Factors which influence corewood stiffness in radiata pine

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Bachelor of Forestry Science

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Executive summary

Increasing stocking and competition with weeds significantly increased Hitman estimates of stiffness at the significance level $\alpha=0.05$. Accuracy of models predicting Hitman from TreeTap measurements can be improved by customizing them for particular silvicultural regimes and diameter at 1.4m (DBH). Controlled factors: genetics, wind sway and fertilizer use, did not significantly influence Hitman estimates of stiffness. Tree height did not significantly influence stiffness estimates, but including DBH in prediction models improved models of stiffness estimates.

Stiffness in 10 year old *Pinus radiata* stems was studied in an experiment with the following factors: genetics, herbicide/fertilizer use, stocking and wind sway. Acoustic velocity was used as an estimate of modulus of elasticity (MOE) and was estimated using 2 different tools: Hitman, a resonance based tool used on 2m log sections, and TreeTap, a time-of-flight based tool used on 1.2m outer-wood sections of standing trees. DBH and tree height were also recorded for each tree. Green density was measured using submersion in order to use the formula:

$$\text{MOE} = \text{green density} * \text{acoustic velocity}^2$$

Stiffness estimates from TreeTap were strongly correlated with Hitman estimates, but were about 30% higher on average. The relationship between stiffness estimates from these tools changed with weed competition and with stocking. No significant difference in stiffness was found between the northwest and the southeast sides of the stems when using the TreeTap tool, and an average value for each tree was used for subsequent analyses.

These findings are similar to those from other studies carried out on different sites, and to a previous destructive sample at the same site. There were a few major outliers, but despite these the final model relating TreeTap and Hitman estimates was significant ($P<0.0001$). Weed competition and stocking significantly affected the intercept ($P=5.71e-05$ and $P=1.08e-05$ respectively) of a model predicting Hitman values from TreeTap estimates of stiffness.

KEY WORDS: Wood stiffness, Modulus of Elasticity, radiata pine, weed control, stocking

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Introduction

Pinus radiata is the most commonly grown plantation species in New Zealand, but wood from the middle portions of *P.radiata* logs has poor intrinsic properties which make it unsuitable for many applications (Walker, 2006). Over time the New Zealand forest industry has trended towards reduced rotation lengths and lower initial stockings, worsening the wood quality issue by decreasing average harvest age. Trees are being grown on shorter and shorter rotations, which are causing a larger proportion of wood to be of poor quality. Moreover, first rotation crops that tended to have longer rotations were planted at exceptionally high stockings, which probably improved wood quality of the middle portions of buttlogs.

Variability of stiffness between trees causes problems for sawmills processing radiata pine and so segregation of logs into stiffness categories is desirable. Segregation of lumber for structural grades has historically been performed by assessing timber appearance, but with increasing intrinsic variation within and between trees there is a need for tools which measure physical wood properties that cannot be accurately quantified visually. Structural grades often require a minimum stiffness which can be determined through machine stress grading methods or use of stiffness measuring acoustic tools (Carter, Chauhan, & Walker, 2006). Knowing the stiffness of a stand before harvesting is desirable, but, in the absence of well calibrated tools that measure velocity of sound in standing trees, this would require destructive sampling.

Acoustic tools can be used to measure stiffness of standing trees, but these measure only the outside of a stem, can be inaccurate, and may require destructive sampling to improve result accuracy (Yang, Seale, Shmulsky, & Dahlen, 2015). A relationship between tools which measure stiffness of standing trees and tools which measure stiffness of felled sections has been developed in previous papers (Grabianowski et al. 2006; Chauhan & Walker, 2006), but how growing conditions might influence this relationship is not fully understood. Moreover, a better understanding of factors which improve stiffness can greatly improve value recovery for forest growers. If factors which cause stiffness to vary can also be identified then processors will have the potential to improve processing strategies, reduce the risk of failure in structural uses, and increase overall structural grade volume recovery.

The study reported here examined whether or not growth factors such as wind sway, herbicide and fertilizer application, genetics and stocking, influenced tree stiffness. It also allowed us to determine whether or not these factors influenced the relationship between standing and felled stiffness estimates. Diameter was also included to ensure the effects of tree size on stiffness estimates were accounted for in the models produced. This research follows on from previous work by Professor Euan Mason.

Background

The wood quality issue:

The exotic conifer species radiata pine (*Pinus radiata*) accounts for 90% of all plantations in New Zealand (Cown, 2005). *Pinus radiata* core-wood from plantation grown crops tends to have a low modulus of elasticity (MOE) and is less stable during drying than outer-wood. It therefore produces less stiff timber than other silvicultural regimes. Lower initial stockings and reduced rotation lengths for radiata pine in New Zealand plantations have resulted in trees with a higher proportion of core-wood than older trees grown at higher stockings (Chauhan & Walker, 2006; Lasserre, Mason, & Watt, 2008). The bottom 2m of the tree tends to have the least stiff wood (Waghorn, Mason, & Watt, 2007). This section also has the majority of the stem's volume, and the largest proportion of low quality core-wood.

‘Outer-wood’ is wood grown on the outside of a log after the tree has formed core wood, or approximately after the first 10 years growth for radiata pine. This is an arbitrarily defined zone since individual trees can produce outer-wood earlier or later than other trees of the same species (Walker, 2006). Generally, core-wood has a lower MOE and makes up a larger proportion of the base of the stem. MOE is associated with stiffness and the gradient of core-wood to outer-wood along the stem causes the bottom 2m have some of the lowest stiffness wood (Waghorn, Mason, & Watt, 2007).

The ‘core-wood’ of radiata pine is considered poorer quality wood than its counterpart ‘outer-wood’, due to lower stiffness and a lower MOE causing poor dimensional stability. It also has lower strength than outer-wood, and comparatively more shrinkage (less dimensional stability) when drying (Walker, 2006). This is partially due to variation of stiffness within the tree; in radiata pine MOE increases from pith to bark (Lasserre, Mason, Watt, & Moore, 2009). Core-wood to outer-wood is the gradient from pith to bark for stiffness, but also includes gradients in tracheid length, density and microfibril angle (Walker, 2006).

A minimum modulus of elasticity is required in New Zealand building standards for timber to meet structural grade specifications. MOE is also one of the main quality indicators in stress grading systems for structural timber globally (Yang, Seale, Shmulsky, & Dahlen, 2015) and is often a more important consideration than board strength (Lasserre, Mason, Watt, & Moore, 2009). MOE refers to the deflection under load, and a higher MOE means the material will not deflect as much under loading, so it is stiffer than materials with a low MOE.

Knowledge about intrinsic properties, like stiffness, can be beneficial either for receiving a log grade premium or for genetic breeding selection (Toulmin & Raymond, 2007). Visual grading is able to broadly segregate lumber and logs by grade, but there is still huge natural variation within these grades (Carter, Chauhan, & Walker, 2006). There may be a premium for forest owners who are able to guarantee their lumber is a particular stiffness, especially where processing strategies can be optimized, or structural material requirements are stricter

(Toulmin & Raymond, 2007; Carter, Chauhan, & Walker, 2006). Intrinsic properties of radiata pine are largely under genetic control (Cown, 2005; Waghorn, Mason, & Watt, 2007; Walker, 2006; Tsehaye, Buchanan, & Walker, 1995) and improvements to physical properties like stiffness can be achieved through selective breeding and clonal propagation.

Factors which influence stiffness in radiata pine:

Wood performance in young pine is more strongly correlated with cell wall characteristics than with density (Chauhan & Walker, 2006). Therefore MOE for timber should be directly measured, where possible, rather than using a relationship with other factors. Acoustic velocity is an accurate measure of wood stiffness, where higher acoustic velocities reflect higher MOE. Wood properties are usually under genetic control to at least some extent, but can also be influenced by environmental conditions (Walker, 2006; Cown, 2005).

Stocking strongly influences tree MOE, with higher stockings causing a higher MOE than stands at lower stockings (Lasserre, Mason, Watt, & Moore, 2009). Trees closer together experience more competition, and they are less susceptible to wind, than trees grown further apart. Wind is expected to have an influence on stiffness, but there might be no systematic difference in MOE between windward and downwind sides of a stem (Grabianowski, Manley, & Walker, 2006). The influence of wind is really hard to control for, but some researchers have suggested that wind sway influenced tree stiffness to some extent with edge trees having different wood properties than trees at the centre of a stand.

Fertilizer and weed competition sometimes influence tree growth. This effect has in some cases had an interaction between the two treatments, where use of fertilizer can cause higher growth increases if paired with competition control treatment (Mason & Milne, 1999). Trees which competed with grass when growing in some trials had slower acoustic velocity measurements, therefore lower stiffness, than trees which were treated with herbicide to reduce competition (Mason, 2006). Many factors which influence growth rates may also have an influence on the internal properties of radiata pine.

A multitude of environmental factors can influence stiffness so it is important to either control these factors or identify stands where variability between trees may be greater. The results from a study by Lasserre, Mason & Watt (2008) indicated that silviculture and tree breeding were complementary approaches to improving MOE in radiata pine and did not interact in their influence on stiffness.

When trees are the same age, larger diameters due to higher growth rates generally produce wood of a lower density and a lower stiffness, but this may not be evidence of a causal effect of diameter growth rate on stiffness (Mason, 2006). Since there is evidence of relationships between physical properties and intrinsic properties, it is worth measuring physical properties like diameter and height. This experiment has controlled for environmental conditions, but it is important to account for diameter and height effects.

