Maramarua Value Recovery Project: Analysing the difference between Predicted and Actual Volumes

Sale Area 604-014-01

A Project Submitted in partial fulfilment of the requirements for the

Bachelor of Forest Engineering (Hons)

Prepared for: Rien Visser | Rayonier | Matariki Forests

by

Seamus Bardoul

Alex Tolan, Project Supervisor

University of Canterbury

October 2018

Executive Summary

Value recovery is vital to a successful forest investment. Value recovery requires both accurate pre-harvest inventory and optimising recovery during harvesting. This trial will analyse harvester head accuracy and the differences between predicted volumes and actual volumes attained for the Maramarua forest, sale area 604-014-01. The project was assigned by Rayonier New Zealand to minimise value loss, maximise returns and meet domestic log supply constraints. The main objective of the case study was to identify variables that are causing harvested volumes to be significantly different from those forecasted.

An operational cruise was undertaken to attain inventory data, before stems were numbered and mechanically processed. Once processed, the logs were manually measured for SED, LED and Length. Using a combination of manual, inventory and STM file data, analysis was taken for predicted, actual and optimal recovery.

The trial found that there was a significant difference in Waratah measurements to manual measurements. The harvesting head was found to be consistently under predicting small end diameter by 0.7 cm, and total recoverable volume by 9% on average.

The pre-harvest inventory data accurately predicted the total recoverable volume within 2% of the '*actual volume'*, significantly smaller than reconciliation data for the year 2016. However, the volume by log grade varied a lot. YTgen predicted a combined volume of 103 m^3 for both S20 and S30 grades; conversely, the Waratah harvested 60 m^3. Consequently, this resulted in a financial loss of 10%. This grade relationship appeared to be inversely proportional to the KM and M20 distribution, caused by a combination of the following;

- YTgen contradicting Waratah cutting strategies
- Waratah cutting strategy not including all possible grade/length combinations
- YTgen priority matrix weightings
- Supply constraints on certain grades
- Influence of head calibration for logs on grade diameter boundaries, in particular (20 – 22 cm)

The Maramarua taper function was deemed to be adequate for vital sections of the stem, despite small overestimations and underestimations for the base and tip of the stem respectively. It is important to note the removal of production pressure on the harvester operator. Thus making it easier to optimise recovery, hence causing a possible bias towards Waratah '*actual volume'*.

Contents

Acknowledgements

Thanks and appreciation go to Lance Balle, Braydon Miller, Tristan Armstrong and Nick Elmigel from Moehau Crew 99 for actively taking part in the trial and offering expertise where required. Thank you to Casey Roper and his team at Pinetech Pacific for the pre-harvest cruise. Thanks to Peter Yardley for his help on the trial and background information. Thank you to Mat Curry for participation in the trial and taper function analysis. A massive thank you to Alex Tolan for his supervision over the project and contribution in data analysis.

List of Acronyms and Definitions

PHI	Pre-Harvest Inventory
STM	File type containing stem information produced by the Harvester head
YTgen	Forest Yield Table Generator, Interpine Innovation
TRV	Total Recoverable Volume
RCA	Root Cause Analysis
NZFOA	New Zealand Forest Owners Association
HTH	Harvester Head Model
SPH	Stems per Hectare
WOF	Warrant of Fitness, calibration and accuracy check
STICKS	Harvester Wood flow Management System
DBH	Diameter at Breast Height (1.4m)
LED	Large end Diameter of the log
SED	Small end Diameter of the log
RFID	Radio-frequency Identification
LiDAR	Light Detection and Ranging
DEM	Digital Elevation Model
DSM	Digital Surface Model
UAV	Unmanned Aerial Vehicle

Introduction

Value recovery is about ensuring the best returns from the forest harvest (Powrie, 2017). It is a method to assess the accuracy of the forest operation and is dependent on the marketing constraints and opportunities of that day. Value recovery analyses the predicted value vs actual forest value to identify activities and areas that are compromising the financial return to the owner. The purpose of this report is to analyse the difference between pre-harvest inventory estimates (PHI) and the actual volume recovered through mechanical harvesting (STM file data). Currently the Maramarua forest is over predicting the expected yield (~11%), and in particular the large domestic saw log volume (~14%) (Tolan, 2018). This is having a significant impact on both economic return as well as meeting Rayonier NZ Ltd log supply constraints.

The over-prediction is most likely to be a result of many inaccuracies from stocking through to transport. In particular, this report will focus on the following three components and analyse the respective objectives;

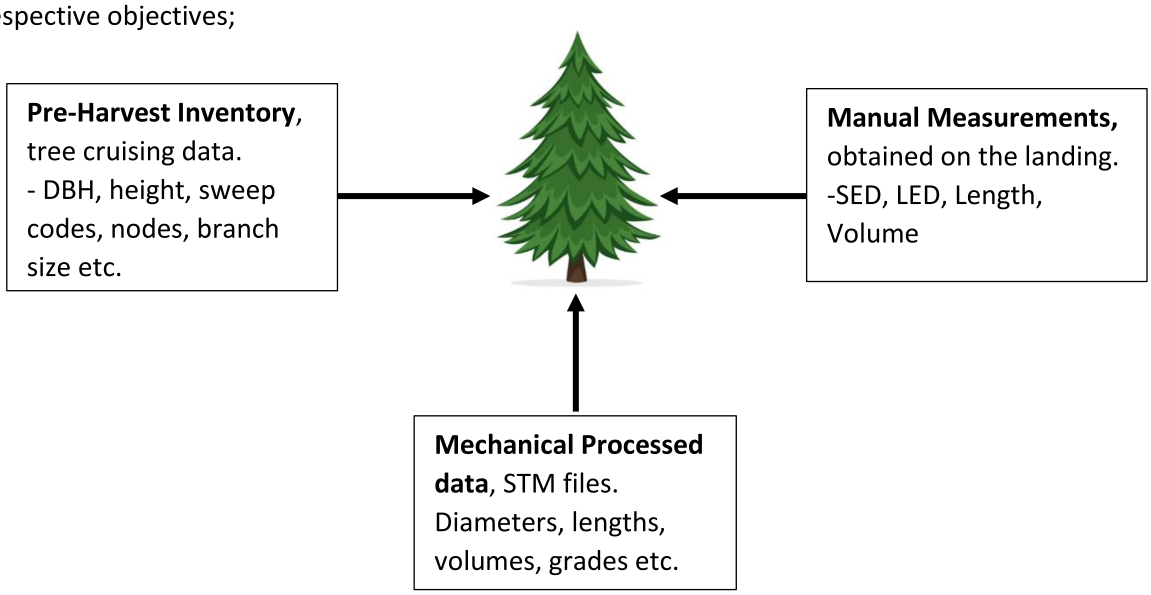


Figure 1 Three main components being analysed to find root cause

- *The accuracy of the Waratah processing head (SED and Length) compared to manual measurements collected on the landing.*
- *Analysis of pre-harvest inventory (PHI) and Waratah measurements (STM file data)*
- *If there is any significant difference in the YTgen 'predicted volume' and the Waratah 'actual volume'.*
    - *Total Recoverable Volume (TRV)*
- *The impact of the cutting strategy on recoverable volumes, and log grade mix*
- *Analysis of YTgen taper functions*

Figure 2 below, shows the Root Cause Analysis (RCA) throughout the project in an attempt to find root causes contributing toward the inaccurate value recovery.

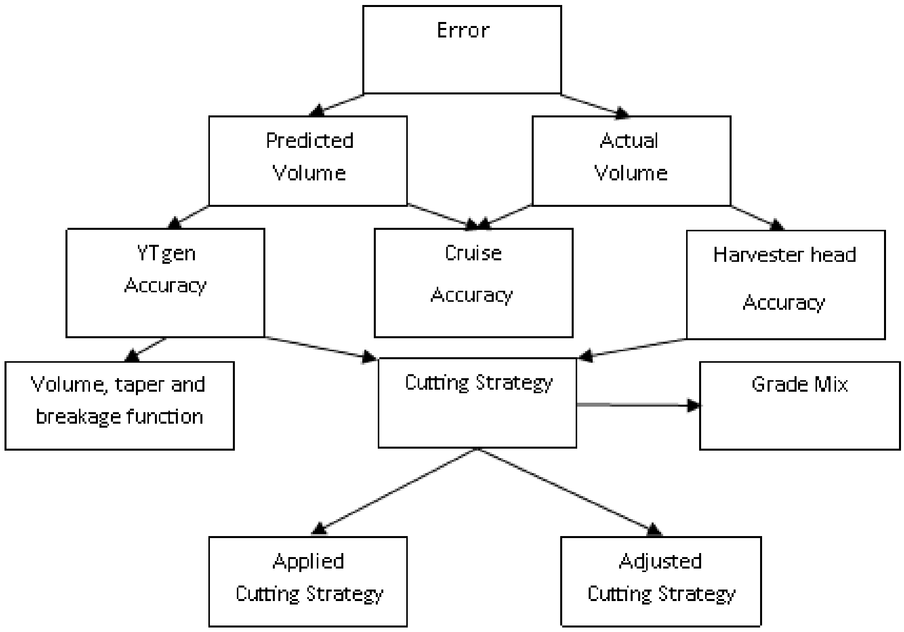


Figure 2 Flow chart of areas of focus

Literature Review

What is Value Recovery?

Value recovery is an attempt to maximise returns through developing tools, processes and disciplines (Dick, 2005). The chase for value recovery can only occur from the use of accurate and appropriate data measurement, the analysis of *actuals* compared to *predicted* is pointless if the inventory and stand data is inaccurate. Not only is it vital to maximise returns but also gain a sustainable forest operation through value recovery. Climate change, as well as the increasing demand for forest products, requires a re-thinking of forest operations regarding sustainability. Reduced waste and increased product value are vital contributors to achieving a sustainable operation (Marchi, et al., 2018). Knowing that operators are experienced and sufficiently trained, the following harvesting processes and tools are used to maximise the recovered value (Dick, 2005);

1. Cutting the broadest range of log grades available that cover the value spectrum.
2. Log making to maximise the relative on-truck value of each stem. This can only be reliably achieved by electronic optimising, therefore applies directly to head calibration.
3. Ensuring that operators do not top up lower value loads with higher value grades.

Market breadth is vital for value recovery; it is important that the resource about to be harvested reflects the range of markets available within your district. Therefore to optimise the returns we must ensure that the cutting strategy reflects market opportunity on a day to day scale.

Improving the value recovered can also have positive ramifications to the environment. By optimising utilisation of the stem through the log making process, waste/slash is minimised. In doing so, lessening the likelihood of adverse environmental effects (NZFOA, 2007). Removing waste and slash from the cutover can also mitigate consequences of debris flow into waterways, reducing both velocity and momentum (Bloomberg, 2018), to ultimately avoid proceedings such as the Tolaga Bay forestry disaster (Barrington, 2018).

Harvester head accuracy

The New Zealand forestry industry continues to change in the direction of becoming fully mechanised. This is driven by both its benefits in production and worker safety. With the increase in mechanisation and inbuilt computer systems majority of decision making has been removed from the operator and placed into the technology of the processing head. Although major advantages to come from mechanisation, processing head accuracy can be insufficient and is limiting their implementation (Thomas Leitner, 2014). This was reinforced by a previous study stating despite these systems giving operators access to advanced computer and measuring systems, their ability to extract optimal value is less than manual log making systems (Marshall & Murphy, 2004).

A recent study found that average log length was overestimated by 0.17 cm. This seems accurate when averaged, however, variability in length errors showed that logs were being both under-cut and over-cut (Saathof, 2014). Log length was found to be over-estimated by up to 15 cm which shows the effect of a poorly calibrated machine. Despite the Waratah HTH 625c over-estimating log length, it was deemed to under-predict the small end diameter by 1.6 cm, with a standard deviation of 2.2 cm. Another study analysed a Komatsu Harvester head and the Woody H60 operating in Australia, it found that 74% of log lengths were being over-cut by more than 6 cm. Along with calibration analysis, the article also analysed the impact on harvest season. The harvester predicted on average 1.8 cm longer in winter, having a greater effect on head accuracy (Leitner, Visser, & Stampfer, 2014).

The slope project looks into integrating processing and control systems for sustainable forest production (Prandi, et al., 2017). Part of the project looks into an improved harvester head, regarding timber quality assessment and tracking of the stem from bucking throughout the entire supply chain.

