/m^3 without sacrificing merchantable volume.

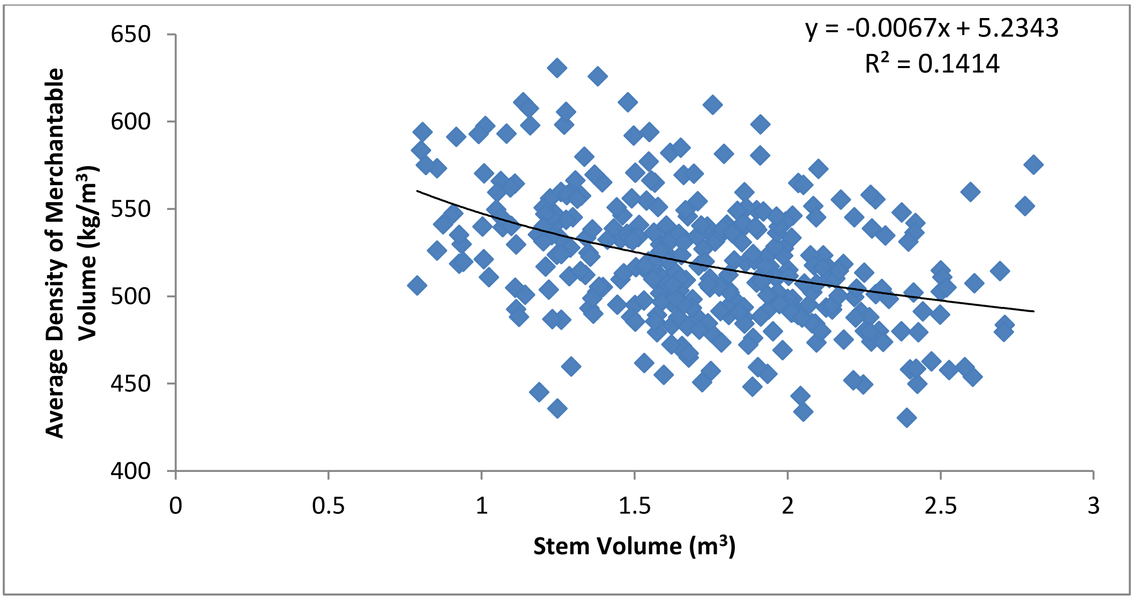

Figure 9: Relationship between average density (kg/m^3) and stem volume (m^3).

The relationship between average stiffness and average density for merchantable stem volume is shown in Figure 10. There was a positive relationship between the two variables. This relationship was found to be statistically significant when an analysis of variance was performed (Table 4). Average density can be used to explain 23% of the variation in average stiffness.