Industry Solutions:

It makes sense to select logs and timber for structural use by directly measuring stiffness, rather than indirect measurements such as cellulose micro-fibril angle (MFA) and density (Chauhan & Walker, 2006). Wave propagation, or ‘acoustic velocity’, is a non-destructive testing method and is an effective surrogate measure of stiffness (Chauhan & Walker, 2006). Acoustic wave measurement is a widely used method of log grading or log sorting in the forestry industry due to its effectiveness (Wang, 2013). It can provide a measurement of MOE for trees, logs or timber, with this value correlated to expected material performance (stiffness) when wood is in use (Chauhan & Walker, 2006). MOE is often used as the selection criterion for structural timber where testing is completed using machine stress grading (Lasserre, Mason, Watt, & Moore, 2009). Requiring a minimum MOE from inputs can help determine how wood products will behave during drying, and eventually when in use.

This allows optimal processing strategies to be adopted, improves value recovery and results in the suitable application of timber to end uses (Carter, Chauhan, & Walker, 2006).

Modulus of elasticity is a measure of stiffness and can be calculated by the equation:

$$MOE = \rho V^2$$

MOE= 'modulus of elasticity' (specified as green or dry) is equal to ρ= 'density' multiplied by V^2= 'acoustic velocity squared'. Most of the relevant literature reports use of this equation in some form or another (Carter, Chauhan, & Walker, 2006; Chauhan & Walker, 2006; Grabianowski, Manley, & Walker, 2006; Lasserre, Mason, & Watt, 2008) to determine the stiffness of radiata pine samples in experiments. Green density for radiata pine can be treated as a constant and is usually assumed to be 1,000kg/m^3, or 1,050kg/m^3 for young radiata pine.

Non-destructive testing requires an initial investment, but provides more uniformity of lumber within a particular log grade (Yang, Seale, Shmulsky, & Dahlen, 2015). Better utilization of non-destructive evaluation technologies is required to separate lumber by MOE and reduce the variability in modern sawn lumber.

Acoustic velocity can be measured in standing trees using time-of-flight (ToF) tools, which measure the time taken by an induced wave to travel a direct path between two probes. This tool can also be used on felled trees, but more often it is used for measuring MOE of standing trees. Felled trees can be sectioned to have two flat ends, and then it is appropriate to use resonance based tools which can take less time to set up than a ToF based tool. Resonance based tools for measuring acoustic velocity provide the cross-sectional average MOE for the lumber by stimulating many acoustic pulse reverberations in the wood. This provides a highly accurate and very repeatable measurement of velocity, which is often considered more accurate than TOF measurements (Wang, 2013).

Tools used in this experiment:

HITMAN HM200 (Hitman) was the resonance based tool used for acoustic velocity of felled trees during this experiment. The tool was developed by Fibre-gen in New Zealand, and is a handheld tool for estimating the stiffness of felled logs or lumber (Carter, Chauhan, & Walker, 2006). Hitman provides a cross-sectional average stiffness, so can underestimate stiffness due to bark inclusion, or overestimate stiffness where there are knots (Grabianowski, Manley, & Walker, 2006). Hitman measures the second harmonic of the introduced stress wave and can have issues measuring this when stem diameters are less than 100mm (Chauhan & Walker, 2006). It also requires 2 flat ends which means it cannot be used on standing trees.

The TreeTap ToF tool was developed by Dr Michael Hayes in New Zealand (Toulmin & Raymond, 2007) and can provide the acoustic velocity for outerwood while trees are still standing. TreeTap has two active probes and a starting probe, which takes time to insert and remove from the outerwood. There are many research papers (Toulmin & Raymond, 2007; Grabianowski, Manley, & Walker, 2004) which have reported differences between ToF measurments on opposite stem sides of an individual tree. It is good practice to measure both sides of a stem with the TreeTap tool and use an average value for each stem, even though there may be no systematic difference in stiffness between stem sides (Grabianowski, Manley, & Walker, 2006).

There is a relationship between ToF and resonance-based measurements of acoustic velocity for an individual tree, but the extent of this relationship depends on a range of factors (Wang, 2013). ToF tools tend to provide estimates of acoustic velocity that are about 10% higher than the true average value (Grabianowski, Manley, & Walker, 2006; Toulmin & Raymond, 2007) and resonance based tools tend to be more accurate (Carter, Chauhan, & Walker, 2006).

Applications in Forestry:

Segregating individual logs and trees by internal characteristics before harvesting is difficult, but ranking stands, forests and regions, on overall stiffness could be completed cheaply with less labour required (Toulmin & Raymond, 2007). Measuring MOE of standing trees usually requires different tools than measuring MOE of logs or timber. The relationship of velocity measurements between trees and logs varies with measurement method, wood moisture content, tree age, operating temperature and tree diameter (Wang, 2013). It is also important that these tools are used on the same section of each tree, especially since stiffness varies within a tree. This is inherently difficult since TreeTap measures outer-wood stiffness, while Hitman provides a cross sectional average value.

Models that predict resonance based measurements from ToF measurements can improve stand sampling strategies and determine the likely stiffness of a resource without destructive sampling. Multivariate equations have helped many researchers to improve their MOE prediction models. Some inputs can include log diameter and log vertical position in the tree. Using only velocity as a sorting criterion is often sufficiently accurate for segregating logs of the poorest quality (Wang, Verrill, Lowell, Ross, & Herian, 2013). There is a need for improved models to predict MOE when felled from standing tree ToF velocity measurements. A study by Wang et al. (2004) found that a multivariate prediction model relating static MOE to stress-wave speed (acoustic velocity), log density and log diameter was able to better predict MOE than the fundamental wave equation. Their study removed trees which had too small a DBH to allow for acoustic velocity measurements.

A clear issue with the development of models that predict MOE from standing acoustic velocity is that experimental conditions in a forest are hard to control. Some studies have taken trees across sites which have trees of different species, ages, different stockings, and very different growth conditions (Wang, et al., 2004; Chauhan & Walker, 2006; Wang et al. 2013). The result is overly complicated multivariate equations with excessive numbers of independent variables, which can take time and effort to measure, and often add very little to account for model variation.

Implications for this study and research aims:

When trying to improve a formula for predicting MOE from standing acoustic velocity, it is helpful to include other physical properties to account for additional variation. Measuring trees at the same height removes some of this variation, as does ensuring trees are all the same age and from the same site. Assessment of outer-wood properties of standing trees ideally requires comparison between trees of the same genetic origin and similar silvicultural treatment (Grabianowski et al. 2006). There is a shortage of research investigating effects of site and genotype on wood quality models (Lasserre, Mason, & Watt, 2008), so this dissartation will provide some insight.

There is a need for intensively controlled and managed large scale forestry trials, with reduced influence from uncontrolled variables. The research reported here aimed to:

a) Identify any systematic difference in acoustic velocity from TreeTap measurements between northwest and southeast sides of a tree stem

b) Determine if Hitman estimates of MOE (stiffness) varied with genotype, stocking, weed competition, fertilizer use and wind sway

c) Investigate if the relationship between Hitman and TreeTap estimates of MOE varied with genotype, stocking, weed competition, fertilizer use and wind sway

A similar destructive sample was completed in 2011 at the same site to investigate the impact of environmental factors on microfibril angle (Doyle, 2011). The dissertation produced by this student not only reported different measures of intrinsic wood quality, but also used two different measurement tools to measure sonic velocity.

The trial used for the study reported here provided a unique opportunity because of the experimental scale and the degree of control over growth factors. Site history was known and detailed silvicultural information was available. Wind sway was also controlled to a level which has not previously been done. There are a large number of plot replicates and the experiment is highly repeatable, which means that this study has the potential to provide strong evidence of causal factors. Factors which influenced stiffness and the relationship between resonance and ToF estimates, should be better identifiable from this study than previous research.

Research hypotheses:

The null hypotheses for the following analyses are:

a) There was no significant difference in stiffness between the northwest and the southeast sides of the stems when using the TreeTap tool.

b) The controlled factors: genetics, wind sway, stocking, weed competition and fertilizer use, had no influence on Hitman estimates of stiffness.

c) Tree height and diameter had no influence on stiffness estimates.

d) There was no relationship between stiffness estimates from the Hitman and TreeTap tools.

e) A relationship between stiffness estimates from Hitman and TreeTap did not vary with: genetics, wind sway, stocking, weed competition and fertilizer use.

Method

Experiment layout:

As part of a larger experimental trial near Rolleston, Canterbury, the data used in this study were collected in the summer of 2015/2016. The site is approximately 69 m above sea level and the mean monthly temperature ranges from 4.4°C to 15.9°C. The mean annual rainfall for Rolleston is 638 mm, with occasional summer-dry conditions.

The trial is a randomized complete block factorial split-split plot design of radiata pine trees that were aged 10 when sampled. There are 48 plots in total with three different stockings and for the first two years all plots had strip weed control undertaken. 16 plots are spaced at 625 stems/ha, 16 plots at 1250 stems/ha, and 16 plots at 2500 stems/ha. Use of fertilizer and herbicide was also controlled in this experiment. 12 plots had no additional chemical treatments, 12 plots had additional herbicide (applied in year 3), 12 plots had fertilizer only, and 12 plots had both chemical treatments. The layout was designed so that the quarter split for chemical treatments is within the plot split by stocking, so there are four complete replicates of each stocking/chemical treatment combination. Where herbicide was applied in year 3, it completely removed the principal weeds; grass, clover and gorse from those plots.