Throughout processing, the prototype analyses the following properties of the log;

- De-branching forces along with their position within the log, taken by an attached load cell
- Cross-cutting forces for each log cut
- Studies defects and inhomogeneity's in the timber through a stress wave propagation test
- Undertakes a vibration response test
- Analyse log quality through hyperspectral and NIR imagery
  - External diameter
  - Diameter under-bark
  - Heartwood
  - Pith position
  - Reaction wood
  - Wood decay
- Data produced from the head is then labelled onto the log via an RFID tag, allowing log attributes to be accessible throughout the supply chain.

In depth detail of the timber facilitates a series of services, from logistic management, pre-sales, real-time information, and stumpage price evaluation to name a few. This highlights; the lack of timber quality assessment in New Zealand harvesters, and possible alternatives to progress in the future. It is important to note that the current prototype would have a detrimental effect on crew production, but is likely to improve as it develops further.

Pre-Harvest Inventory (PHI)

The most reliable yield forecasts are obtained through stand measurements. These usually involve measuring sample plots. However, approaching harvest, a high level of detail is required in tree measurements and descriptions (Crawley, May 2007). Plotsafe is a software tool for collecting forest inventory data (Herries, 2018). Plotsafe data is fully compatible with YTgen to forecast grade recoveries and cutting strategies based on forest yield. Thus, producing both the *Predicted* volumes and the *estimated* value of the stand. Log parameters of interest in determining '*predicted'* (pre-harvest inventory) volumes include (Gordon, Wakelin, & John, November 2005):

- Size (diameter, length)
- Shape (e.g., taper, sweep)
- Branching (e.g., internode index, branch index, etc.)
- Defects (e.g., resin, knots)

Therefore it is important that the pre-harvest cruise acquires accurate characteristic data to allow inferences to be made around harvesting processes or head calibration. Failing to achieve accurate pre-harvest inventory will result in an undesirable bias.

Taper Analysis

Tree volumes are estimated through stem taper functions. The taper function essentially describes the shape of each stem based on measurements acquired throughout the cruising process. Polynomial taper models are the tree profile equation that is used to describe the stem profiles of New Zealand Radiata pine (*Pinus Radiata D. Don*) in supporting management decisions (Sabatia, 20 August 2016).

Variations between the taper function and the actual stem taper will cause inaccurate inventory data, making an analysis of value recovery irrelevant. These functions have been taken from the Permanent Sample Plot (PSP) system developed for use in different regions, crop types, and stand ages (Dunlop, 1995). Taper functions predict individual-tree under-bark stem volume from height and diameter at breast height. The compatibility of a taper equation can be tested in many different ways. Including upper stem diameters as additional taper model predictors is a widely used method to check that the taper function is accurate and accounts for inter-tree stem profile differences (Kilkki, Saramaki, & Varmola, 1984). However, a more in-depth analysis will check the validity of the taper function for the Maramarua stand.

The most commonly used volume functions are 182 and 237 for Radiata pine (Silcock, May 2007). Theses taper functions were developed in 1980 and were applied to all *Pinus Radiata* stands. However, its relevance today is uncertain. He also stated that the list of taper functions is too long and out-dated this contributing to the difficulty experienced by users. It is important to note that taper functions vary from stand to stand. Hence, taper function compatibility is essential in determining an accurate predicted volume (Xialou, et al., Jan 22 2016).

Maramarua Existing Condition

Analysing the Value recovered from the Maramarua Forest was a project assigned by Rayonier NZ Ltd. To gain an accurate forestry operation is being undertaken in the future is vital for Maramarua, as the current volumes recovered from the forest is substantially less than forecasted. This is displayed on the following page. Figure 3 shows the relationship of predicted vs actual TRV's for the six years leading up to 2017. Figure 4 overleaf, shows the error or forecasted volume that was not recovered.

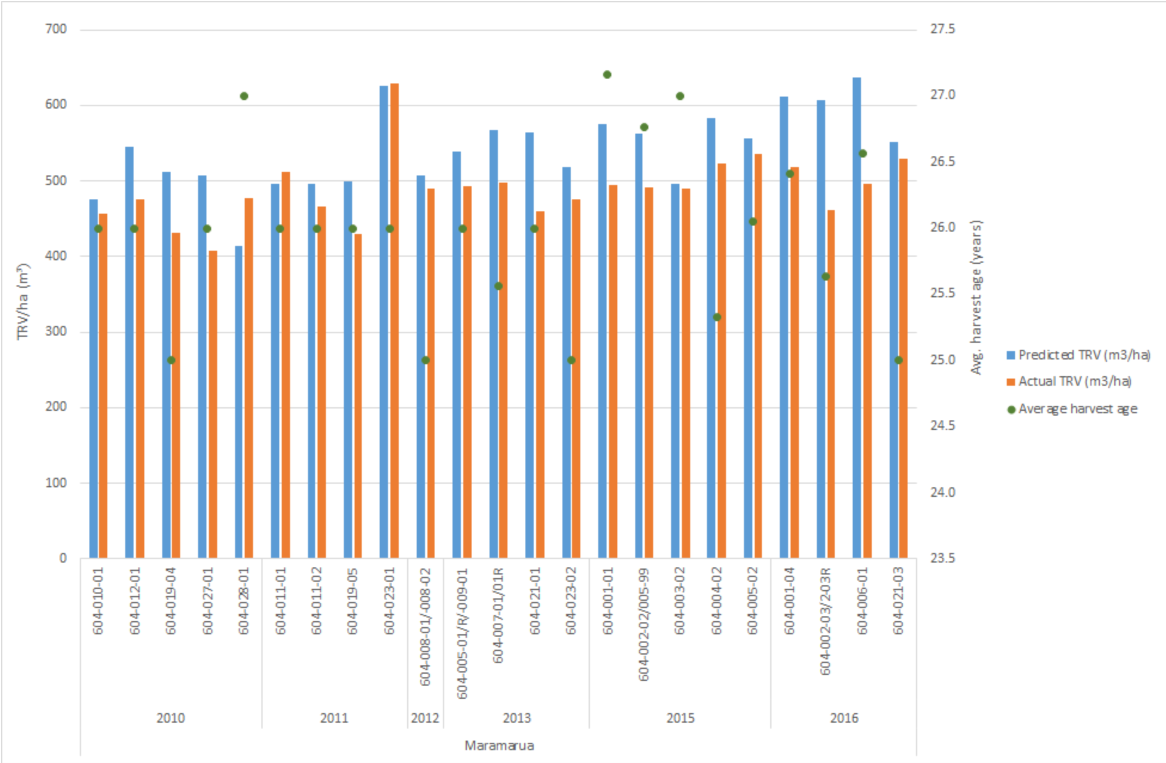
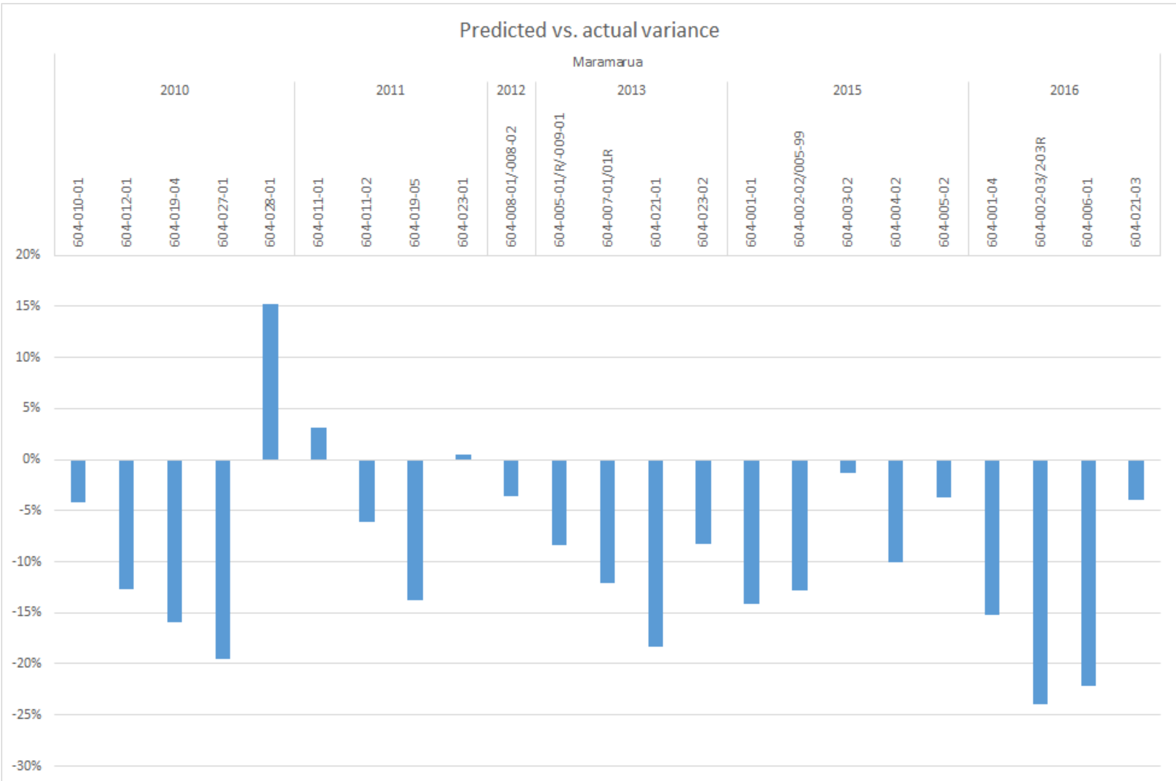


Figure 3 Predicted vs Actuals by Sale Area in Maramarua (2010-2016)



4 Difference between Predicted vs Actual by Sale Area/Year

The variance suggests the forest is losing approximately (5-10%) of the predicted value during harvesting based on values taken during the (2010-2016) period. It's important to note that the worst reconciliation occurred in 2016, with sale areas 604-002-03 and 604-006-01 recovering volumes exceeding 20% less than expected, thus making it vital to remediate as soon as possible.

Figure 5 on the following page shows the wood-flow plan for the western Bay of Plenty and forecasts the future volumes to be harvested by forest. Maramarua (grey) shows a decline in production over the next four years to minimise the value lost until the recoverable volume is more accurate to that of the predicted. The production drop has been put in place to minimise financial loss in the near future. However, in doing so, the average age class of the forest will increase, making It is crucial for this project to gain an understanding of where the value is being lost. Whether it is an over-prediction of pre-harvest inventory or an underutilisation of the forest from harvesting crews.