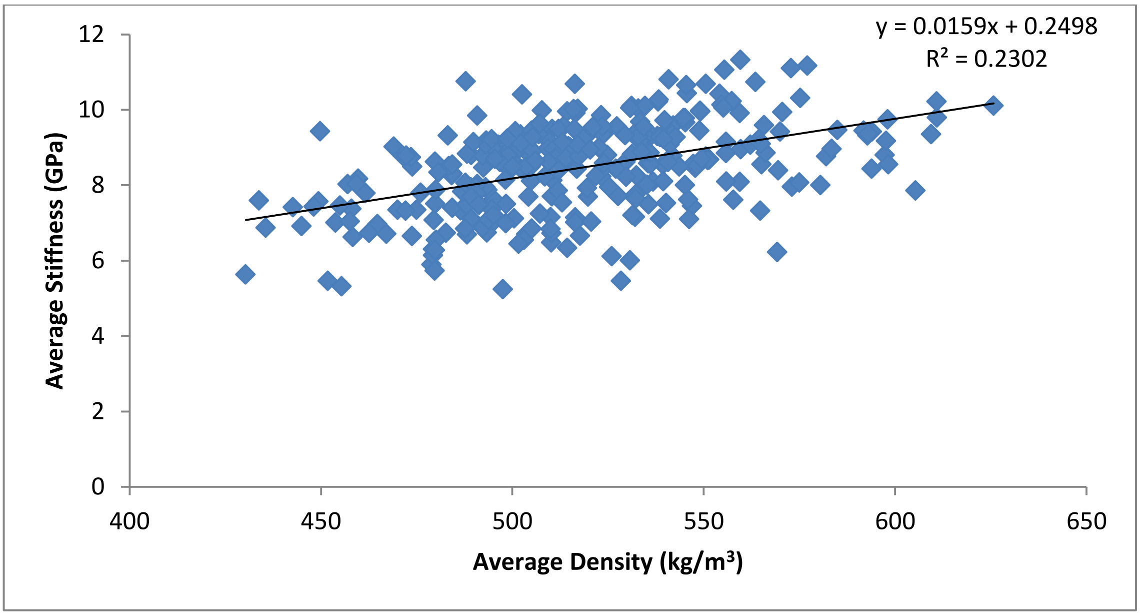

Figure 10: Relationship between average density (kg/m^3) and average stiffness (GPa).

Table 4: Analysis of variance results for regression between average stiffness and average density.

	Estimate	Standard Error	T Value	P Value
Intercept (Stiffness)	0.250	0.863	0.290	0.772
Density	0.016	0.002	9.550	$< 2 \times 10^{16}$
Adjusted R-squared	0.228			

8.2 Economic Analysis

Total stem value was calculated by applying the volumetric values to the volume of each strength grade contained within each stem's merchantable volume (Figure 11). Around 60% of the stand had a total stem value between \$100 - \$200. Stem value, the proportion of high stiffness wood within the merchantable stem volume and the average MOE value for the merchantable volume is shown in Table 5. The most valuable stem had a total stem value of \$411 and six stems were worth over \$300. The average stem had a total stem value of \$157. The ratio of high stiffness wood to low stiffness wood in the most valuable stem was close to twice that of the average. The average MOE value for the stand was 8.4GPa which is above the threshold for MSG8. The most valuable stem had an average MOE value of 11.3GPa which is enough for the MSG11 grade. The difference in average stem value/m^3 between the max and the average was caused by a large increase in the proportion of high stiffness wood within the stem and the average stiffness. This proportion is also shown in the average MOE values which show that the more valuable stems have a higher average stiffness than the stand average.

Table 5: Total stem value, average stem value/m^3, average MOE value and the proportion of low stiffness wood to high stiffness wood for the average stem, average of the ten most valuable stems and the most valuable stem.

	Total Stem Value	Value/m3	Proportion of High Stiffness Wood In Merchantable Volume	Volume Weighted Average MOE of Merchantable Volume (GPa)	Merchantable Volume
Stand Average	\$157.68	\$ 91.77	0.419	8.4	1.75
Average of Ten Most Valuable Stems	\$ 318.51	\$ 117.54	0.727	10.5	2.72
Most Valuable Stem	\$411.77	\$ 131.01	0.831	11.3	3.14