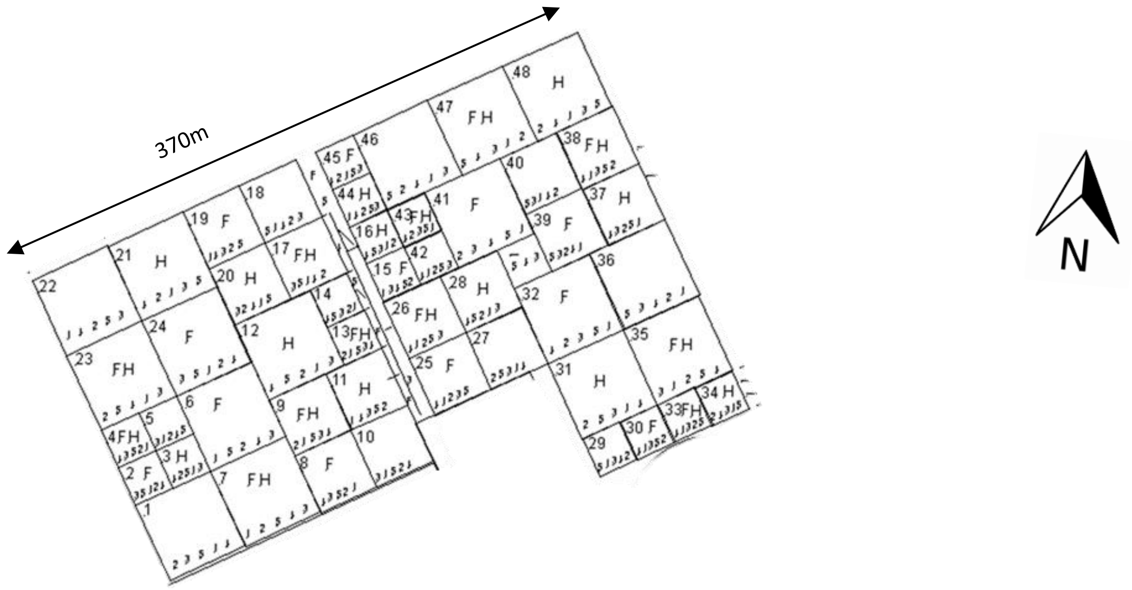

Figure 1: Plot layout for trial located (43°37'02.9"S, 172°20'43.7"E) south of Rolleston, Canterbury, New Zealand. 'F' = plots where fertilizer was applied, 'H' = plots where herbicide was applied. Stems per hectare: large plots=625, medium plots=1250, small plots=2500

Four trees from every plot were harvested during this experiment to get a total of 192 trees. These trees comprised two different clones: clone 1 and clone 2. Clone 1 was sold as one with low microfibril angle and high basic density while clone 2 was reported to have high microfibril angle and low basic density. Among the harvested trees one tree of clone 1 and one tree of clone 2 were randomly selected to be bound in each plot, and therefore experienced reduced wind sway while growing. The subplot plot design has a hierarchy of factors with bound trees being within the clone groups, clone groups within herbicide/fertilizer treatment and herbicide/fertilizer treatment within stocking. This is within a complete block factor (1-4) as the highest factor level.

Sampling:

During the initial trial walkthrough the trees selected to be destructively sampled were labelled with spray-paint to record their plot number, clone number and genotype number. Trees were pruned if any branches obstructed the stem. The vertical height of 1.4 m was marked on each stem using spray paint and a 2 m tape. At the same time 0.8 m and 2 m heights were marked on both the northwest and southeast side using the 1.4 m height as absolute. The diameter of the tree at 1.4 m was then measured, also referred to as the 'diameter at breast height' (DBH). If there was significant swelling or other defects at 1.4 m, two measurements were taken above and below 1.4 m then averaged to represent the tree's DBH.

The TreeTap tool was used on every tree before harvesting. The first measurement probe was placed at 2 m on the northwest side of the stem, and the second measurement probe was placed below this at the 0.8 m mark. Probes were inserted downwards through the bark into the outer-wood at a 45^{o} angle to the stem. A third inducer probe was placed below 0.8 m pointing upwards into the stem. To induce a stress wave the inducer probe was hit by a hammer 8 times per side. On some occasions the TreeTap reader indicated measurements were wrong, or the induced stress wave was not measured properly, so these measurements were deleted and repeated until accurate. The southeast side of the stem was then measured the same way until 8 successful measurements were recorded per side.

Trees were then felled as close to the ground as possible and delimbed to 4 m. Height was measured for each tree using the 1.4 m mark as the starting point (removing 1.4 m from the total height) and measuring to the tip of the stem. The stem was then cut at 1 m below DBH and 1 m above DBH to provide a 2 m section of stem to measure acoustic velocity. The Director HM200 'Hitman' tool was then used with the Hitman's accelerometer pressed to the centre of the 0.4 m cut face (below DBH). A stress wave was introduced to the stem section by hitting the 0.4 m face with a hammer. Where Hitman failed to get an accuracy of 99% measurements were retaken until 3 measurements were taken that were the same value. Some stems had too small a diameter to use the Hitman tool, so this measurement was occasionally impossible to acquire. Both acoustic velocity tools provided green acoustic velocity since the trees hadn't been dried when measurements were taken.

Later field reconnaissance was required due to the predictions of stiffness from the Hitman tool being improbably high. The velocity measurements taken by Hitman HM200 were about twice as high as expected for 10 year old radiata pine trees, so Michael Frampton from the University of Canterbury's electronic engineering department investigated potential causes. Based on his analysis, it was concluded that the values of acoustic velocity were twice as high as they should be, and therefore all recorded Hitman values were divided by 2. The resonance based acoustic velocity from Hitman was measuring the second harmonic due to the small size of the samples. The formula to convert harmonic to acoustic velocity assumed the first harmonic was being measured.

In the middle of the Hitman stem section, at the 1.4 m mark, a section 5 cm long was taken with 2.5 cm above DBH and 2.5 cm below DBH. If there was a knot or a defect at the 1.4 m point then the disk was taken either above or below this height, depending on where the nearest clear stem section was. These 5 cm thick disks were initially refrigerated until all the samples were collected. They were stored in a fridge at 4^{o}C in airtight plastic bags. These disks were then peeled and weighed to get green weight. Volumetric displacement (immersion) was then used to get the volume of each disk in litres. The equation used to calculated green density was: $Green\ density = \frac{Green\ mass}{Green\ Volume}$

The times from TreeTap were averaged for the northwest and southeast separately. Length was divided by time to get the velocity of the stress wave. Stiffness was then estimated by the equation: $MOE = pV^2$ where Modulus of Elasticity (MOE) is equal to density (*p*) multiplied by velocity (*V*) squared. Density is in kg/litre and velocity is in km/second. The same formula was used for the data from Hitman where the value of velocity was squared, then multiplied by the green density for every specific tree.

Analysis carried out:

The statistical program R was used for all the analyses in this study. Initial exploratory data analysis was carried out using DBH and height as dependent variables and wind sway, herbicide, fertilizer, clone number and stocking as the independent variables. Values were entered into R as factors to be used in the models. Factors included DBH, height, wind sway (bound), genetics (clone), stocking, herbicide (H) and fertilizer (F). Trees which had missing values were excluded from the analysis so that they did not influence the data. The threshold for significance was $\alpha=0.05$, where P-values<α were considered significant factors.

The initial data set had the factor F:H created for the combination of fertilizer and herbicide used; either C:C (no chemicals), C:H (no fertilizer, herbicide used), F:C (fertilizer used, no herbicide) or F:H (both herbicide and fertilizer used). Since the experiment is a split-plot design and has treatments split by block, a hierarchy was added at the end of each model so that all other model factors were nested within block factor. Stocking was the next nested factor, then F:H was within this. When fertilizer was no longer considered a significant determining factor, 'F:H' was replaced with 'H' in the code for nested factors. It was clear from visual inspection that herbicide use had a very large impact on the abundance of weeds, with virtually no weeds at all where herbicide had been applied, and abundant grasses and gorse where it had not been applied.

A model (model 'e') was created using a data set with TreeTap measurements from each side of the tree included as separate measurements with an allocated side (either northwest or southeast). The factor for stem side in the model had a P-value above 0.05 in Table 1, so TreeTap measurements were averaged for each stem for all analyses. The difference between sides was not considered a significant factor even though the average TreeTap value for the first stem measurement (northwest side) was 4.63 GPa and 4.79 GPa for the second measurement (southeast side). The southeast side was 3.5% higher stiffness on average.

Table 1: Relevant section of the ANOVA output from R for model 'e', Hitman as a function of TreeTap and stem side of TreeTap measurement

Model 'e'				
Factor	**effect DF**	**residual DF**	**F-value**	**p-value**
TreeTap	1	313	195.9902	<.0001
Stem side	1	313	3.5914	0.059

Models were developed where Hitman MOE estimate was the dependent variable. These models included height and DBH as independent variables, as well as the other experimental factors mentioned previously. Data were plotted into boxplots by treatment and further models were created in an attempt to partition as much variability between measurements as possible. This also helped to determine how much of the model variability was due to each independent variable, and if any significant interaction effects existed. A probability value (P-value) for a type I error of 0.05 or less was regarded as significant for the results of the analyses. P-values above 0.05 were considered insignificant and the associated factors were unlikely to influence the model's dependent variable.

Multiple linear regressions were then also carried out with Hitman MOE estimates as a function of TreeTap MOE estimates. Experimental factors stocking, fertilizer treatment, weed competition, wind sway and clone were included in this model to determine what caused variation in the relationship between the two velocity measurements. Not all the values for all the interaction factors were included for the summary tables of the model factors. Only the experimental factors, alongside any interactions that had a P-value less than 0.05, were listed in these tables.

Box plot graphs were produced to compare the range of Hitman values from different stocking and weed competition treatment factors. The results are presented in the following sections. Hitman estimates as a function of TreeTap estimates were then plotted and a trend line fitted. Later this was done by subgroups of certain treatments with a trend line fitted for each subgroup.

Model fit was also assessed by residual analysis of the models produced in R (models a-f). Plots of fitted values against residuals were included in the appendix for this report.

Sensitivity analysis of the data was completed by removing the 4 identified outliers from the data set and looking at summary statistic for the final model. The final model was built in R by adding in the factors 'TreeTap', 'Herbicide' and 'Stocking', to predict Hitman. Interactions were then removed until all the factors included had P-values that were significant (at $\alpha=0.05$). The same model was then run with DBH included as a model factor. The outliers were then removed and the process was repeated to create four different versions of the final model.