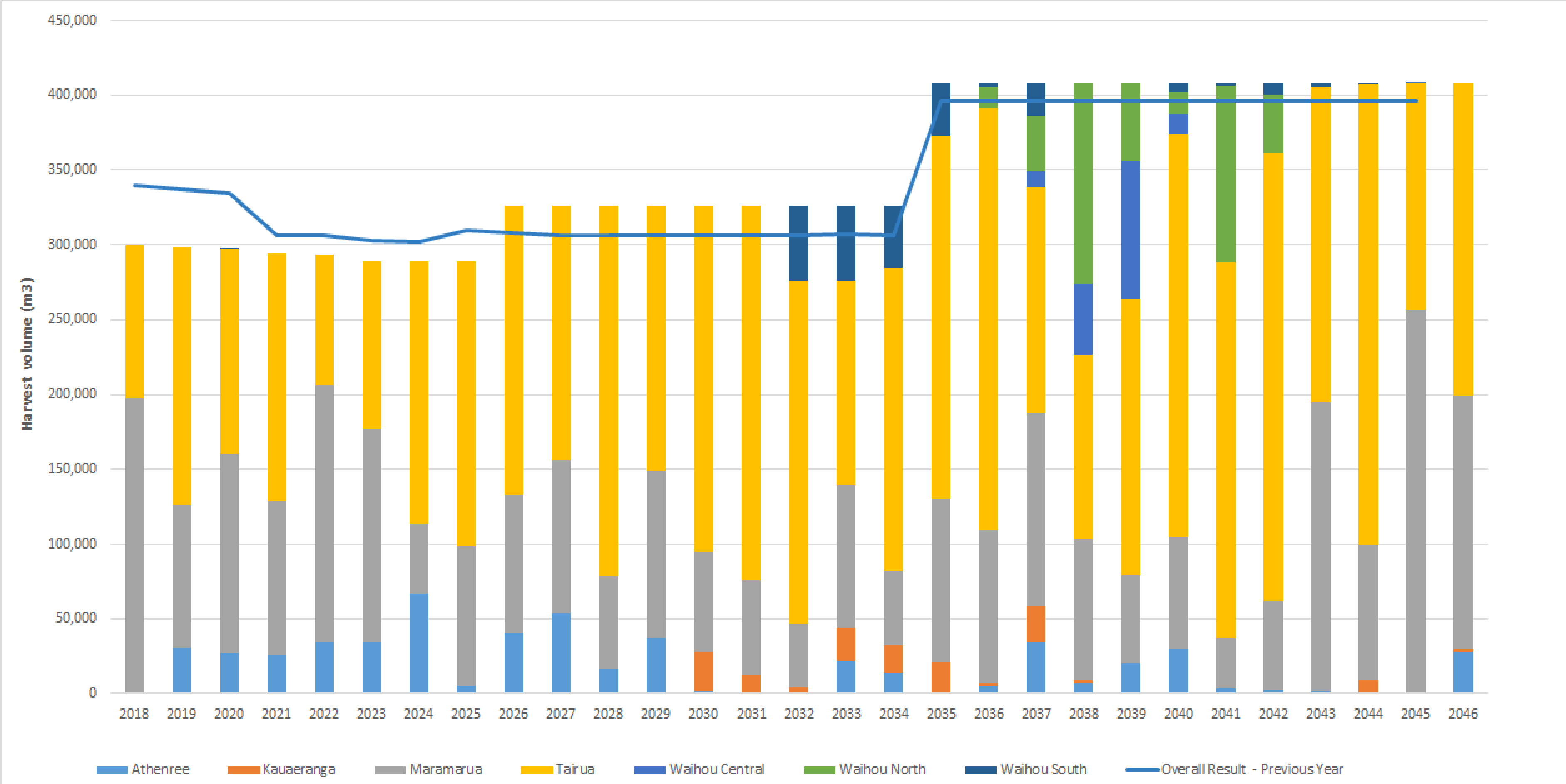


Figure 5 Western Bay of Plenty wood flow forecast

Goals

1. Analyse value recovery and previous studies to gather a broad understanding of the current situation in Maramarua Forest.
2. Undertake a trial to compare;
   a. The accuracy of the Waratah Processing head compared to manual measurements obtained post-processing.
   b. Analyse the difference between predicted volumes produced by a pre-harvest cruise and YTgen, to actual volumes taken from the processing head STM file.
3. Undertake a root cause analysis to identify key areas producing a lack of consistency between pre-harvest volume estimates and the recovered volume.

Approach

The trial took place in Sale Area 604-014-01. The Radiata stand was aged 26 with an estimated stocking of 318 SPH and piece size of 1.55 m^3/stem. This sale area was chosen due to it being reasonably flat topography with ground-based extraction, refer to the sale area map in the appendices. 100 trees from the sale area were analysed for the Value Recovery trial. From these 100 stems, six stems were analysed for the reconciliation of the harvesting head. The stems were felled mechanically and shovelled to the landing where they were processed using a Waratah HTH625c harvesting head. The last calibration and WOF of the harvesting head was on the 7/9/2017 (approximately three months before the trial took place).

Stems were cruised by Casey Roper and his team at Pinetech Pacific LTD. Casey roper is very experienced at pre-harvest inventory and has been in the industry for 25 years, thus providing confidence in the level of accuracy of PHI. Throughout this process each of the 100 stems had the following data obtained through a vertex hypsometer, clear wood ruler, and diameter tape;

- Diameter at breast height (1.4m)
- The height of the tree
- Length of clear wood (butt log with no branches)
- Branch classification (null,<4 cm,<7 cm,<10 cm) with corresponding heights of changes
- Sweep codes: Shorts, Longs, 1,2,3 with corresponding heights of changes
- Forks

Once the trees were cruised and numbered, they were felled and butt marked to ensure numbering wasn't lost throughout the shovelling process. Following shovelling to the landing, the first six stems (35 logs) were processed and manually measured for head reconciliation. Manual measurements were taken using a loggers tape for length and measuring tapes for both small end, and large end diameters. The rest of the stems were then processed and recorded to establish a stem sequence. No stems were lost throughout the process. However, two stems (86, 98) were misread due to the number similarity. This was recognised throughout data analysis, having no effect to the accuracy of the trial.

Using the stem sequence recorded on the landing and the corresponding time stamp from the Waratah's STM file, inventory tree numbers were matched.

Assumptions and Accuracy of measurement

- Manual measurements were taken as true/actual values for head reconciliation. Human error was not factored for, (human error = 0).
- Waratah measurements were expected to be true/actual when comparing to the YTgen data. This has major implications on recoverable volume. Analysis of adjusted volumes with respect to manual measurements and pre-harvest cruise data may be necessary.
- Majority of stems processed had little to no bark on them. Therefore diameter measurements from the harvester head were assumed to be under bark diameter.
- Each tree felled by the head had an estimated stump height of 30 cm or 0.3 m. Therefore; DBH was taken as the diameter at 1.1m along the processed stem.
- Under bark diameters produced through manual measurements were calculated using the NZ Forest Research Ltd. Bark equation;

  $$d = -0.644 + 1.0465D - 0.004428D^2 + 3.558x10^{-5} \, x \, D^3$$

  Where;

  $$d = diameter\ under\ bark, \qquad D = diameter\ over\ bark$$

The associated accuracy with trial measurements is represented in table 1 on the following page.

Table 1 Measuring methods and respective accuracy

	Measurement/tool	*Measurement Accuracy*
Inventory Measurements	Tree Height – Vertex hypsometer	± 0.1 m
	Tree diameter – Diameter tape	± 1 mm
	Breast height – Ruler	± 1 cm
	Height to first branch – Ruler	± 0.1 m
Manual Measurements	Log length – Loggers tape	± 1 cm
	SED, LED – Builders tape	± 1 mm
Waratah Measurements	Log length – Measuring wheel	± 0.1 m
	Diameter – Rollers	± 1 mm

Results and Analysis

Waratah Head Analysis

The STM file values were analysed against measured values to test the calibration of the head and any error associated with it. Figure 6 below display's the distribution of Waratah length error (Waratah – Manual) by log number.

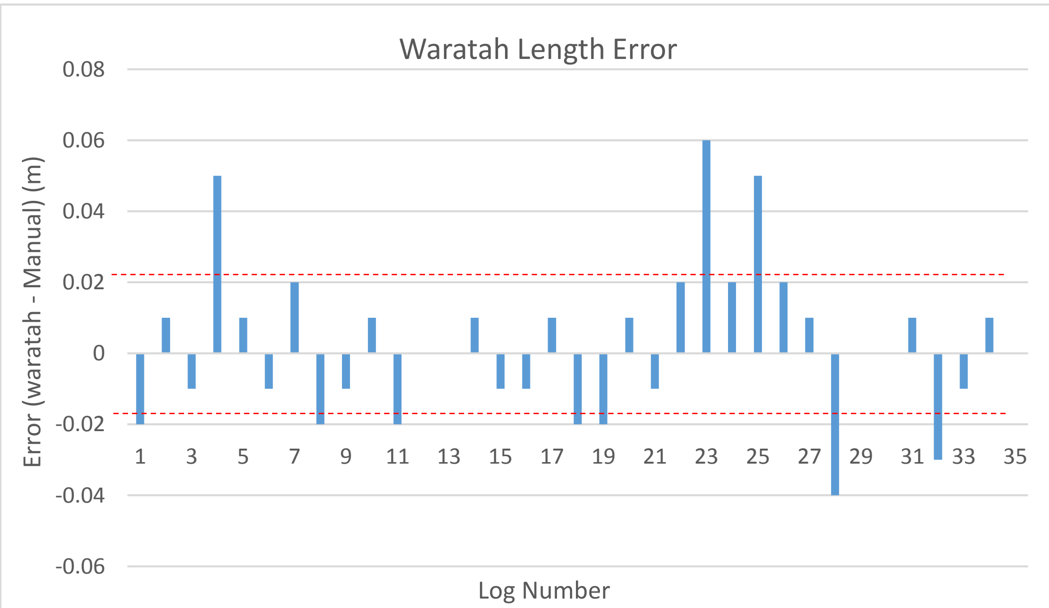


Figure 6 Waratah Length error (Waratah length - Actual Length)

As displayed in figure 6, the harvesting head accurately predicted lengths within 6 cm of the true measurement. Note that the high error in stem number 23 was to be expected due to wheel spin that was observed on the landing. The dashed red lines represent the average errors (over-prediction and under-prediction) at values +21 cm and -17 cm respectively.

A measurement error greater than 6 cm falls outside the calibration specifications for Rayonier of ±5 cm for processor length measurements and has the potential of major ramifications down the supply chain (Charlotte, 2018).

The following figure 7 tests the length accuracy against the Swedish 'best-5' standard, where 90% of logs must fall within five adjacent 1 cm error classes. For the 35 logs in the trial, 85% of the logs fell within the 'best 5' adjacent error classes. The spread of the error is not skewed. This is demonstrated by the normal distribution around '0' error. Therefore we can conclude that the length is not being over or under-predicted. However, the precision of the harvester head calibration is poor.

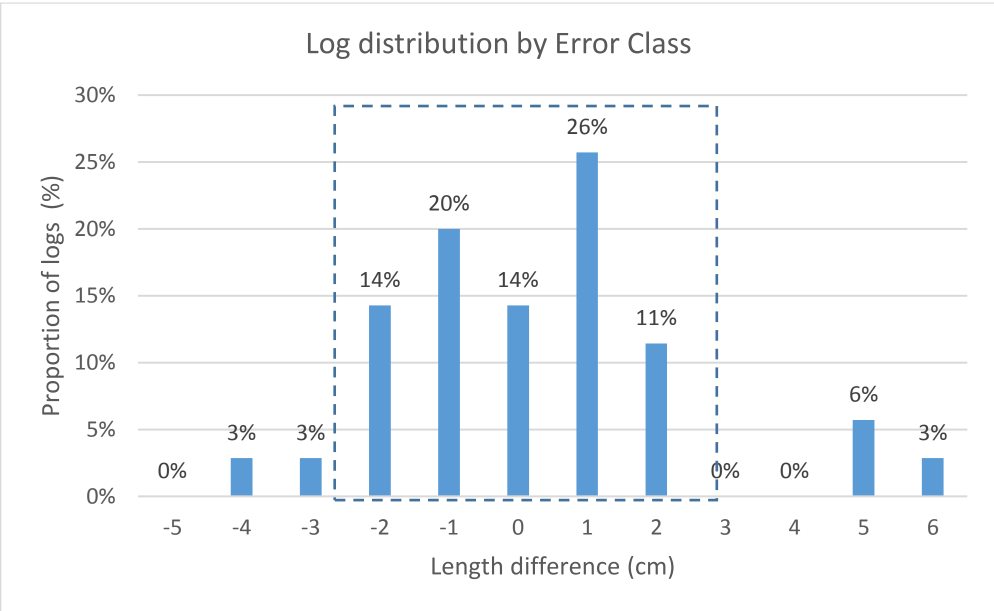


Figure 7 'Best 5' standard for length measurement accuracy (Waratah - Manual)

Incorrect length measurements have been found to be the main cause of non-quality related log rejections by customers in the Australian pine plantations (Strandgard, 2012), making it a high priority. Inaccurate length measurements may be due to a combination of the following; (Roth, 28/7/2016)

- 'Wheel spin' or the loss of traction of the head measuring wheel with the stem. Can be due to uneven stem shape.
- Measuring wheel penetrating bark at different depths depending on bark hardness.
- Stem roughness, causing the wheel to travel extra distance.
- Bark slipping under the measuring wheel and blocking the wheel from spinning.

The comparison of the 35 SED's is shown in figures 8 and 9 below. The distribution of Waratah vs Actual (manual) shows that the Waratah diameter is under predicting the manual (*true diameter*). This is demonstrated by its left position to 'zero error'. Figure 9 reinforces this trend. Diameter error fluctuates throughout the (-8 cm to +1.5 cm) range, showing the inconsistency of the head's precision. The results of the trial revealed that the head was under-predicting the SED by approximately 0.7 cm on average or 2% of the total diameter, this is represented by the dashed red line.