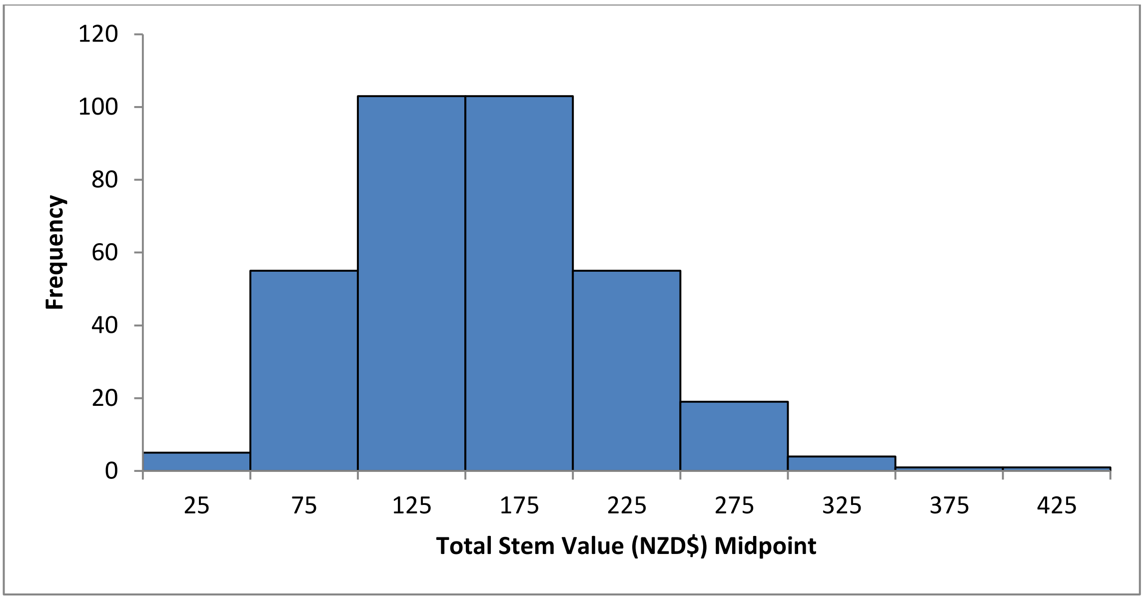

Figure 11: Total stem value of each stem in the stand.

The five most valuable stems and five least valuable stems are shown in Figure 12. It can clearly be seen that the more valuable stems were of a larger size than the average and least valuable stems. The difference in size occurs after year 10, where the least valuable stems begin to slow down growth while the more valuable stems continue to add a large amount size at breast height. On average, the top ten stems produced MSG11 wood in year 7 and MSG13 wood in year 8. Meanwhile, on average, the stand produced MSG11 wood at age 11 and MSG13 wood at age 12. This shows that the more valuable stems were producing high stiffness wood earlier and were producing more of this wood.

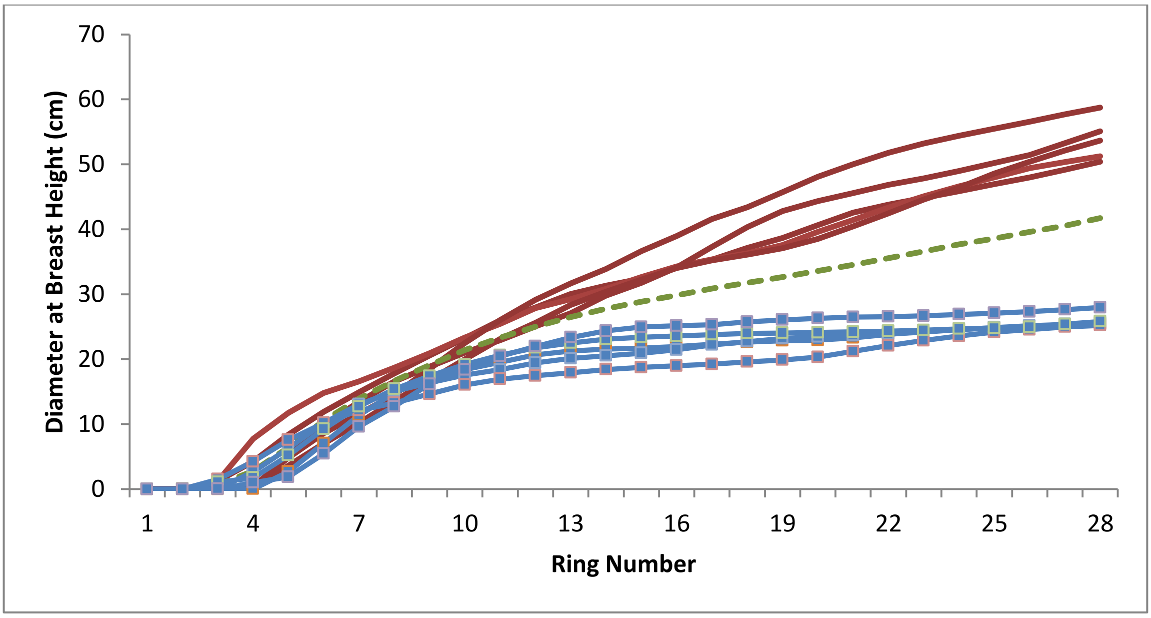

Figure 12: DBH (cm) growth for the average stem (dashed, green line), five largest trees (solid, red line) and five smallest trees (dotted, blue line).