Type 2 Anova tests were run in R for each of the four iterations of the final model to get the overall effect of each factor on Hitman estimates of stiffness. The P-values from this were included in the table alongside the residual standard errors. Lower values for residual error indicate a better fitting model.

Results

Model building and ANOVA tests:

The model ‘a’ of DBH as a function of stocking, fertilizer, weed control, clone (genetics) and wind sway, had the ANOVA test output from R in Table 2. Stocking, weed control and clone all had P-values that were below 0.05, so are significant factors for determining DBH in young radiata pine at this site. Fertilizer had a P-value that was 0.9, which is too high to be considered a significant factor.

Table 2: Relevant section of the ANOVA output from R for model 'a', DBH as a function of Stocking, Fertilizer, Weed control, Clone and Wind sway. Interactions were only included if they were significant (P-value<0.05)

Model 'a'				
Factor	effect DF	residual DF	F-value	p-value
Stocking	2	6	15.6935	0.0041
Fertilizer	1	27	0.0073	0.9325
Weed control	1	27	30.8773	<.0001
Clone	1	107	7.8317	0.0061
Wind sway	1	107	0.0497	0.8241
Stocking:Wind sway	2	107	3.5983	0.0307
Stocking:Fertilizer	2	27	3.5172	0.0439
Stocking:Weed control	2	27	4.5861	0.0193

ANOVA results for model ‘b’ are in Table 3, where Hitman values were predicted as a function of TreeTap. TreeTap had a P-value of <0.0001 which suggests that Hitman and TreeTap values are strongly correlated.

Table 3: Relevant section of the ANOVA output from R for model 'b', Hitman as a function of TreeTap

Model 'b'				
Factor	effect DF	residual DF	F-value	p-value
TreeTap	1	313	195.9902	<.0001

To see if fertilizer had a significant influence on the variability of Hitman predictions, a preliminary model ‘Cc’ was run. Fertilizer had the highest P-value of 0.7772 in Table 4 and was not included as a factor in later models since it was also too high to be a significant factor in model 'a'. It was removed from the code for analysis by blocks, and replaced with weed control from model 'c' onwards.

Table 4: Relevant section of the ANOVA output from R for model 'Cc', Hitman as a function of Stocking, Fertilizer, Weed control, Clone and Wind sway

Model 'Cc'				
Factor	effect DF	residual DF	F-value	p-value
Stocking	2	6	12.332	0.0075
Fertilizer	1	26	0.0817	0.7772
Weed control	1	26	10.8749	0.0028
Clone	1	101	1.5369	0.218
Wind sway	1	101	1.7148	0.1933

When Hitman is the dependent variable in model 'c', both stocking and herbicide have P-values low enough to be considered significant factors in Table 5. Weed control had a higher P-value in model 'c' than in model 'Cc', but the P-values for stocking, clone and wind sway all decreased slightly.

Table 5: Relevant section of the ANOVA output from R for model 'c', Hitman as a function of Stocking, Weed control, Clone and Wind sway. Interactions were only included if they were potentially significant (P-value<0.05)

Model 'c'				
Factor	effect DF	residual DF	F-value	p-value
Stocking	2	6	12.429	0.0074
Weed control	1	9	11.7346	0.0076
Clone	1	142	1.6464	0.2015
Wind sway	1	142	1.8198	0.1795
Clone:Wind sway	1	142	3.9419	0.049

The effect of diameter was accounted for in model 'd' by including DBH as an independent variable when predicting Hitman estimates. Table 6 shows that DBH and Hitman were strongly correlated with a P-value of <0.0001. With DBH variance accounted for, the influence of stocking on hitman became non-significant with a P-value of 0.0521. This was only a small difference between the P-value and the threshold of 0.05, so stocking should still be treated as a potentially significant factor for predicting values of Hitman. Weed control in Table 6 had a P-value of 0.0118 and is therefore a significant factor when predicting Hitman values, even when the variation due to DBH is accounted for. The variation which was previously explained by this interaction was better attributed to variations in DBH.

Table 6: Relevant section of the ANOVA output from R for model 'd', Hitman as a function of DBH, Stocking, Weed control, Clone and Wind sway. Interactions were only included if they were potentially significant (P-value<0.05)

Model 'd'				
Factor	**effect DF**	**residual DF**	**F-value**	**p-value**
DBH	1	140	19.9632	<.0001
Stocking	2	6	5.0338	0.0521
Weed control	1	9	9.8862	0.0118
Clone	1	140	0.9741	0.3254
Wind sway	1	140	2.3496	0.1276
Clone:Wind sway	1	140	3.254	0.0734

Height was included in model ‘f’ to allow for an interaction with the other independent variables. In Table 7 stocking had a P-value of 0.0102 so it remained a significant factor for predicting Hitman values when height was included in the model. Weed control had a P-value of 0.0073, so both factors had lower (more significant) P-values than in model ‘d’, based on the ANOVA output in Table 7. Height had a P-value of 0.8425, so was not a significant factor for predicting Hitman values in model ‘f’.

Table 7: Relevant section of the ANOVA output from R for model 'f', Hitman as a function of Height, Stocking, Weed control, Clone and Wind sway

Model 'f'				
Factor	**effect DF**	**residual DF**	**F-value**	**p-value**
Height	1	140	0.0396	0.8425
Stocking	2	6	10.8413	0.0102
Weed control	1	9	11.9116	0.0073
Clone	1	140	2.5165	0.1149
Wind sway	1	140	2.1481	0.145

The fitted models all had fairly even residual distributions. Table 8 is a summary of the characteristics of the plots of residual values against fitted values for all the models. These plots have also been included in the appendix for reference (Figures A1-A7). Most of the models fitted the data set well based on their residual distributions. Model ‘a’ had no obvious outliers and fit the dataset really well. The outliers present when Hitman was plotted against TreeTap remained consistent between models ‘b’ and ‘e’, so were later removed to perform a sensitivity analysis.

Table 8: Summary of fitted values against residual values for all models

Model	Model description	Description of residuals
'a'	DBH~Stocking*Fertilizer*Herbicide*Wind sway*Clone	Unbiased homoscedastic
'b'	Hitman~TreeTap	Unbiased homoscedastic, few outliers
'Cc'	Hitman~Stocking*Fertilizer*Herbicide*Wind sway*Clone	Unbiased, fairly homoscedastic, few outliers
'c'	Hitman~Stocking*Herbicide*Wind sway*Clone	Unbiased homoscedastic, few outliers
'd'	Hitman~DBH+Stocking*Herbicide*Wind sway*Clone	Unbiased, fairly homoscedastic, few outliers
'e'	Hitman~TreeTap*Stem side	Unbiased, fairly homoscedastic, few outliers
'f'	Hitman~Height+Stocking*Herbicide*Wind sway*Clone	Unbiased, homoscedastic, few outliers

Boxplots of significant factors from ANOVA tests:

The above analysis in R provided evidence that stocking and weed control were significant determinants of stiffness estimates in young radiata pine trees. To further investigate this relationship, the boxplot in Figure 2 was produced.

Weed control (herbicide) reduced the average stiffness of trees compared to trees without herbicide use in Figure 2. Lower stockings of 625 stems per hectare also had a lower average stiffness than higher stockings of 2500 stems per hectare. Figure 2 has some clear outliers marked as black dots, and also shows the range of values from this experiment.

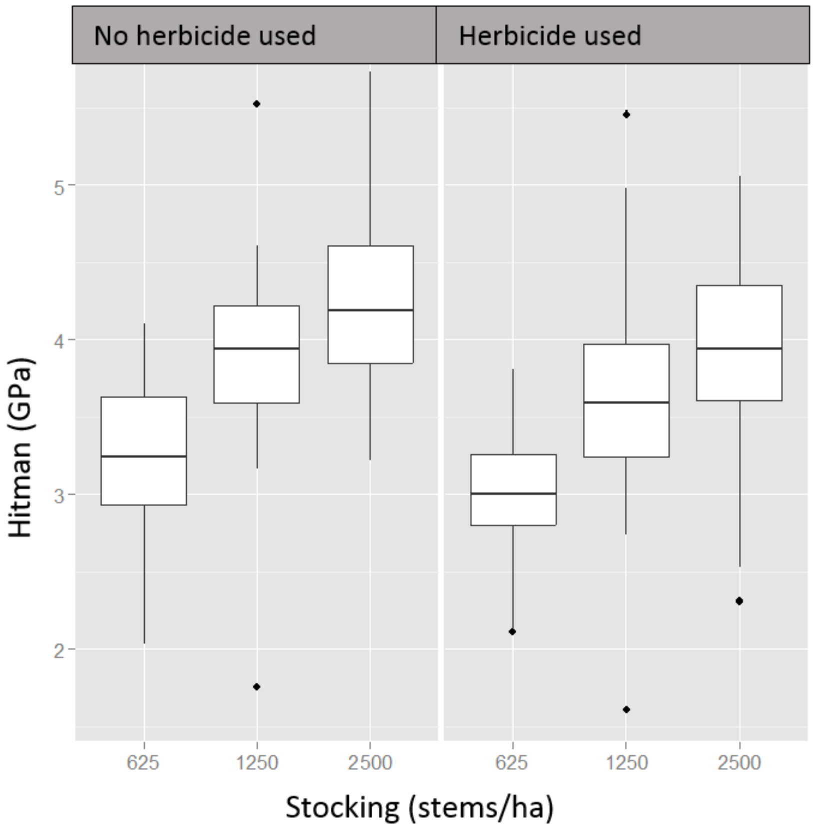

Figure 2: Boxplot of stiffness (Hitman) estimates by stocking and herbicide use

The distribution in Figure 3 is nearly the complete opposite of Figure 2, with increasing stocking causing lower DBH measurements. Weed control also caused higher DBH measurements, and not controlling for weeds caused lower DBH measurements. The lowest stocking of 625 stems per hectare had the highest increase in DBH between herbicide use and no weed control. DBH was higher on average in Figure 3 when herbicide was used to control weeds, or if stocking decreased.