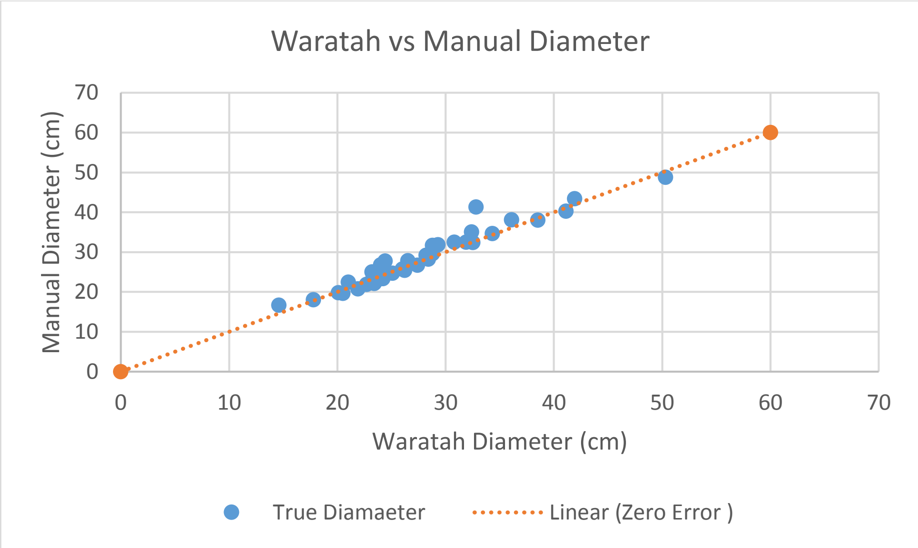


Figure 8 Waratah (predicted) vs Manual (actual) diameter distribution

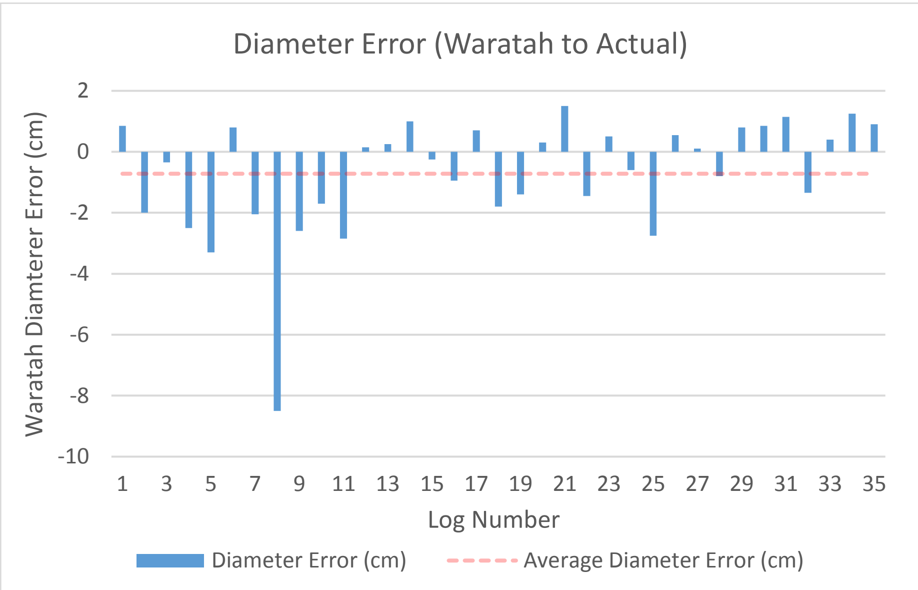


Figure 9 Waratah SED as a proportion of manual (actual) SED

Diameters were further analysed against the cruised data. Once again the average over the entire trial sequence was found to be underestimating the diameter measurement. Diameter error was found to be a lot larger at breast height compared to SED measurements, with the Waratah under predicting the true (manual) DBH by approximately 7% error on average.

The linear trend line displayed in figure 10 represents the Waratah/Manual measurement ratio. Here we can see that the Waratah is under-predicting manual diameters at breast height. However, it is important the relevant assumptions associated with both Manual and Waratah diameters;

- Processed stems had minimal bark on them. Therefore diameter measurements from the harvester head were assumed to be under bark diameter.
- Each tree felled by the head, had an estimated stump height of 30 cm or 0.3 m. Therefore; DBH was taken as the diameter at 1.1m along the processed stem.
- Under bark diameters produced through manual measurements were calculated using the NZ Forest Research Ltd. Bark equation;

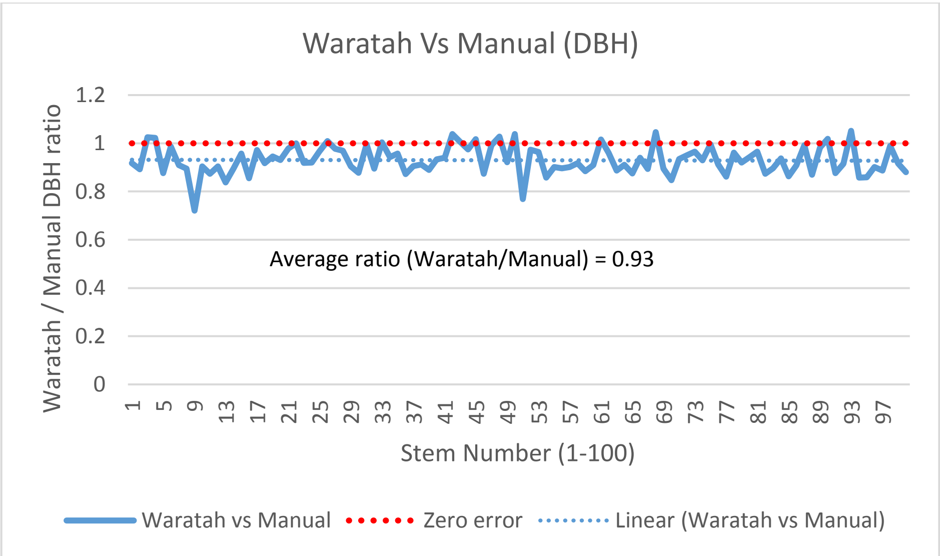


Figure 10 Comparison of Waratah and Manual DBH (@1.4m) for cruised data

Using the STM file data, volume was compared to the volume calculated using the 3D formula (Ellis, 1993). The formula is shown below;

$$V = \exp(1.944157 * \ln(L) + 0.029931 * d_0 - 0.038675 + 0.884711 * \ln\left(\frac{d_1 - d_0}{L}\right) + 0.078540 * {d_0}^2 * L$$

$$V = \text{Log}\, Volume$$
$$L = Log\ length$$
$$d_0 = Small\ end\ diameter\ (SED)(cm)$$
$$d_1 = Large\ end\ diameter\ (LED)(cm)$$

The distribution of formulated volume vs Waratah volume is shown below. The Waratah was also under predicting volume. It is important to note that the STM file also included waste volumes. This does not include breakage which may be a contributing factor to the discrepancy. Assuming the 3D formula to be the *true volume* of the log, the Waratah was calculated to be under predicting the *true volume* by 9% on average.

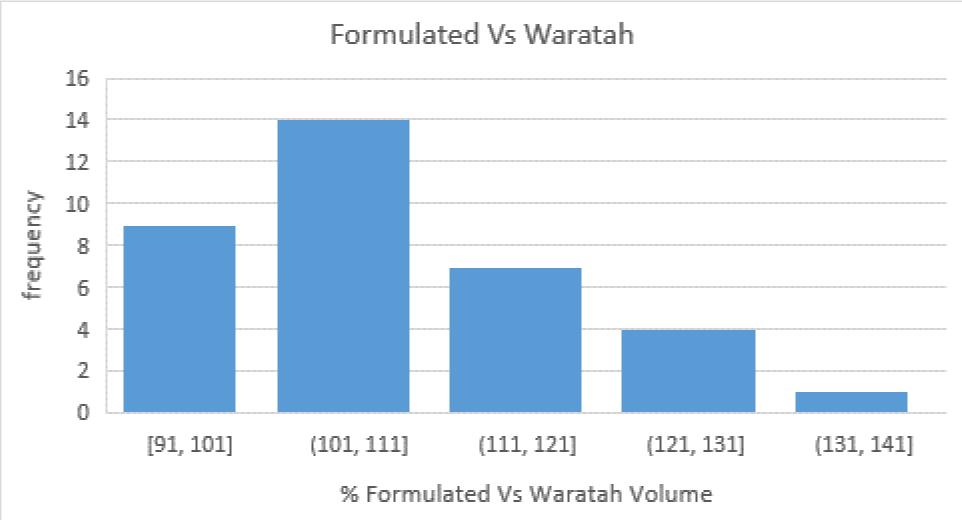


Figure 11 Formulated (3D formula volume) vs Waratah Volume

This volume was then analysed by log grade to identify if the log grade influenced the accuracy of the harvester head. This is shown below in figure 12.

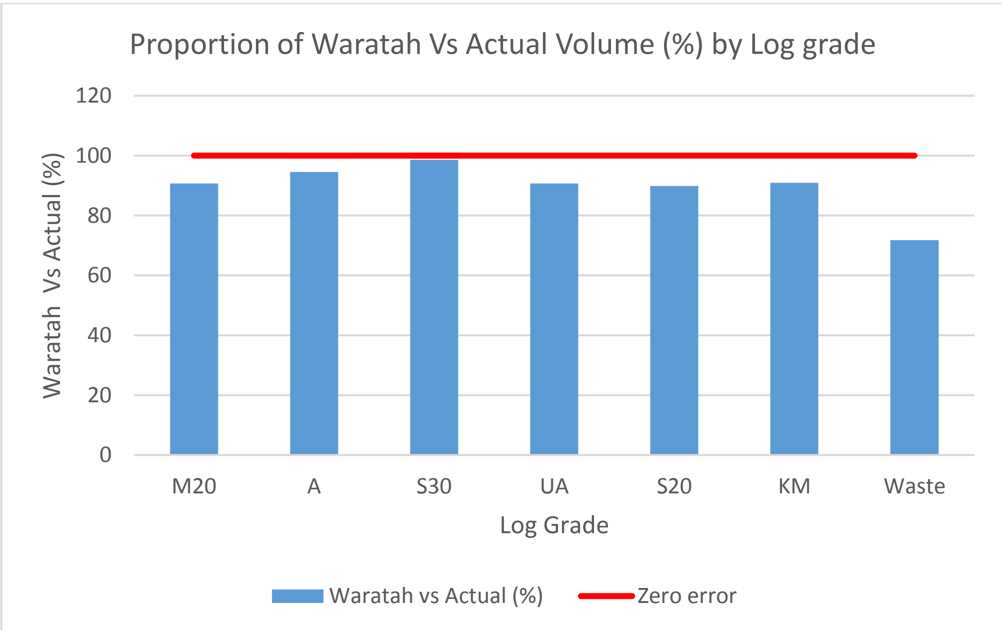


Figure 12 Accuracy of Waratah volume prediction by log grade

This shows that the Waratah is consistently underestimating the volume across most grades. Logs grades with larger diameter's had a superior accuracy 'S30' (98.6%) and 'A' (94.6%). The high inaccuracy of the waste (71.8%) is most likely to be accounted for by the 3D formula as opposed to the head, due to the lack of data and the irregular shape of these sections.