The five most valuable stems are shown in Figure 13. It can be seen that the most valuable stem does not have the largest merchantable volume but does have the largest amount of MSG13 wood. Trees 17, 91 and 286 all produce high stiffness wood at an early age. This is evident by the lack of an MSG8 wood being present and the volume of <8GPa wood is largely contained within unusable 80mm peeler core which is unavoidable waste. Table 6 shows the difference in the volumes of each strength grade contained with the merchantable volumes for the average stem in the stand and the most valuable stems. There were large differences that occurred between the stand average and the most valuable stems. Average volumes for the ten most valuable stems were used in Table 6. These ten stems contained more MSG11 and MSG13 wood than the stand average and contained 0.11m^3 less MSG8 wood. The amount of <8GPa wood was 0.16m^3 less in the 10 most valuable stems compared to the stand average. The more valuable stems begun producing high stiffness wood earlier than the stand average as was explained earlier. This is also reflected in the decreased volumes of <8GPa and MSG8 wood and increased volumes of higher stiffness wood. This shows that the more valuable stems were not only larger in terms of merchantable volume but also produced a more valuable composition of high stiffness wood to low stiffness wood.

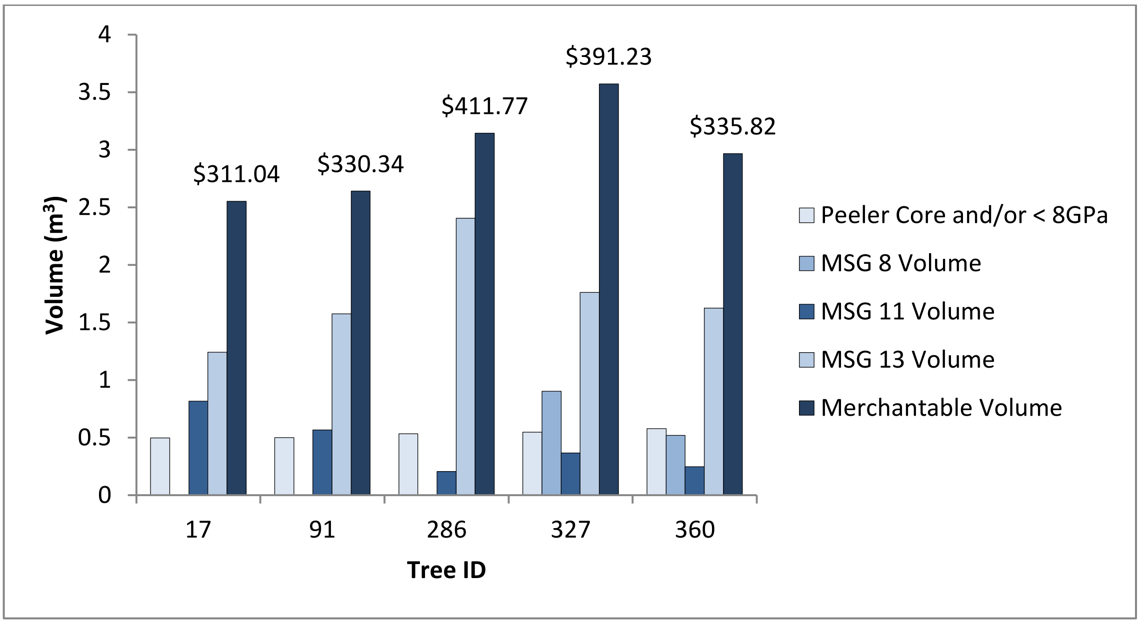

Figure 13: Volumes of each grade of wood and the total merchantable volume for the five most valuable stems (m^3). Total stem value is shown in data label.

Table 6: The volumes of each strength grade contained within the merchantable volumes for the stand average, the ten most valuable stems and the most valuable stem (m^3).

Strength Grade (MSG)	Stand Average (m^3)	Average of Ten Most Valuable Stems (m^3)	Most Valuable Stem (m^3)
<8	0.67	0.51	0.53
8	0.36	0.25	0.00
11	0.39	0.62	0.21
13	0.33	1.34	2.40
Total	**1.75**	**2.72**	**3.14**

The value/m^3 of each stem is shown in Figure 14. Around 60% of stems in the stand had a per cubic metre value of \$80 - \$110. The stem with the greatest total stem value (tree no. 286) also had the greatest value/m^3 (131/m^3). No stems were worth less than \$60/m^3 as this was the value assigned to the peeler core and <8GPa wood. The stand average was \$91/m^3.