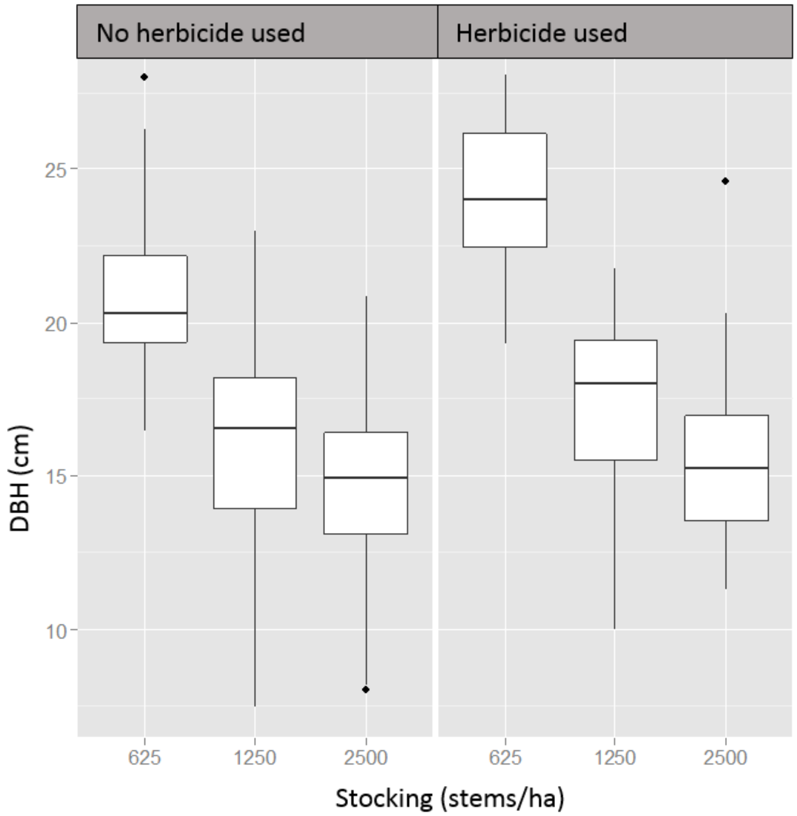

Figure 3: Boxplot of DBH estimates by stocking and herbicide use

Hitman plotted estimates of MOE against TreeTap:

When Hitman estimates of stiffness were plotted against TreeTap estimates of stiffness there were four major outliers which appeared to be an unusual distance from the trend line in Figure 4. It is likely that these would have a disproportionate impact on the trend line and may cause some irregularities in the data set. Overall the two estimates were strongly correlated, which is expected since model 'b' had a P-value of <0.0001 for TreeTap as a predictor of Hitman. By comparing averages for the total dataset (excluding individuals with missing measurements) values for TreeTap were 29% higher than the Hitman estimates of MOE.

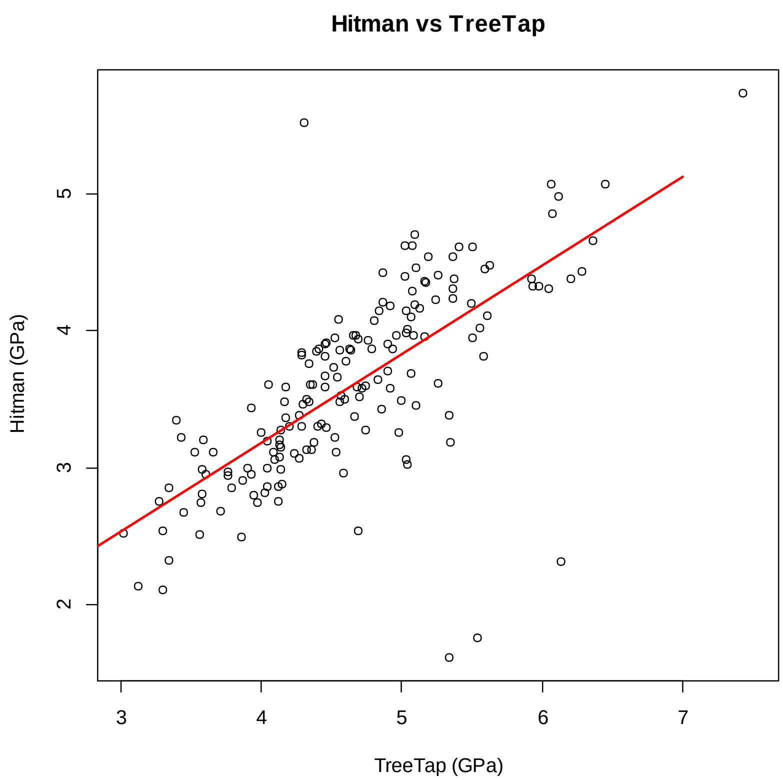

Figure 4: Hitman plotted against TreeTap for estimates of stiffness with red trend line

When plotted by subgroups of DBH independent variables had a visible influence on the relationship between Hitman and TreeTap estimates. There was no obvious trend caused by DBH in Figure 5, but it is likely that the three blue outliers beneath the green trend line had a disproportionate influence on the trend line for DBH<16cm. Excluding the samples below 16cm, the red trend line (16-20cm) was steepest, then the yellow trend line (20-25cm) and then the green trend line (25cm+) was the least steep. This indicates that the steepness of trend line is higher for samples with a lower DBH, in most cases. It is hard to comment on the group DBH<16cm because some trees were too small to use Hitman on.

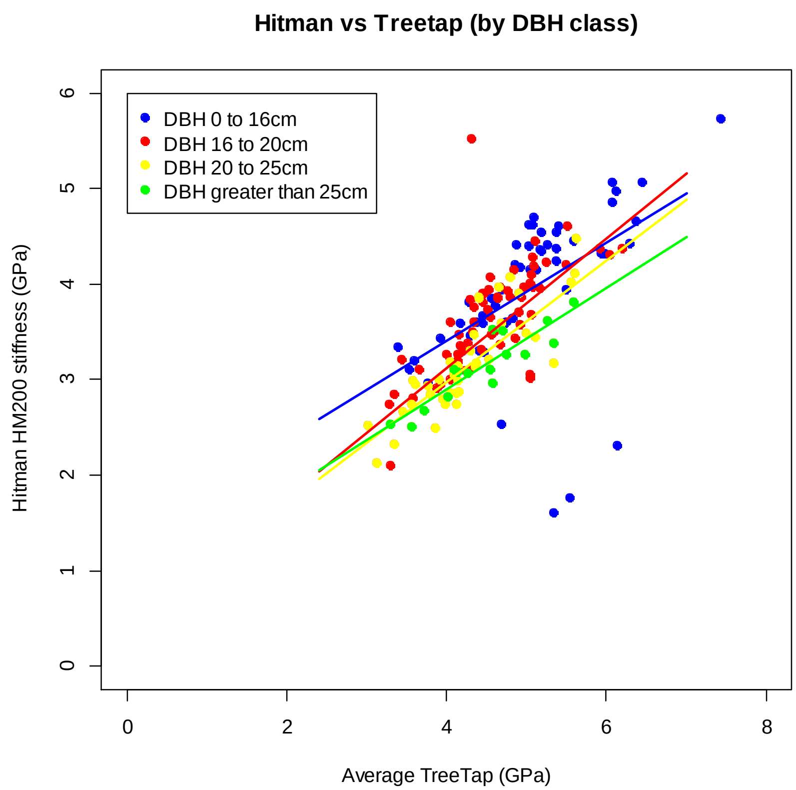

Figure 5: Hitman estimates graphed against TreeTap estimates of stiffness, split by DBH size classes: blue=DBH less than 16cm, red=DBH between 16-20cm, yellow=DBH between 20-25cm and green=DBH greater than 25cm

The same outliers in Figure 4 are an issue when graphing Hitman as a function of TreeTap by stocking groups in Figure 6. The green and red trend lines in Figure 6 run parallel to each other, while the blue trend line is pulled downwards, probably due to the two extreme values beneath it. Stockings of 2500 stems per hectare (red) had higher Hitman estimates of stiffness than stockings of 625 stems per hectare (green). All three subgroups have very different trendlines which would warrant the use of different prediction models for each subgroup.