Analysis of Yield Estimate (YTgen prediction) and Recovered Volume (Waratah)

Base Case Analysis

Firstly the Waratah (actual) volume was analysed against a base case (YTgen prediction with all log grades turned on). The recoverable volumes produced were 150.1 m^3 and 155.7 m^3 respectively. Resulting in YTgen over predicting the total recoverable volume by 3.7%. Although this prediction appears to be reasonably accurate, the log grade mix shown in figure 13 reveals a large variance;

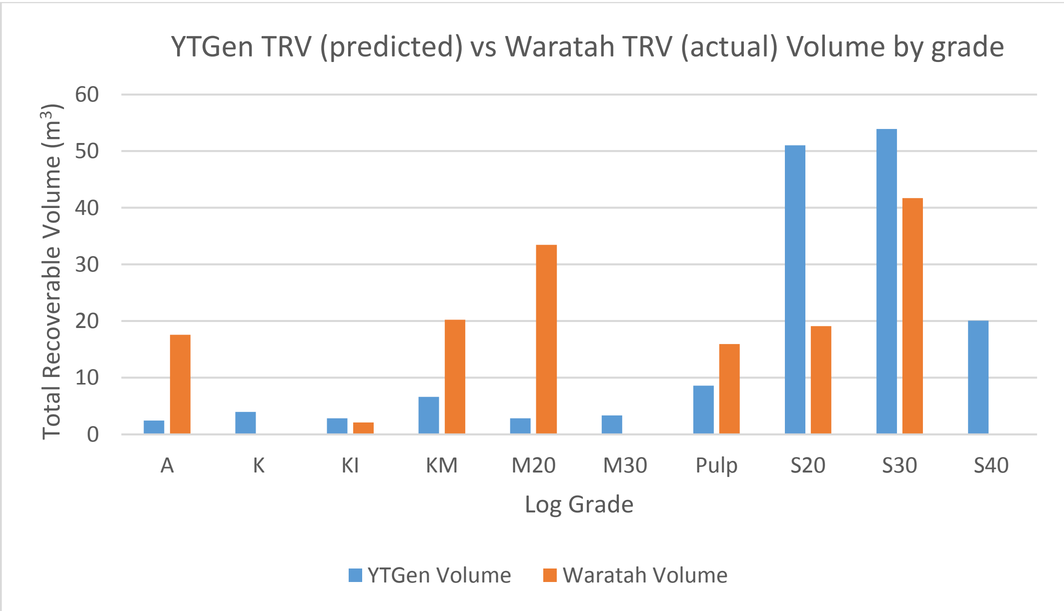


Figure 13 Predicted vs Actual volume by log grade

The grade distribution illustrates YTgen predicting a higher production of saw log grades S20, S30 and S40. However, due to market constraints and cutting strategies the Waratah is harvesting larger volumes in M20's and KM grade. This corresponded to YTgen predicting a more optimal solution and in turn a better financial return. YTgen estimated a return 10% higher than what was received from the Waratah. Taking Rayonier NZ Ltd monthly average prices for December 2017 (Tolan, 2018). Refer to log revenue table in the appendices.

The following analysis looked at the distribution of TRV prediction error for each tree (actual – predicted). The chart below shows that majority (55%) of the trees fell within that (0-0.2 m^3) interval. This does show two trees (18, 89) that have been poorly optimised (- 1 m^3 from YTgen prediction).

This is most likely to be due to a deformity within the stems, as there was a large portion of pulp in both of these stems.

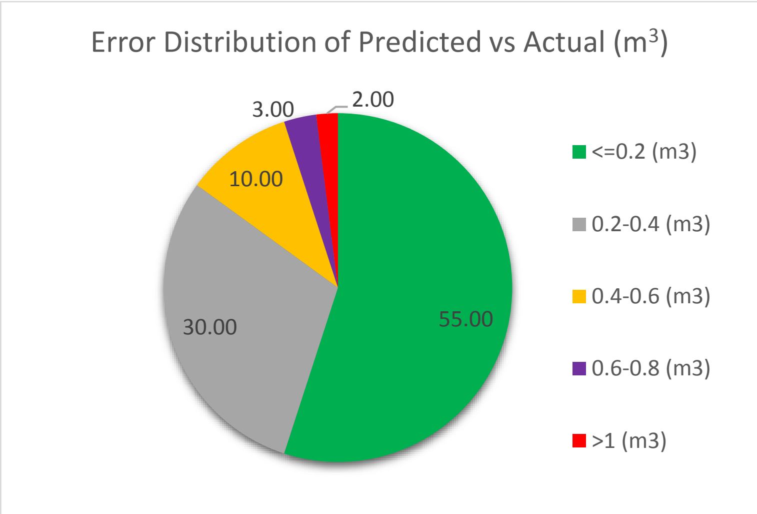


Figure 14 Prediction error by 0.2 m3 intervals

Adjusted YTgen 1 – Waratah Cutting Strategy

The Cutting strategy and priority matrix weighting values were changed to match that of the Waratah (refer to the cutting strategy table in the appendices). This saw the removal of K, M30, and S40. In theory, we would expect the predicted to be more accurate to the actual recovered volume. The total recoverable volumes for predicted and actual were found to be 153.1 m^3 and 150.1 m^3 respectively. Thus producing an overestimation of 2% and a 1.7% improvement on the base case. The grade mix of the two case remains very similar, undercut of S20 by 41.8 m^3 resulting in an overcut of M20 and KM by 25 m^3 and 14 m^3 respectively.

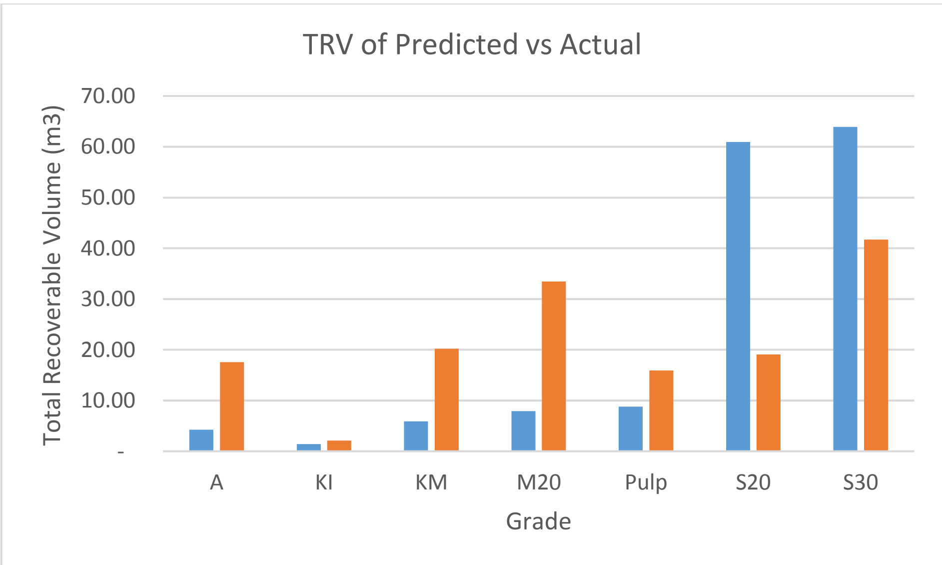


Figure 15 Adjusted Case Total recoverable volumes by log grade

It was also important to note that the operator was only cutting S20's at lengths of 6.1m due to the max supply constraint of three loads to CHH. Lengths of 4.9m and 5.5m were also listed on the cutting strategy, although they were not cut by the operator three loads was achieved by 6.1. Refer to cutting instructions and weekly production summary in the appendices.

The result of the 2% undercut in total recoverable volume resulted in an estimated revenue loss of $1,009 or 6% across the 100 stems. Although this appears to be reasonably accurate, a 6% drop in revenue across an area as vast as Maramarua is much more significant.

Adjusted YTgen 2 – Implemented Cutting Instructions

This section analyses the effect on the PHI when putting cutting instructions into YTgen, both log grades and appropriate lengths that were going to be cut. The figure below shows that this change was minimal in total recoverable volume and grade mix to the previous case. The pre-harvest inventory once again estimated total recovered volumes were 153.1 m^3 and 150.1 m^3 respectively. With an undercut of 2%. There is a 6.9 m^3 increase in the expected volume of S30 to 70.8 m^3, resulting from the additional 4.9m log included in the cutting strategy. Majority of this volume has come from the S20 grade volume, reducing 4.6 m^3 to 56.4 m^3.

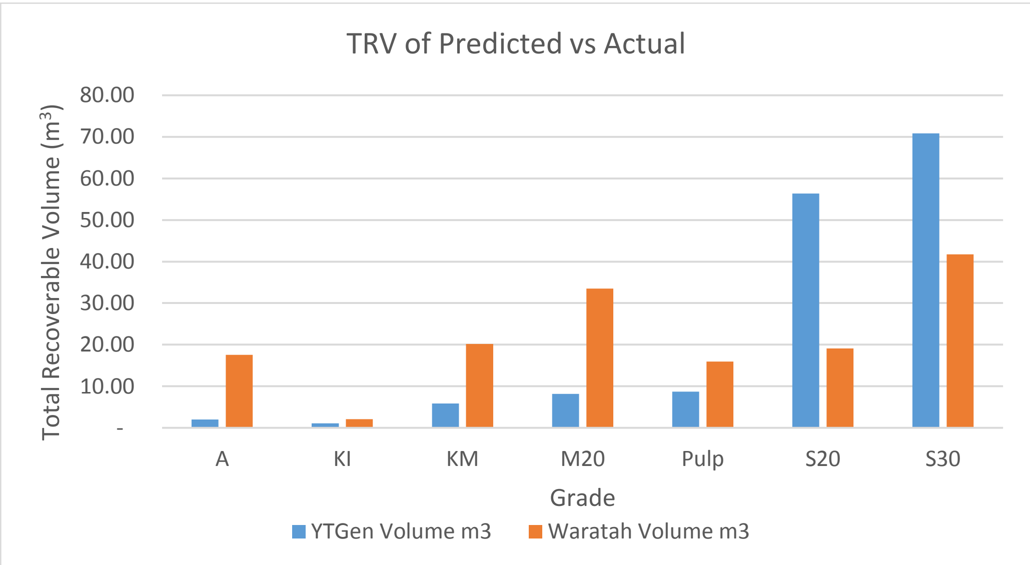


Figure 16 TRV by log grade for implementation of cutting strategy into YTgen

It was evident in the Waratah data that the operator was only cutting S20's at 6.1m lengths for an unknown reason. Although the constraint of three loads was met by the week's end, this cut-plan was deemed to be sub-optimal when compared to the length mix produced by YTgen. This is displayed figure 17 below.

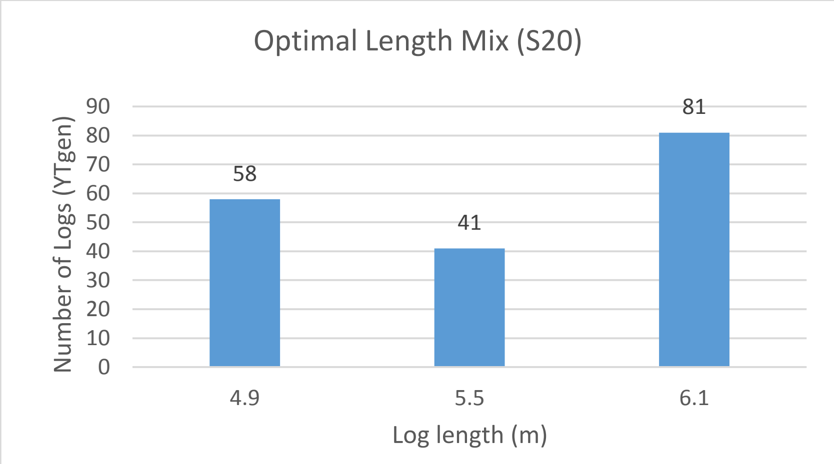


Figure 17 Frequency of Log distribution by length class for S20 logs

Influence of Head Calibration on Volume

Table 3 analyses the effect of diameter calibration error found in the head reconciliation section. This was investigated as a ratio (%) level along with an absolute (cm) level. Assuming the head error to be the average of the SED (2.13%) and DBH (7.34%) inaccuracies, the YTgen grade specifications were recalibrated to match that of the Waratah. This is shown below;

Table 2 Recalibration of grade SED specification

Grade	*Original SED specification*	*Recalibrated SED specification (+4.74%)*
A	34	35.61
KI	28	29.33
KM	16	16.76
M20	24	25.14
Pulp	10	10.47
S20	20	20.95
S30	30	31.42

The effect on the TRV remained the same with actual volume recovered falling 2% short of the predicted. The difference in revenue dropped to $783.40 or 4% as opposed to 6% for the previous case, this is to be expected by the downgrading of logs due to the increase in SED specifications. Readjusting the YTgen diameters to the average length error by (1.6 cm) altered the SED limits, this is represented in table 4 on the following page;

Table 3 Recalibration of SED's to absolute error

Grade	*Original SED specification*	*Recalibrated SED specification (+1.6 cm)*
A	34	35.6
KI	28	29.6
KM	16	17.6
M20	24	25.6
Pulp	10	11.6
S20	20	21.6
S30	30	31.6

The predicted TRV remained at 153.1 m^3 over the 100 stems under the new log specifications. However, making it 'more difficult' for logs to reach the SED requirements of each grade meant that the volume mix was influenced. The effect on volume mix is displayed in figure 18 below.