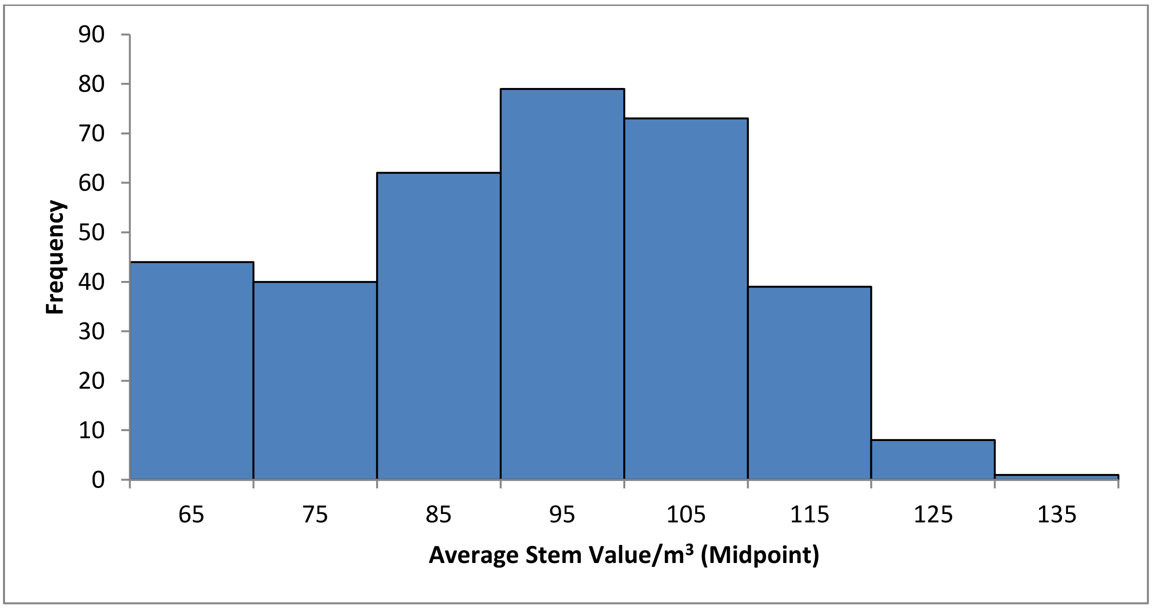

Figure 14: The average stem value/m^3 for all trees in the stand.

8.3 Volume and Value Analysis with Excess Wood at Top of Stem Removed

The volume and value analysis performed above included wood at the top of merchantable volume that would be too long to be cut into a 2.7m log (A. Van Houtte, personal communication, 18 August 2014). When this volume of wood was removed from the analysis, a different stem became the most valuable in the stand with a total stem value of $388 or $127/m^3 (Table 7). On average, the ten most valuable stems decreased by 2.6% in terms of total stem value and decreased by 5.1% in value/m^3 (Table 8). The stand average total stem value decreased to $145 (decrease of 7.5%) while the average value/m^3 only decreased to $90. The average merchantable volume of the 10 most valuable stems increased by 3.4% and 13% for the most valuable stem.

Table 7: Stem value, proportion of high stiffness wood in merchantable volume and merchantable volume for the stand average, ten most valuable stems and the most valuable stem when excess wood at the top of the merchantable volume was removed.

	Total Stem Value	Value/m^3	Proportion of High Stiffness Wood Within Merchantable Volume	Merchantable Volume (m^3)
Stand Average	$ 145	$ 90	0.396	1.64
Average of Ten Most Valuable Stems	$ 310	$ 111	0.673	2.81
Most Valuable Stem	$ 388	$ 127	0.810	3.55

Table 8: Change when excess wood at the top of the merchantable volume is removed in stem value , the proportion of high stiffness wood in the merchantable volume and merchantable volume for the stand average, ten most valuable stems and the most valuable stem.