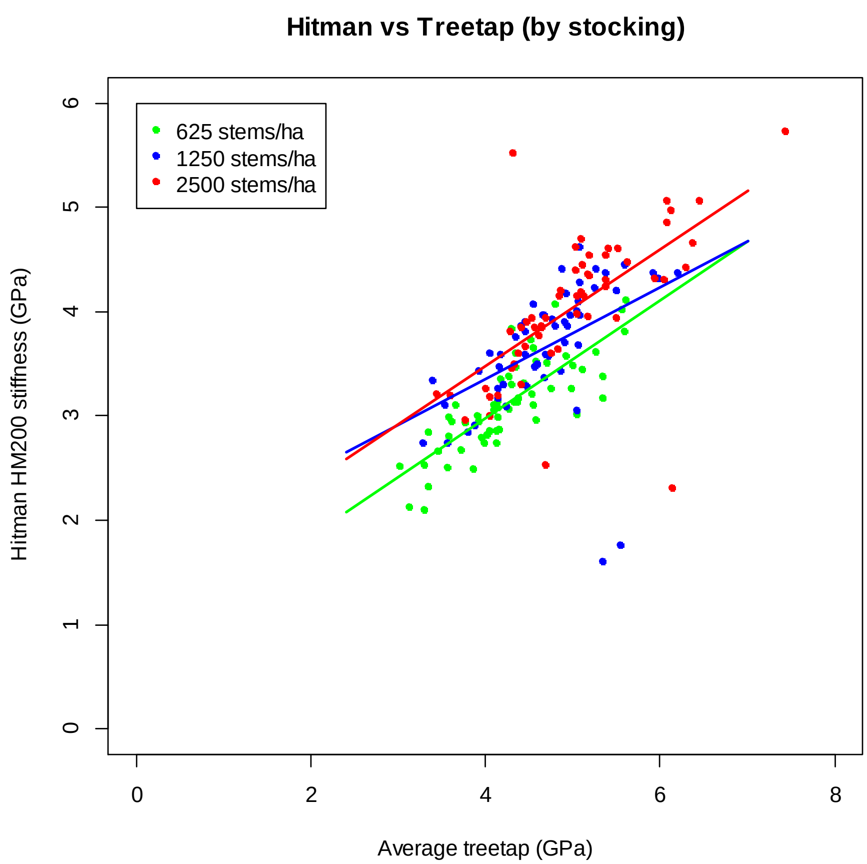

Figure 6: Hitman estimates compared to TreeTap estimates of stiffness, split by different stockings: green=625 stems per hectare, blue=1250 stems per hectare and red=2500 stems per hectare

In Figure 7 Hitman values are plotted against TreeTap values by weed control (herbicide use) subgroups. The control group with no herbicide treatment had a steeper trend line (blue) than the group that had weed control (red). The red trend line is underestimating values of Hitman from TreeTap measurements more than the blue trend line. The four key outliers mentioned earlier are far away from the corresponding trend line, but are also separate from the rest of the dataset. There are 2 red outliers underneath the red trend line, which is likely pulling the trend line downwards. The 2 blue outliers are on either side of the trend line, which likely reduced the influence these points had on the blue trend line. The red points also appear more scattered than the blue data points, and on average appear further away from the trend line than the blue subgroup.

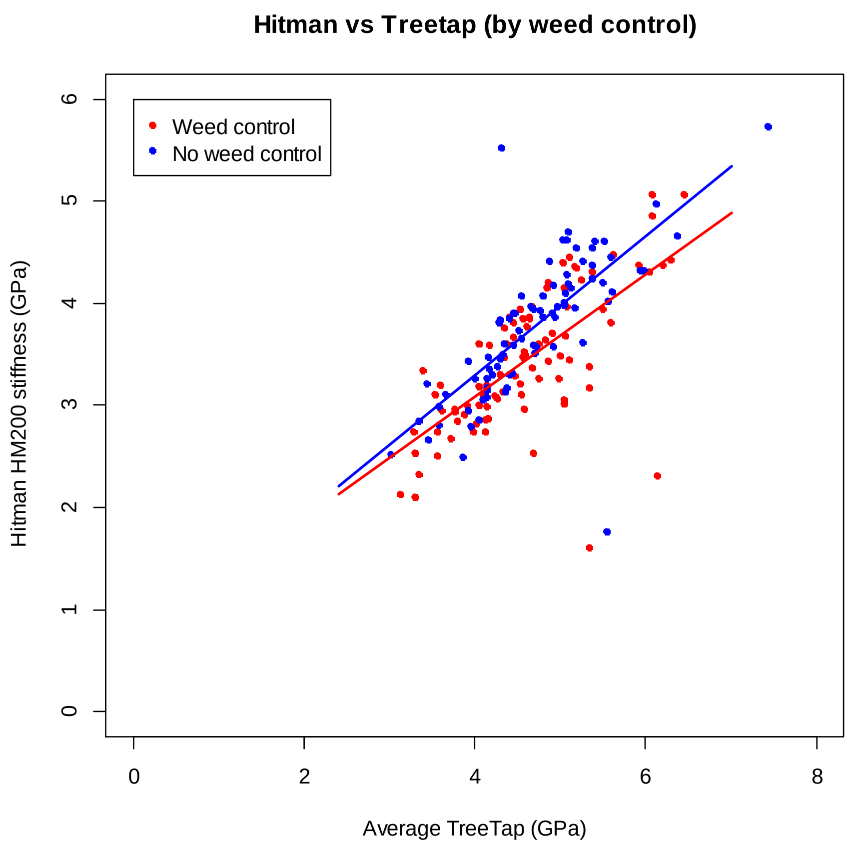

Figure 7: Hitman estimates of stiffness compared to TreeTap estimates, by herbicide treatment subgroups: red=weed control applied, blue=no weed control applied

Influence of outliers and the final model:

Hitman values plotted against TreeTap values can be seen in Figure 8 alongside the dataset's trend line and the five potential outliers (labelled with letters and red arrows). The point at letter A) had a much higher Hitman value than the TreeTap value, which was unusual for this dataset and this point is far away from the trend line. The three points at the letter B) had Hitman values which were much lower than the TreeTap values and are also outliers in this dataset. The point at the letter C) is unusual as it is near the trend liner, but much higher than the rest of the dataset. Since it is close to the trend line in Figure 8 it is potentially not an outlier, so has been included in the following section. Points at A) and B) are the 4 points that were removed for this sensitivity analysis.

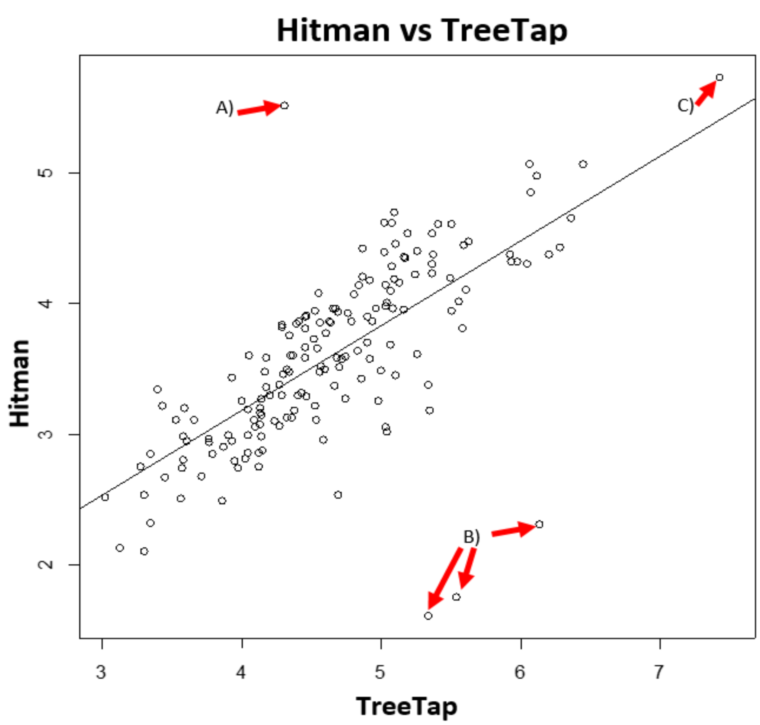

Figure 8: Hitman vs TreeTap with a trend line and identification of: outliers (A and B), a point of high influence (C)

Outliers had a major influence on the model fit and the residual standard error reduced from 4.4e-01 to 2.7e-01 in Table 9 when they were removed. DBH had very little impact on improving the model fit, only changing the third decimal place with outliers included or excluded. Including DBH made the residual standard error 0.0006 higher, so very slightly worse, when outliers were included in the model. With outliers excluded the model's residual standard error decreased by 0.003 when DBH was included in the model.

With the inclusion of DBH as a factor in the final model, weed control and stocking became less significant as the P-value for these factors decreased. The summary statistics in Table 9 provide strong supporting evidence that that stocking and weed control were significant factors that should be included in models predicting Hitman estimates of stiffness from TreeTap measurements. TreeTap was always less than $2.2*10^{-16}$ and was therefore always highly significant for determining Hitman estimates of stiffness. DBH was an insignificant factor for determining stiffness in this model as it always had P-values exceeding 0.05 regardless of outliers.

The worst P-values for stocking and weed control were the highest P-values, 1.08e-05 and 5.71e-05 respectively, in Table 9. Since these are both well below 0.05, stocking and weed control were both significant factors in the final model. Removing outliers for sensitivity analysis reduced the P-values further making weed control and stocking even more significant. This improvement to the model was not needed for testing the hypotheses in this report, as factors remained significant despite the outliers. The sensitivity analysis provides statistical evidence that the goodness of model fit is being influenced significantly by the outliers, and that removing these 4 points would likely produce a more accurate prediction model.

Table 9: Summary statistics for the final model with outliers included and excluded, and DBH included and excluded as a factor in the model. Factors were additive since no interactions were deemed significant at the level α=0.05 and TreeTap values were always less than the P-value. Residual standard error is for the entire model

Final model: Hitman~TreeTap+Stocking+Herbicide(+DBH)				
	Outliers included		Outliers removed	
Factor	**P-value**	**P-value (+DBH)**	**P-value**	**P-value (+DBH)**
TreeTap (always <)	2.20E-16	2.20E-16	2.20E-16	2.20E-16
Stocking	4.39E-08	1.08E-05	3.10E-15	1.23E-05
Weed control	5.71E-05	4.85E-05	4.93E-07	1.62E-05
DBH	NA	4.60E-01	NA	3.57E-01
Residual standard error	4.40E-01	4.40E-01	2.70E-01	2.70E-01

The residual distribution for the final model including outliers and excluding DBH is shown in Figure 9. The residual distribution is approximately normal, homoscedastic and unbiased, which is expected since the residual standard error for the final model was very low. The histogram of residuals (Figure 10) has a normal distribution and some extreme values where the the outliers are. The final model is a good fit for the dataset despite a few key outliers.