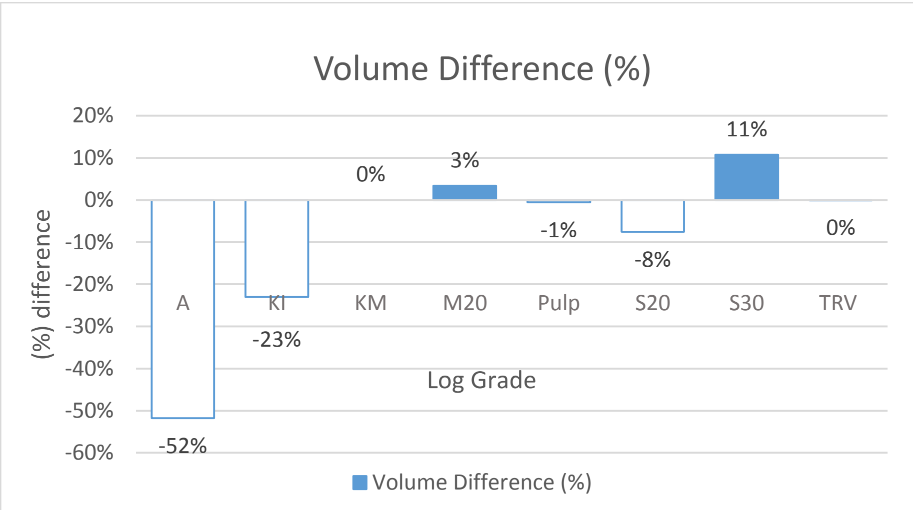


Figure 18 Volume change with a change in YTgen log specifications

As expected there was a decrease in both 'A' and 'KI' grade, due to trees now falling outside of the SED boundary. This effect appears to be great, though it is important to note the sensitivity of these grades due to the low production. Vice versa to this the impact on S20 and S30 grades seems minimal. However, due to the large production of these grades it is much more significant to the value recovery of the forest. Figure 19 on the following page shows the small end diameter class distribution of the trial data. This shows a relatively normal distribution around the (~26 cm) mean. This also displays the concentration of logs on or around the grade boundaries (dashed lines). The largest of which was within the (20-22 cm) interval (13%). This highlights both the importance of head accuracy in optimising the value of the log and provides reasoning for the large increase in S30 being cut after the changes to the YTgen cutting strategy.

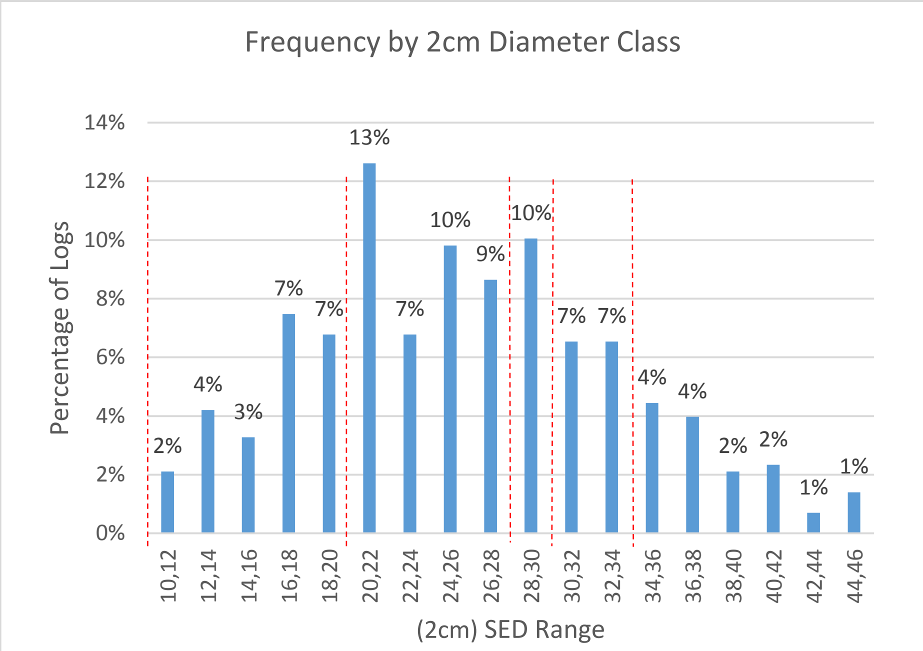


Figure 19 Distribution of logs by 2cm diameter log class

Taper Analysis

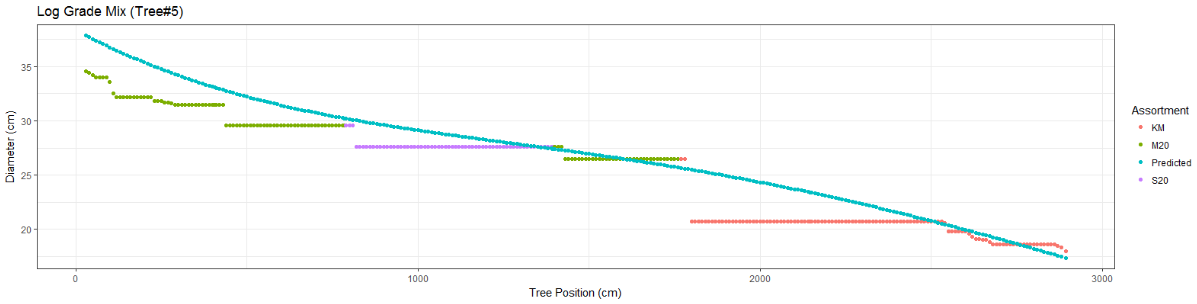


Figure 20 Taper function vs Actual taper for stem #5

Figure 20 shows the relationship between the predicted taper and the actual of stem number 5 along with the grade mix. The YTgen taper function appears to be reasonably accurate. However, it does begin to deviate as it approaches the butt of the log. It is also important to note the way diameters have been recorded in the STM file. Please refer to taper analysis in the appendices for more taper function comparisons.

The following figure compares the average Waratah taper over the 100 stems, against the YTgen taper function. This demonstrates the overall accuracy of the taper function for this particular stand of trees. The average Maramarua stem appears to be well predicted throughout the middle interval (5m-18m) however, the deviation trend is noticeable once again not only at the butt of the stem but also towards the top. The black dotted lines show diameters of particular interest (20 cm and 30 cm). At a diameter of 30 cm the taper function is accurately predicting the Waratah (*true diameter*), this is not the case at a diameter of 20 cm with an average error of approximately ~3 cm. This may cause more or fewer logs to make grade specifications, hence affecting possible yield.

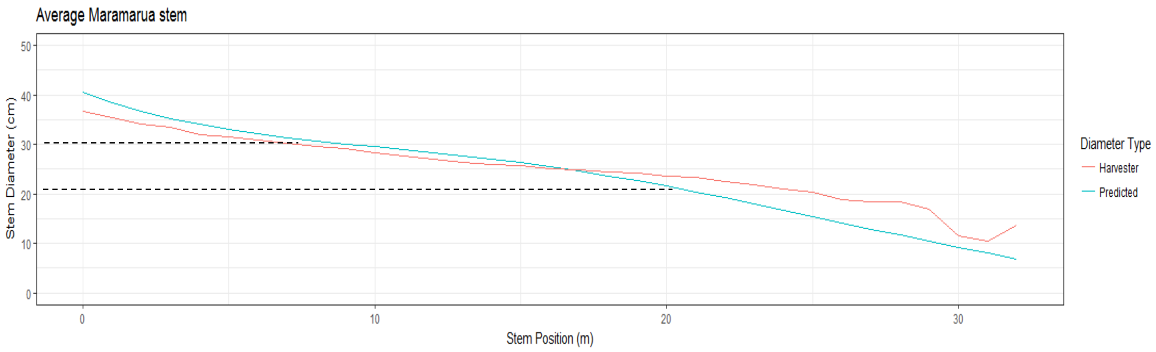


Figure 21 Taper Function Predicted vs Actual (Waratah) diameters

Figure 22 further symbolises this trend. This shows that the taper function is over predicting stem diameter at the base and over predicting at the tip. Although the average diameter error fluctuates from one end of the stem to the other, it stays within ± 2 cm of the Waratah measurements. Large variance towards the top of the stem (27m+) can be attributed to the number of stems within this height class; represented in figure 23 below. Note how variability increases as the number of stems within the height class decreases, making each data point having a more substantial influence on the error. Therefore any relationship towards the end of the stem is statistically insignificant due to the sample size 'n'.

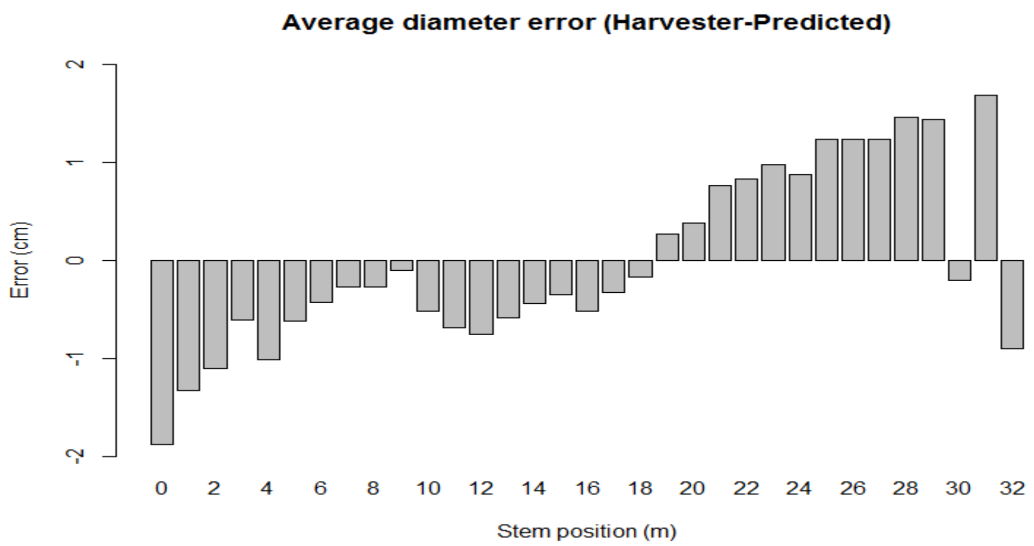


Figure 22 Diameter error along the length of the stem

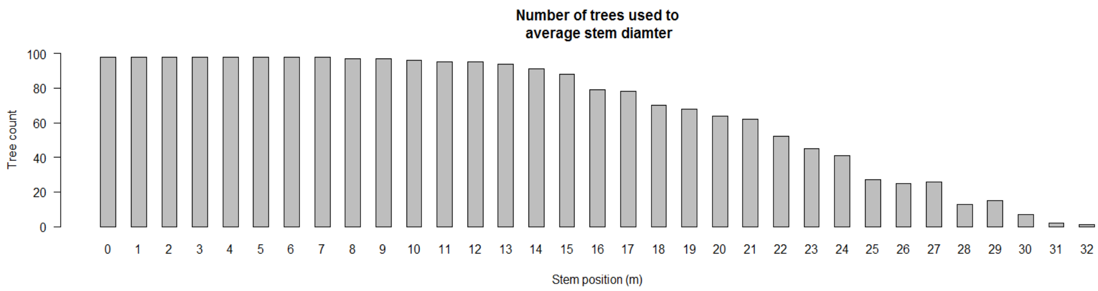


Figure 23 Number of trees within the height class

Future Possibilities and Recommendations

Inventory Data

As technology advances, so does the ability to model different management operations, and improve the integration between targeted intelligent systems (Prandi, et al., 2017). The trial used manual inventory data collection. This method is accurate for the current scale of the project, however, at a stand or estate level this method is not physically feasible nor financially viable. To allow for findings to be applied at a larger scale, alternative methods must be used for inventory collection. Light Detection and Ranging (LiDAR) is a relatively new technology that has bought forestry inventory to a new level, and its application to tree measurement and attribution is forever advancing (Wu, 2015). Using LiDAR, digital elevation models (DEM's) can be produced allowing for tree measurements to be obtained. To achieve accurate data factors such as; point cloud density, spatial resolution, interpolation and other environmental elements must be considered (Wu, 2015).