	Decrease from Original Analysis (% Change)			
	Total Stem Value	Value/m^3	Proportion of High Stiffness Wood Within Merchantable Volume	Merchantable Volume (m^3)
Stand Average	$ 11.80 (7.5%)	$1.52 (1.7%)	0.023 (5.5%)	0.111 (6.4%)
Average of Ten Most Valuable Stems	$ 8.39 (2.6%)	$ 6.00 (5.1%)	0.054 (7.4%)	+0.091(+3.4%)
Most Valuable Stem	$22.98 (5.6%)	$ 3.41 (2.6%)	0.020 (2.5%)	+0.407 (+13.0%)

8.4 Relationship Between Value and Volume

The relationship between total stem value and merchantable volume is shown in Figure 15 while Figure 16 shows the relationship between average stem value/m^3 and merchantable volume. These graphs show the increases in stem value that can be achieved through selecting for higher stiffness. For stems of a similar merchantable volume, there is the potential to increase the value of the stem by 100%. Figure 16 vividly shows the large range in stem value between stems of a similar merchantable volume. In Figure 15 there appears to be a trend of greater variation in stem value as merchantable volume increases. This is in similarity to Figure 8 which shows that as merchantable volume increases, the variation in average stiffness increases.

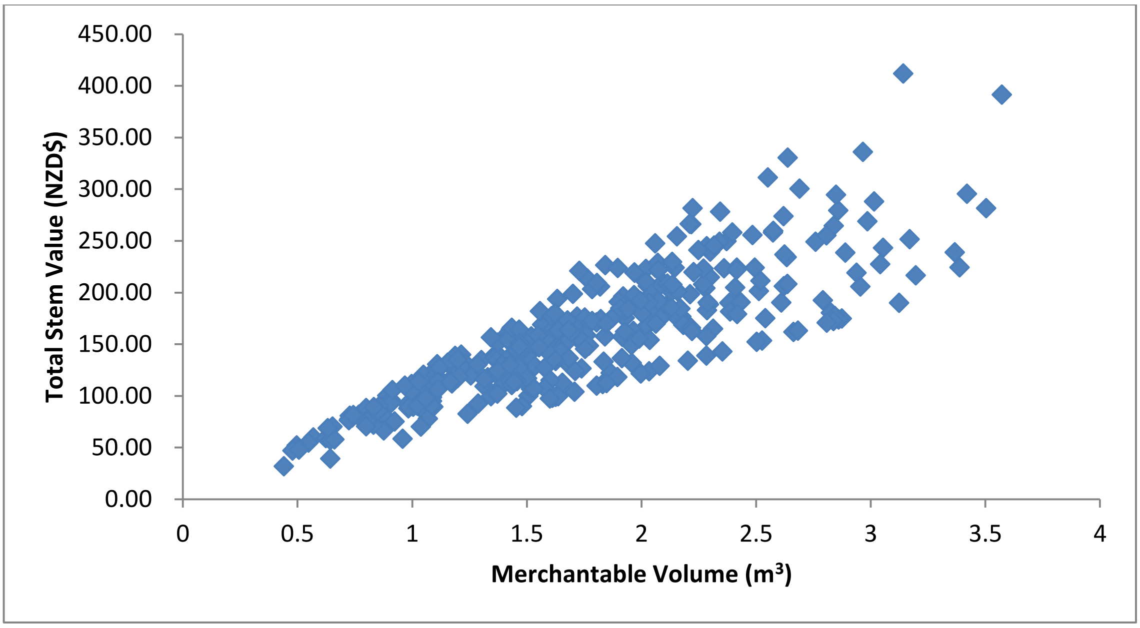

Figure 15: Total stem value (NZD$) against merchantable volume (m^3).