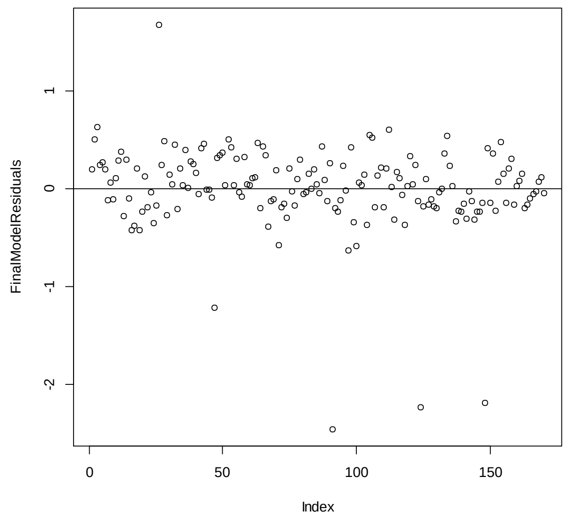

Figure 9: Final model residual distribution including outliers: Hitman ~ TreeTap + Stocking + Herbicide

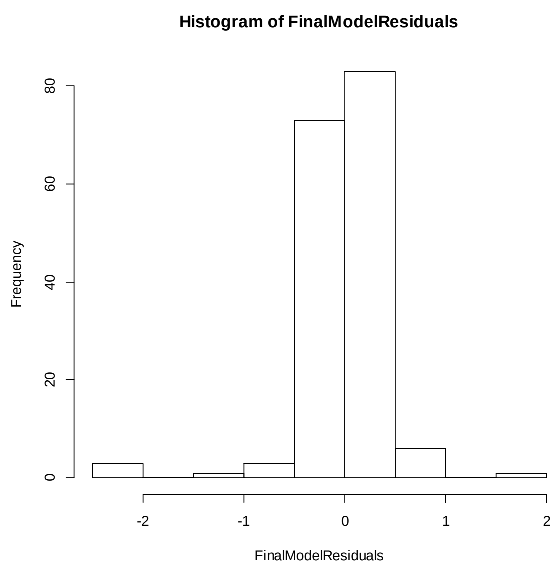

Figure 10: Final model residual distribution histogram including outliers: Hitman ~ TreeTap + Stocking + weed control

Discussion

The statistical design of this experiment has 4 complete replicates of each stocking, fertilizer and weed control treatment combination. Individual measurements were occasionally missing for a tree, so out of the 192 trees that were sampled, some individuals were excluded from the analyses. Since there was a high level of repetition these missing values have not had a major impact on the overall validity of this analysis.

Some trees had a DBH that was too small to accurately use the Hitman tool, which was also an issue for Wang et al. (2006), and it is therefore likely that trees with smaller diameters are not proportionately represented in these results. There was an influence of DBH on stiffness that was present in trees with a higher DBH, and more data for smaller trees would have better helped to identify a trend. Unlike DBH, height was not a significant factor for determining stem stiffness.

There was no significant difference in stiffness between sides of the stem so it was appropriate to use the average values for TreeTap for each individual tree. Grabianowski et al. (2006) reported similar findings with no systematic difference in stiffness between stem sides in their experiment. The destructive sampling in 2011 by M. Doyle had found a difference in microfibril angle between stem sides, but was using different tools and measuring a different intrinsic property. It was worth confirming there was no significant difference in stiffness between stem sides since in 2004 Grabianowski et al. had speculated a potential stiffness difference between stem sides in a different study.

In most cases estimates from TreeTap were higher than those gathered from Hitman; on average they were 30% higher. This was much higher than in other studies, with the usual difference being about 10% higher (Grabianowski, Manley, & Walker, 2006; Toulmin & Raymond, 2007). One possible explanation is that the high proportion of corewood resulted in much lower Hitman estimates. TreeTap only measures the outer-most wood (Grabianowski et al. 2006), so it avoids the influence of bark on measurements taken. Since the stand was 10 years old it is likely that the trees had formed a small portion of wood which was closer to outer-wood in stiffness, and immediately next to the bark. The other research papers reviewed also had trees of different ages grown in different regions, so findings were not expected to be directly comparable.

The lengths being measured also differed between TreeTap and Hitman since Hitman required a minimum log section of 2 m in length, and TreeTap was done on the trees while they were still standing. A consequence of the latter is that the height of the top probe was limited to 2 m (not 2.4 m as in Hitman) since the researchers using the tool could not practically (safely and efficiently) reach any higher. Since both tools were centered around 1.4 m however, this should have had minimal impact on the results being different between tools. If there is an issue it may be that taper in the lowest section of the stem resulted in more core-wood being included (more than the additional outer-wood included) for the Hitman measurement section.

The lowest stocking of 625 stems per hectare had the highest increase in DBH between weed control and no weed control which is likely caused by reduced competition. Weed control had a lower impact at higher stockings due to high competition already between the closely spaced trees. Weed control had a larger improvement in diameter growth when used at lower stockings, which is analogous with the results of other research.

There is a tradeoff between stiffness and diameter growth in this study, where volume may need to decrease for stiffness to increase. For forest managers in Canterbury this will result in either a reduction of volume or a reduction in stiffness, so silvicultural decisions should be based on personal objectives. It may not be practical to reduce volume, unless the increase in value is reflected by an increased profit or decreased silvicultural costs.

This trial had high degree of control over factors which are usually varied within and between sites/samples/individuals. It may be helpful for forest managers in the Canterbury region to know that stiffness is more influenced by diameter than height, or different relationships of

TreeTap and Hitman estimates exist for different herbicide and stocking treatments. A similar experiment would have to be carried out at multiple sites across New Zealand to form a national stiffness estimate prediction model, but for Rolleston in Canterbury these growth factors have now been analyzed.

Although the outliers definitely influenced the trend lines for different subgroups, there was insufficient evidence to remove them from this study. It is possible they reflect trees which had defects or other anomalies in growth which caused unusual readings, or they were errors in recording/measuring values. The 3 outliers beneath the trend line (at point B in Figure 8) all had a DBH below 16 cm in Figure 5 which could indicate higher error in smaller DBH trees. Including the 4 outliers only slightly reduced P-values, but may have masked trends in the relationship between Hitman and TreeTap at different stockings. It is likely that the line predicting Hitman stiffness from TreeTap gets steeper as stocking increased.

No weed control resulted in stiffer trees, but since this was countered with smaller DBH values it is unlikely to be adopted in a structural lumber regime. The scatterplots of herbicide subgroups for Hitman stiffness against TreeTap estimates show that the relationship between these measurements varies with herbicide application.

A key implication from this study is that models relating Hitman estimates of stiffness to TreeTap measurements may be biased if they do not include silvicultural influences. This is important for managers who should use a different model for different silvicultural circumstances. Some managers at present are using an algorithm that may lead to biased predictions, and they should consider improving their prediction models by using different Hitman vs TreeTap relationships for different stockings, herbicide treatments and DBH size classes. It could be argued that trees in this experiment were younger and smaller than those for which the algorithm is commonly employed, but there could still be an issue with algorithm use in older stands. The problem may be diminished in scale for older stands because they have a higher proportion of outer-wood, and the scale of the problem for these older stands needs to be assessed in a designed experiment.

A potential issue in this report was the point with the high values of 7.4 Gpa for TreeTap and 5.7 GPa for Hitman. This value falls within the expected range for all the data subgroups so it is potentially improving the trend lines for the entire dataset and for the subgroups. It may have undue influence on the model coefficients by extending beyond the reasonable range of predicted values, but since it is likely to be an accurate value that represents a high stiffness tree it was not treated as an outlier. This is a potential source of error where relationships may be less significant with this value excluded, but it was insufficiently far enough from the other points to warrant exclusion.

There are a few key limitations to this analysis, such as the use of P-values and residual standard error. The use of 0.05 as a threshold for significance is an arbitrarily selected number, but still indicated factors which were likely significant for influencing stiffness. These are likely to be genuinely significant factors, but it is important to note that other factors that were excluded by this value may also have been significant. Since fertilizer had an extremely high P-value in most of the models produced, it is very likely that it had no influence on stiffness. It was excluded from the later models due to high P-values whenever it was included in a model.

Wind sway had an insignificant impact on stiffness, but level of wind sway control is tough to quantify. Having trees that were either bound or unbound may have not prevented the influence of wind to a high enough extent. If this had been a significant factor however, it would be possible to state that the method of binding was sufficient to reduce wind sway for some trees.

Another limitation is the range of genetics used. Unfortunately there were only 2 clones sampled due to time constraints, so it is hard to completely rule out genetics as having had an influence on stiffness at this site. A significant implication of this report however is that weed competition and stocking may have greater impacts on stiffness than genotype. It is widely accepted that stiffness is a heritable trait, but the findings of this report would be applied unsuitably if used as an argument against investing in superior quality tree stock.

Since all trees were the same age and species on a flat site with the same establishment practices there is likely to be limited confounding influence of other uncontrolled variables. The results are also very similar to the previous destructive sample on the site (Doyle, 2011) which adds to the validity of these findings. Microfibril angle is a different measure to MOE, but the two are strongly correlated. Although Doyle (2011) previously found that stocking and weed competition had an influence on sonic velocity, this likely reflects the same findings of this report: MOE was strongly influenced by stocking and weed competition.

There is likely to be much discussion around the applicability of this report for older, mature stands. Since the worst wood is put on in the first 10 years, the relationship between tools will likely be most prevalent at 10-years old. Although the relationship may change as the trees mature, factors which influence the relationship will likely remain relevant. Also since we are hoping to suggest improvements that can be made to increase stiffness in the core-wood, 10 years old is the best age to test tree core-wood stiffness. The majority of the stems should consist of core-wood at age 10 so factors which have increased stiffness have improved the core-wood quality.