3D models can also be produced through remotely sensed data (aerial or UAV) and ground-based data (terrestrial laser scanning). Unmanned Aerial Vehicle (UAV) features such as flexibility of use in flight planning, low cost, reliability and autonomy, and capability to produce high-resolution data within limited time serve as major advantages compared to alternative options (Chiara Torresan, 2016). Through photogrammetric post-processing, UAV imagery can then be turned into Digital Surface Models (DSMs). Integration of the DSM with terrestrial data enables for a 3D model to be generated. The 3D model can be used for many purposes, for value recovery, we are particularly concerned on the predicted volume and volume by grade.

These technologies are readily available and offer scale to pre-harvest inventory that manual measurements are unable to capture. The application of these would not only apply to the Maramarua forest. The slope project (Prandi, et al., 2017) also mentioned the ability to schedule timber grade distribution to market requirements providing that the 3D model is accurate. This is symbolised in figure 24 below with the log grades represented by colour;

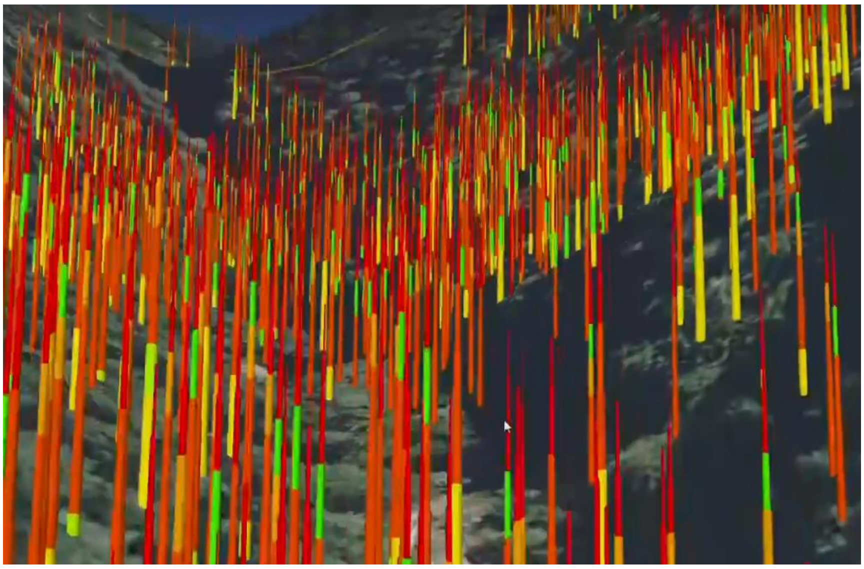


Figure 24 3D data obtained through UAV, Aerial Photography and terrestrial laser scanning

Actual Volumes

The Waratah produced a total recoverable volume error of 2% compared to the adjusted YTgen strategy. This would resemble a reasonably accurate volume recovery compared to that symbolised through recent reconciliations (2016). It is essential to note that the YTgen grade mix has been adjusted to the weekly cutting strategy. Thus highlighting the importance to update the yield table generator to the relevant markets to the highest level of detail. The cutting strategy for Sale Area 604-014-01 consisted of four domestic clients and four export markets, comprising nine log grades. Therefore through the integration of both Pre-harvest inventory and surrounding markets, we can identify relevant and irrelevant log grades along with supply constraints to the forest. Figure 25 below displays the distribution of markets for the Maramarua forest;

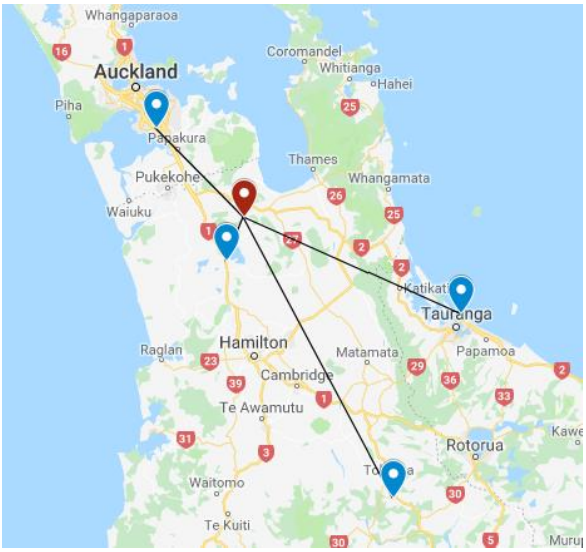


Figure 25 Map of Client distribution from Maramarua forest (red)

Mapping of Value Recovery

When harvesters are equipped with a Global Navigation Satellite System (GNSS) receiver, the STM file of the tree includes a location reference and a time stamp (Farias, 2016). This enables stem details to be extracted to a certain location. This is achieved through the Inverse distance weighted (IDW) interpolation tool within ArcMap. The IDW tool determines raster cell values using a linearly weighted combination of point data (STM files). As the GNSS receiver is based on the cab of the machine, the GPS location recorded carries a discrepancy up to the furthest boom reach of the harvester, along with accuracy of the GPS itself, *± 2.75 m* (Veal, Taylor, McDonald, McLemore, & Dunn, 2001). However, (Farias, 2016) stated that a cell size between 40 and 60 m is the most suitable to avoid noise in underlying trends, and as to be expected larger areas are better to map as they fit a larger number of points to be interpolated.

Figure 26 shown below illustrates the distribution of total recoverable volumes for *predicted volume* (YTgen) and *actual volume* (.STM file) to stem location. These locations were estimated based on the inventory data as the harvester used in the trial did not have the GPS attachment as shown in figure 26 the volume fluctuated from ~0.5 m^3 – ~4 m^3 throughout the trial area. The map shows a large amount of noise due to the small cell size, as a result of this it is difficult to identify underlying trends.

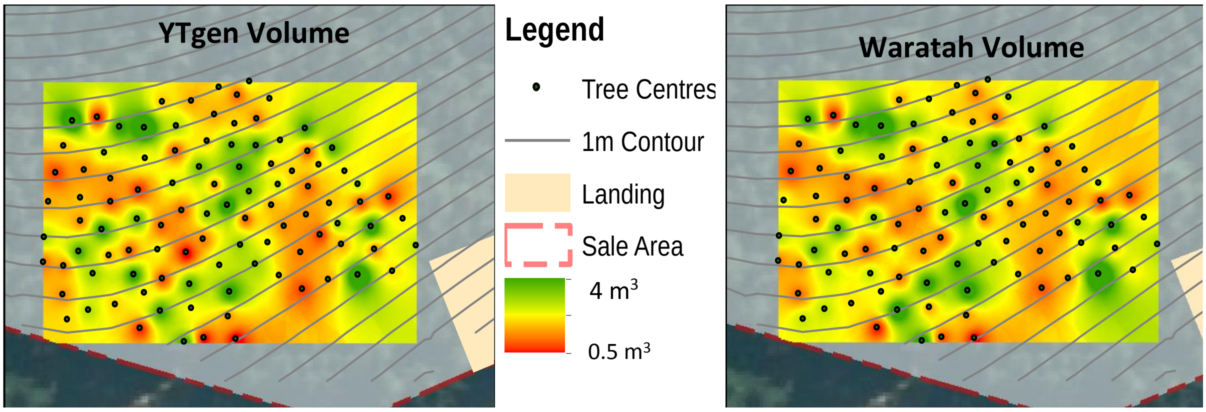


Figure 26 Distribution of total recoverable volume throughout trial area

Figure 27 better displays the effect of cell size on the raster. The figure displays interpolation to a 10 m output cell size. This enables forest managers to identify areas with high and low productivity for both predicted and actual volumes. Predicted volume distribution at a stand or estate level would help managers to schedule timber to meet market demand and ensure the best returns to stakeholders. However, this would rely heavily on the accuracy of data retrieval.

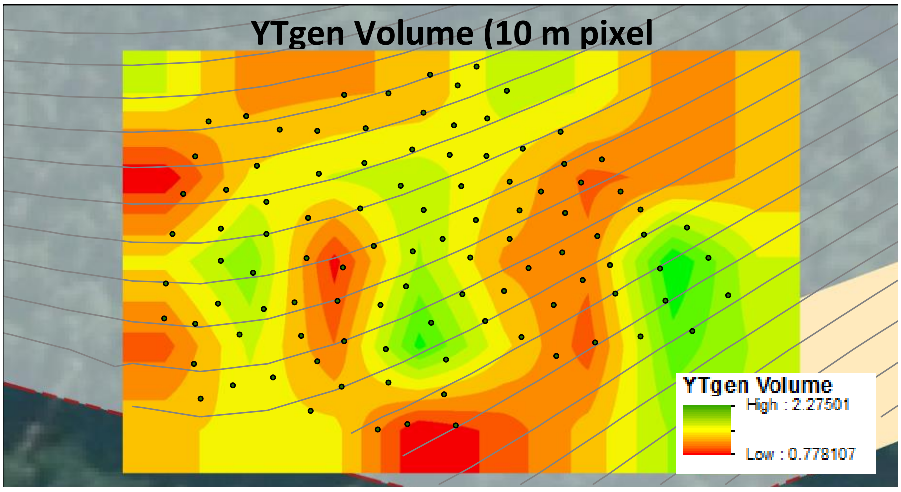


Figure 27 YTgen volume (10m pixels) distribution throughout trial area

Through the use of both *predicted* and *actual* volume distributions, the distribution of error can be calculated using the raster calculator tool within ArcGIS. This is shown below in figure 28. The distribution of error highlights areas of inaccuracy in either pre-harvest inventory or volume recovery from the Harvester. Identifying these areas at a stand level could improve finding the root cause of poor value recovery. This could be due to the slope, aspect, growing conditions, working conditions, soil quality or a number of other reasons. The distribution of poor value recovery also opens up the opportunity to plant an alternative species or revert to native, having biodiversity, environmental and social benefits. Modelling could also be achievable through sample plots. However, extrapolating could cause inaccuracies due to the large variability within a stand. As remote sensing continues to advance its role within pre-harvest inventory and value recovery could be substantial, I believe there needs to be more research in modelling of the entire forest to identify areas that yielding less than expected. Through the use of terrestrial scanning, remotely sensed data, along with the GPS attachment in the harvester, a stand raster can be produced. Similar to the map shown in figure 28.

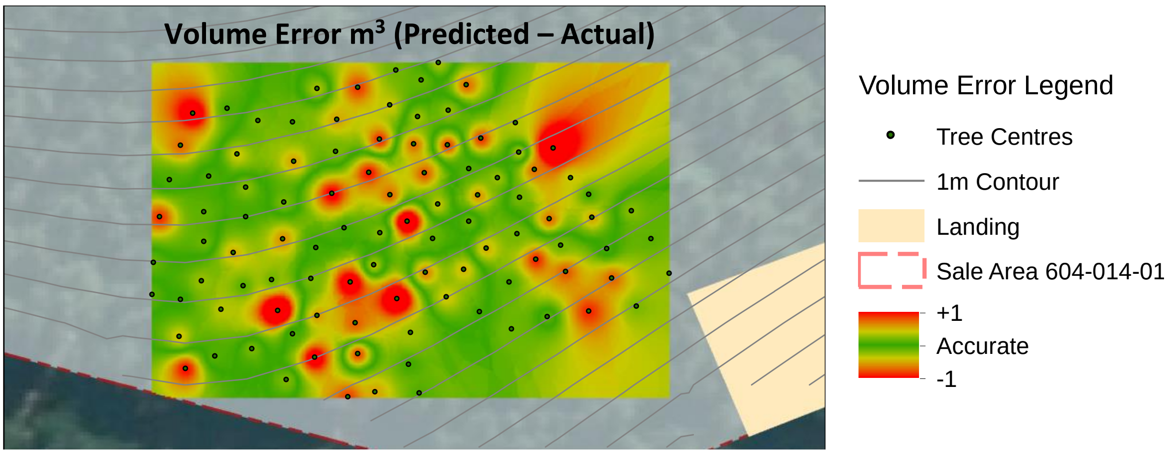


Figure 28 Distribution of error (predicted volume - actual volume)

Summary

Analysis indicated that the Waratah harvesting head was not calibrated to the standard it should have been. The Waratah showed a consistent under-prediction of approximately 1.6 cm for diameters, and the consistency of length measurements was not to Rayonier's specifications fluctuating beyond ±5cm. Consequently affecting the Waratah volume accuracy against the 3D (true) volume. Analysis of YTgen data showed that the software was accurately predicting the total recoverable volume. However, there was a significant difference in volume by log grade. This was found to be a result of the following;

- YTgen and Waratah cutting strategies correspondence
- Not including all possible grade/length combinations in cutting strategies
- YTgen priority matrix accuracy
- Supply constraints on certain grades
- Influence of head calibration for logs on grade boundaries

The Harvester was found to be cutting 60% of the predicted sawlog volume. Thus resulting in a 10% financial loss over the 100 stems. Adjusting the YTgen cutting strategy to match that of the head caused a 4% financial loss, 6% improvement on the base case. This highlights the significance of correspondence between the two cutting strategies. Further analysis on YTgen showed that the taper function was accurately predicting the vital (middle) section of the average Maramarua stem. Taper error fluctuated to a greater extent at the base and tip of the stem. Conversely the influence on log grades is less significant in these sections.