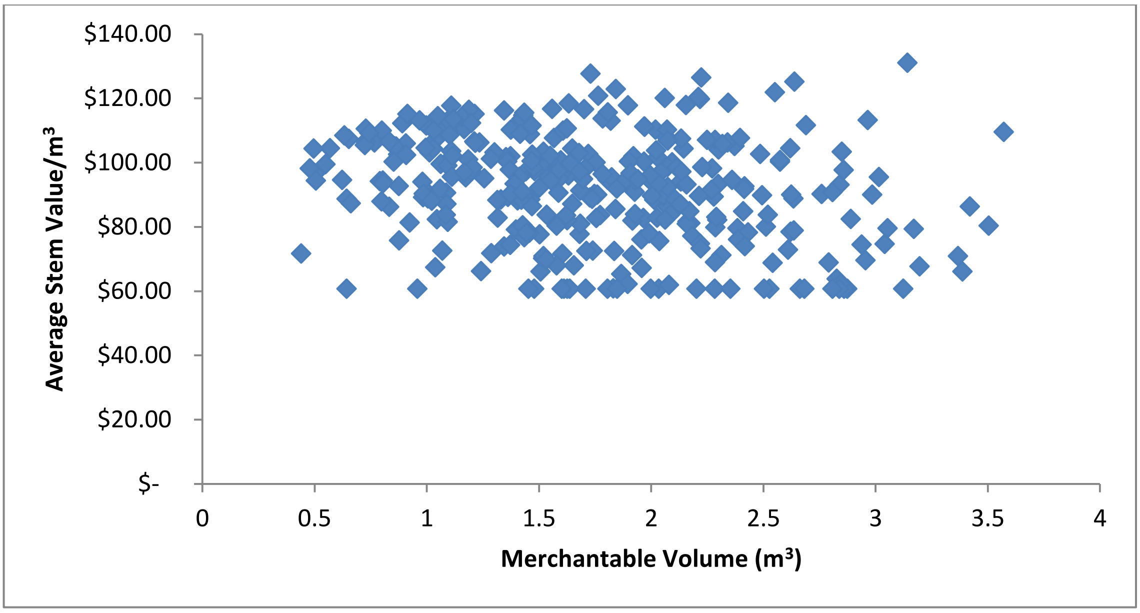

Figure 16: Average stem value/m^3 (NZD$) against the merchantable volume (m^3).

9. Discussion

9.1 Limitations

9.1.1 Modelling of Height and Volume

The first limitation was that the original dataset used for this analysis lacked height and volume information. This information had to be modelled using height, volume and taper equations. Having to model this information reduced the accuracy of the data but was the best way to analyse this otherwise very impressive dataset. A number of assumptions had to be used in order to model this volume information of the entire tree and of wood in each stiffness grade within the stem.

The first assumption was that stiffness does not vary up the stem. Unpublished data is likely to prove this assumption to be false and that stiffness increases up the stem (Euan Mason, personal communication, July 2014). Due to this assumption, estimates of each grade of wood further up the stem are likely to be conservative. This was deemed to be an acceptable loss of accuracy as this assumption allowed for a much clearer and easier model to work with and estimates are likely to be most accurate in the bottom log which is the largest and therefore the most important. The error in each estimate up the stem will increase further up the stem. Logs further up the stem are smaller in size and therefore the greatest error will occur in the least important logs.

The next assumption that was limiting was that the merchantable volume was in a frustum shape and that each stiffness grade within the frustum was cylindrical in shape. This assumption is also known to be false but allowed for a model that was easier to create and modify using Microsoft Excel. The frustum volume was sometimes greater than the total stem volume calculated using the volume equation. Therefore the frustum assumption was causing an over prediction of merchantable volume as it did not model the true shape of the stem. Walker and Xu (2004) stated that the stiffness gradient within the butt log is in a conical shape but that in logs higher up the stem, stiffness gradients are more cylindrical. Therefore the assumption that stiffness gradients are cylindrical is a fair assumption for logs further up the stem but will over predict volumes in butt logs.

This will reduce the accuracy of the estimates for the butt logs which are the largest and therefore the most important.

DBH was assumed to be the diameter of the large end of the frustum. In reality, the bottom of the merchantable volume would be cut lower down the stem and therefore have a larger diameter.

When classifying wood into each stiffness grade, only wood that was consistently above that specific stiffness grade threshold was entered into that grade. That is, if wood from an early age was above the threshold but then at a later growth ring, stiffness dipped below this threshold, all of this wood was included in the lower stiffness grade. This ensured that all of the wood included in each stiffness grade was at or above the designated stiffness threshold. In reality, at an LVL mill, the higher stiffness wood contained between rings of a lower grade would be tested and graded accordingly. Therefore this method likely underestimated the amount of wood in the higher stiffness grades.

9.1.2 Economic Analysis

Wood was assumed to be used solely for LVL purposes. With this assumption, this new method of analysis was able to calculate the volume of wood in each strength grade that could be extracted from a log using an LVL peeler. It was also assumed that the LVL peeler would be able to utilize all of the wood from the merchantable frustum apart from the 80mm peeler core. Therefore it was assumed that all of the wood on the outside of the frustum is able to be peeled. It was assumed that the log peeler was able to peel parallel to the taper of the merchantable log and utilize all of the outside wood in the frustum. Barnes (1993) suggested there is the ability for log peelers to perform this but it is not known if this is common in New Zealand LVL mills.