Another destructive sample will likely be completed on the site in the future and provide additional information about the relationship between Hitman and TreeTap estimates over time. There is also processing of samples that is still occurring which will provide more information about the intrinsic properties of the sampled trees. Future steps could also include nationwide trials of the same experimental layout to develop national prediction models.

Conclusions

Stocking and weed competition were the most significant silvicultural factors correlated with tree stiffness. DBH was strongly correlated with tree stiffness, and when included in a stiffness prediction model DBH accounted for a large portion of the variation caused by stocking, making stocking an insignificant predicting factor at $\alpha=0.05$. Although weed competition increased stem stiffness, it also decreased DBH making this a potentially impractical finding.

There was no significant difference in stiffness measurements between the northwest and southeast sides of a tree even though the northwest side was 3% higher on average. This finding if paired with the P-values for wind sway would indicate that for the Rolleston site, wind had an insignificant impact on tree stiffness in this trial.

Hitman and TreeTap measurements were strongly correlated, and in this study TreeTap estimates of stiffness were about 30% higher than Hitman estimates. The estimates of Hitman and TreeTap were more scattered for trees which had weed control, and the trend line was also higher from this group. There may be a similar increase in model trend line caused by stocking, but this was heavily influenced by outliers.

When building a model to predict Hitman from TreeTap estimates for young radiata pine trees, factors such as stocking and weed competition are likely to be significant. Model accuracy could also be improved by including DBH as an independent variable. Sampling should be stratified by groups of herbicide treatment types and stocking if silviculture varies across the site. It is inappropriate to use the same relationship of TreeTap estimates as predicting factors for Hitman stiffness for all silvicultural treatments. Model accuracy would be improved by having different models based on stand stockings and herbicide use to improve accuracy of predictions from a model and reduce bias.

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Appendix

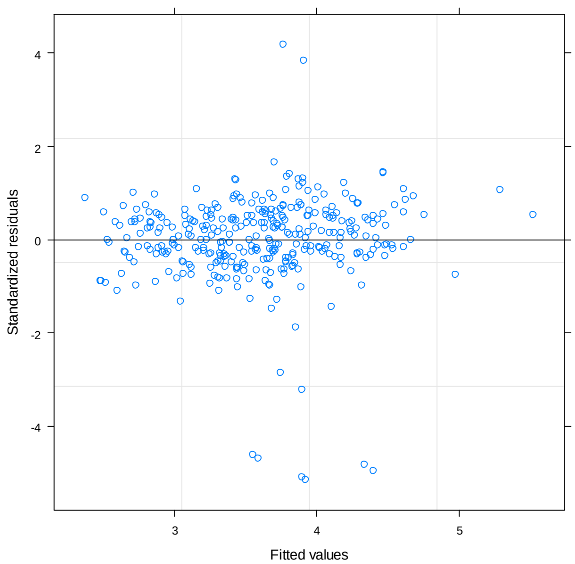

Figure A1: Residual distribution for model 'e'

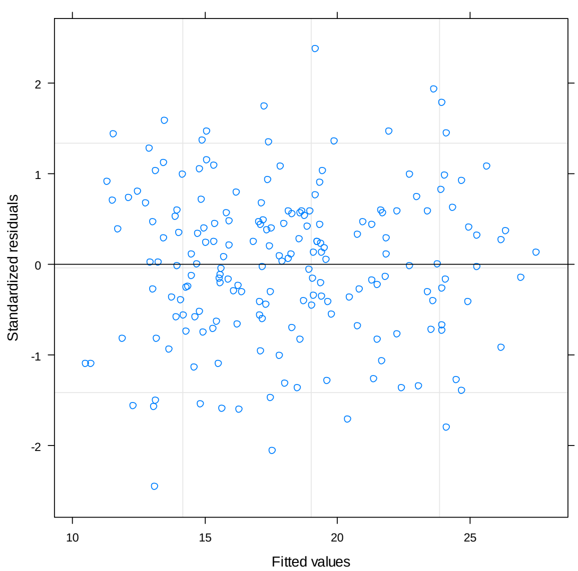

Figure A2: Residuals from model 'a'

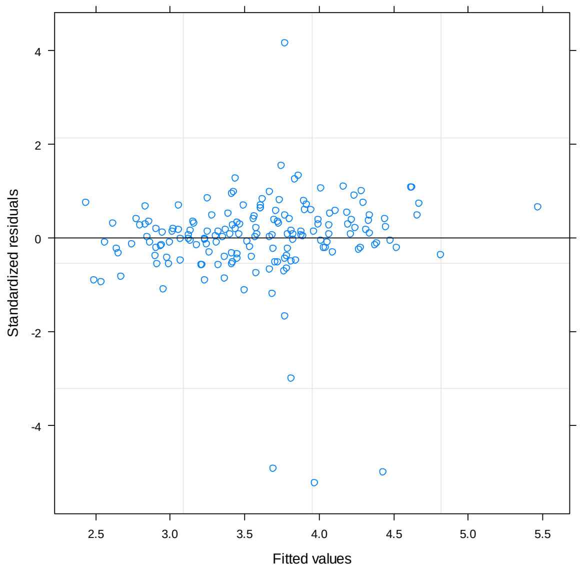

Figure A3: Residual distribution from model 'b'

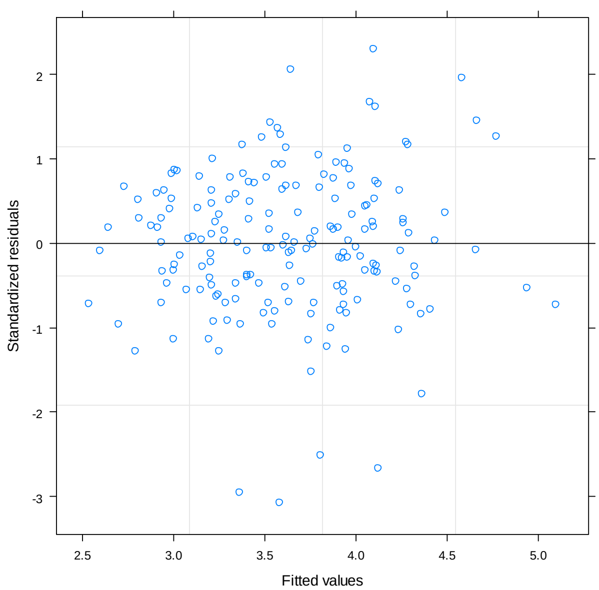

Figure A4: Residual distribution for model 'Cc'

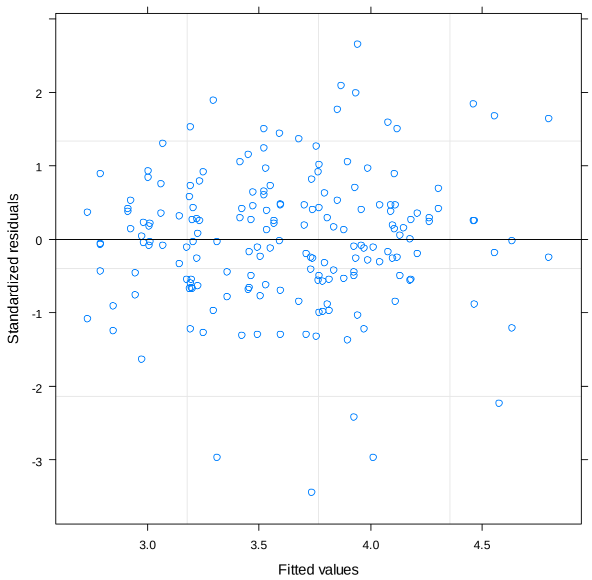

Figure 11: Residual distribution for model 'c'

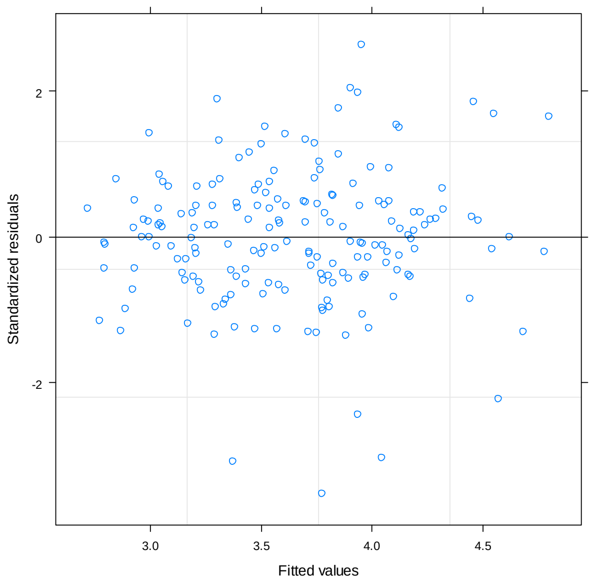

Figure 12: Residual distribution for model 'd'

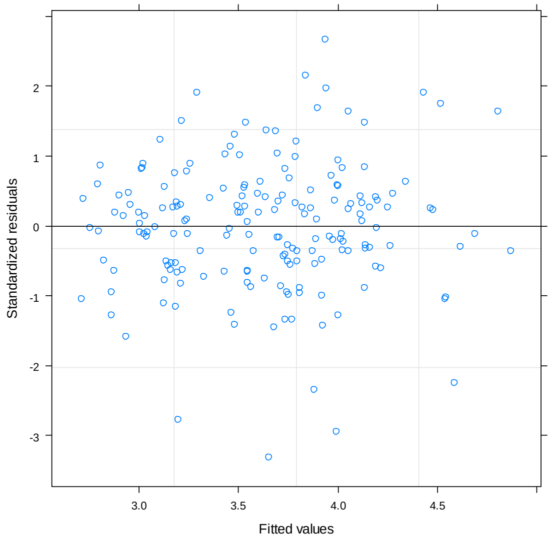

Figure 13: Residual distribution for model 'f'