The volume based value figures that were used in the economic analyses were derived from gathering consumer prices for MSG8, MSG11 and MSG13 LVL from Placemakers. The consumer price premiums for each grade were then applied to an average MSG11 log value of \$120/m^3. This method assumed that the consumer price premiums for each log grade were the same as the wholesale price premiums that forest growers receive. Ideally, real wholesale values for each grade would be used for this analysis but as this is sensitive information, forest growers and LVL manufacturers were reluctant to part with this information.

9.2 Future Analysis

This new method for valuing the volume of different stiffness grades contained within a stem would easily be adapted to suit an alternative dataset. Future analysis could be undertaken to utilize an improved dataset that could relax a number of the assumptions used in the analysis and improve the accuracy of the analysis. The accuracy of this new method could be improved if a dataset with real height and volume information is utilized. With this type of dataset, height and volume would not have to be modelled. The true shape of each log could be measured. Also, stiffness would be able to be measured at different points up the stem. If wholesale prices per cubic metre for each LVL grade are able to be gathered, this too would improve the analysis.

10. Conclusions

This new method for valuing the volumes of different stiffness grades within a stem is easily adaptable to different datasets. There were a number of limitations to this analysis but the assumptions required to perform this analysis could be relaxed if the recommendations for future analysis are followed. These recommendations include using a dataset with height and volume information as well as stiffness data at different points up the stem. Even with these limitations the results from this analysis are still valuable.

In terms of average stiffness, the stand average was 8.4GPa which is slightly above the national average stated by Sorensson *et al.* (2002). The minimum average stiffness of the stand was 5.3GPa and the maximum was 11.3GPa. This improvement in average stiffness between the stand average and the most valuable stem is an increase of an entire strength grade which is consistent with the results of Tsehaye *et al.* (2000). There was no relationship between average stiffness and merchantable volume. There was also no relationship found between tree diameter and average stiffness which is contrary to the strong negative relationship found by Lassere *et al.* (2004). It was found that there was the ability to select for higher stiffness trees without sacrificing merchantable volume. These higher stiffness trees had average stiffness values around 5GPa greater than the minimum at a given volume. These gains in stiffness were even more prominent at larger merchantable volumes.

Average stem value/m^3 and total stem value were found to vary greatly between trees. The average stem of the stand was worth \$157 or \$91.77/m^3. On average, the 10 most valuable stems in the stand were worth \$318 or \$117/m^3. The total stem value of these 10 stems was worth twice that of the average of the stand and the most valuable stem in the stand had a total stem value (\$411) around two and a half times greater than the stand average.

Compared to the stand average, the most valuable stems produced an average of 0.16m^3 less <8GPa wood and 0.11m^3 less MSG8 wood. These stems also produced 0.23m^3 more MSG11 and 1.01m^3 more MSG13 wood. The more valuable stems produced high stiffness wood at an earlier age than the stand average and had higher growth rates while producing this high stiffness wood. The proportion of high stiffness wood contained in the tree merchantable volume and the average stiffness values for each merchantable volume were also greater in the more valuable stems.

Average stiffness can be measured using an acoustic tool such as a hitman. Using these tools, average stiffness is more easily measured than the proportion of high stiffness wood and therefore average stiffness should be the variable under selection. Measuring average stiffness could therefore be an easy method for establishing which stems have potentially greater stem values. By selecting stems for increased stiffness, an increase in MFA and density is also likely to occur (Dungey *et al.*, 2006) Longitudinal shrinkage in juvenile wood will also improve as there is a strong negative relationship between longitudinal shrinkage and stiffness as measured with MOE (Ivković *et al.*, 2009).

If tree breeders are able to create the same increases stiffness seen in this analysis then these potential gains in stem value may be realised. Stem value may be increased further if a suitable silviculture regime is implemented (Lassere *et al.,* 2005). This silviculture regime may include increasing initial planting density to around 2500 stems/ha (Lasserre *et al.*, 2005). Tree breeders can also use the results of this economic analysis to develop an accurate economic weighting for the production of high stiffness wood. Forest managers can also use this information on the potential improvements to stem value to justify the use of a more expensive, improved stiffness seedlot.

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