The trial produced a 2% difference between predicted and actual TRV's, significantly less than that experienced in previous sale areas. This can be partially attributed to the working environment, and pressure on operators to perform during the trial. However, this also highlights the inhomogeneous nature of a forest, and importance to model error at a stand level. For the future, I would recommend;

- Educating crews on the influence and importance of harvesting head calibration to value recovery.
- Ensure that the YTgen cutting strategy reflects the grades that are to be cut.
- Regular updates on the Waratah cutting strategy to ensure all grades and lengths match the market opportunities for the week.
- Include separate weightings for different lengths of the same grade into YTgen.
- Look into increasing sawlog customers to prevent downgrading the value of saw logs.
- Opportunity to model volume error at a larger scale to identify areas of poor recovery.

Appendices

Sale Area 604-014-01 Map

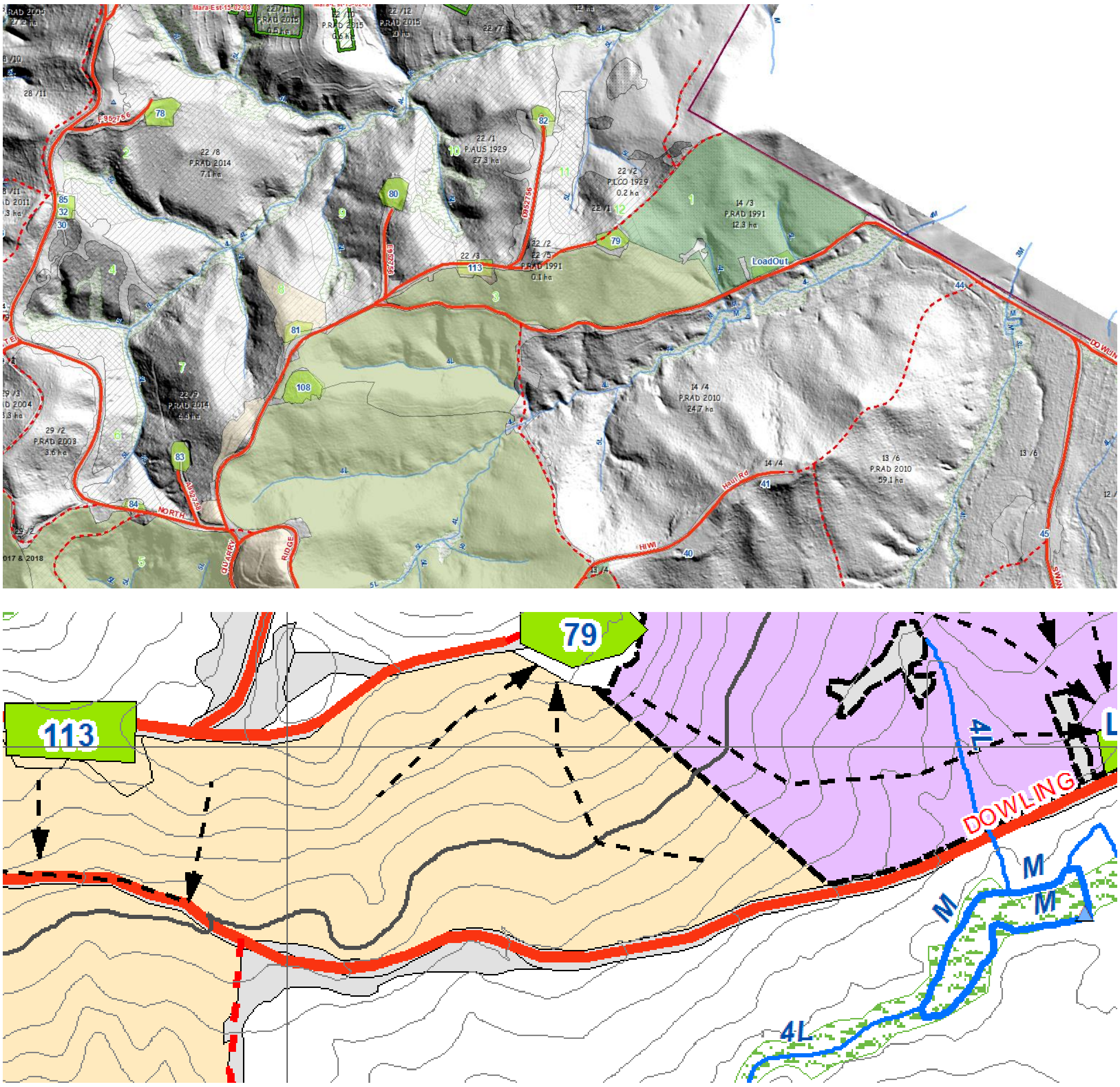


Figure 24 Map of sale area where the trial took place

Log Revenue

Table 4 Base case Revenue

Grade	YTGen Volume	Waratah Volume m3	AWG Log Price (12/2017)	YTGen Revenue	Waratah Revenue
A	2.46	17.59	$ 146.30	$ 360.62	$ 2,573.86
K	4.00		$ 134.00	$ 535.84	$ -
KI	2.87	2.09	$ 140.63	$ 403.07	$ 294.20
KM	6.62	20.22	$ 127.65	$ 845.10	$ 2,581.47
M20	2.86	33.48	$ 116.31	$ 332.21	$ 3,893.71
M30	3.33	-	$ 138.22	$ 460.11	$ -
Pulp	8.60	15.93	$ 52.93	$ 455.21	$ 843.17
S20	51.03	19.10	$ 126.17	$ 6,438.28	$ 2,409.22
S30	53.91	41.71	$ 132.96	$ 7,167.87	$ 5,545.89
S40	20.06	-	$ 150.00	$ 3,008.45	$ -
			total	$ 20,006.75	$ 18,141.52

Table 5 Adjusted case Revenue

Grad	TGen Volume (	Waratah Volume (m	AWG Log Price (12/2017	YTGen Revenue	Waratah Revenue
A	4.26	17.59	$ 146.30	$ 623.34	$ 2,573.86
KI	1.42	2.09	$ 140.63	$ 199.90	$ 294.20
KM	5.89	20.22	$ 127.65	$ 751.77	$ 2,581.47
M20	7.92	33.48	$ 116.31	$ 921.69	$ 3,893.71
Pulp	8.77	15.93	$ 52.93	$ 464.09	$ 843.17
S20	60.93	19.10	$ 126.17	$ 7,687.74	$ 2,409.22
S30	63.94	41.71	$ 132.96	$ 8,502.11	$ 5,545.89
			total	$ 19,150.64	$ 18,141.52

Table 6 Export Log Prices (December 2017)

Sale Month:	Dec-17				Financial Month	Dec-17						Freight Point	Tauranga Su
Korea CFR		P 3.6m	AO 3.6m	A 5.4m	A 3.6m	K 7.3m	K 5.1m	K 3.6m	KM 3.6m	KI 3.6/4.0m	KI 3.0m		KIO 3.6/3.9m
CFR Price	**US$/JAS**	**190.00**	**142.00**	**139.00**	**139.00**	**136.00**	**134.00**	**134.00**	**126.00**	**129.00**	**124.00**	**0.00**	**134.00**
Freight	US$/JAS	25.50	25.50	25.50	25.50	25.50	25.50	25.50	25.50	25.50	25.50	25.50	25.50
FOB Price	US$/JAS	164.50	116.50	113.50	113.50	110.50	108.50	108.50	100.50	103.50	98.50	0.00	108.50
Exchange Rate	US$/NZ$	0.6923	0.6923	0.6923	0.6923	0.6923	0.6923	0.6923	0.6923	0.6923	0.6923	0.6923	0.6923
FOB	NZ$/JAS	237.61	168.28	163.95	163.95	159.61	156.72	156.72	145.17	149.50	142.28	0.00	156.72
Forest Growers Levy	NZ$/JAS	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Port Cost	NZ$/JAS	28.75	13.25	13.25	13.25	13.25	13.25	13.25	13.25	13.25	13.25	13.25	13.25
Rayonier Fee	NZ$/JAS	10.01	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
AWG	**NZ$/JAS**	**198.58**	**150.76**	**146.43**	**146.43**	**142.09**	**139.20**	**139.20**	**127.65**	**131.98**	**124.76**	**0.00**	**139.20**

Table 7 Domestic Log Prices (December 2017)

Fiscal year/period	001.2017	002.2017	003.2017	004.2017	005.2017	006.2017	007.2017	008.2017	009.2017	010.2017	011.2017	012.2017	**Overall Result**
Market Type	Domestic	Domestic	Domestic	Domestic	Domestic	Domestic	Domestic	Domestic	Domestic	Domestic	Domestic	Domestic	
Product	NZD / TON	NZD / TON	NZD / TON	NZD / TON	NZD / TON	NZD / TON	NZD / TON	NZD / TON	NZD / TON	NZD / TON	NZD / TON	NZD / TON	**NZD / TON**
A30	60.00												**60.00**
L20			110.00										**110.00**
L30	92.34	92.76	90.97	93.78	93.95	86.37	90.98						**91.79**
M20	102.95	102.93	102.37	103.91	103.29	103.57	113.27	114.00	113.75	113.92	114.59	116.31	**109.99**
M25	94.58	97.16	99.17	100.89	101.74	101.74	102.32						**100.21**
M30	114.95	114.94	114.04	112.87	115.36	113.79	114.27	120.73	121.86	123.69	129.99	138.22	**116.71**
P35	184.42	186.85	186.17	191.93	189.75	190.98	190.32	191.75	190.87	190.76	189.58	188.24	**189.36**
PP35		140.00	140.00	140.00	140.00	140.00	140.00						**140.00**
R10									104.00	104.00	104.00		**104.00**
S20	116.87	117.24	115.78	121.92	120.85	125.76	126.03	125.93	122.17	127.63	130.53	126.17	**123.23**
S25					118.00	118.00	118.00	121.74	119.18	124.00	124.00	124.00	**120.70**
S30	125.17	124.22	125.33	128.79	130.28	129.45	128.84	129.14	128.50	133.73	133.54	132.96	**129.25**
S35		138.00	138.00		147.42	148.00	148.00	148.00	148.00	150.00	150.00	150.00	**148.39**
UA	51.88	52.02	50.84	51.56	52.03	53.40	51.40	49.05	48.06	49.61	50.61	52.58	**50.40**
UAS			44.00										**44.00**
UC	46.25	46.71	45.24	46.46	46.78	47.45	46.36	0.00	44.73	45.62	46.08	47.93	**46.49**
UH	77.00	77.00											**77.00**
UH	53.50	54.23	52.99	52.57	53.72	55.26	52.01	48.72	48.40	49.38	50.65	53.28	**51.52**

Waratah Cutting Strategy

Table 8 Waratah Cutting strategy matched to YTgen for case # 2

S30 (10)

Length (cm)	290	300	310	320	350	380	400	450	500	550
600	840	840	840	840	840	840	840	840	840	840

S20 (10)

Length (cm)	190	200	210	220	250	290	300	310	350	400
480	700	700	700	700	700	700	700	700	700	700
540	715	715	715	715	715	715	715	715	715	715
600	740	740	740	740	740	740	740	740	740	740

A (14)

Length (cm)	320	340	350	400	450	500	550	600
360	520	520	520	520	520	520	520	520
510	560	560	560	560	560	560	560	560

M20 (10)

Length (cm)	220	230	240	260	280	300	320	340	360	380
384	300	300	300	300	300	300	300	300	300	300

KI (14)

Length (cm)	280	300	350	400	450	500	600
360	210	210	210	210	210	210	210

UH (10)

Column1	290	300	340	350	400	450	500	550
290	20	20	20	20	20	20	20	20
390	20	20	20	20	20	20	20	20
490	20	20	20	20	20	20	20	20
590	20	20	20	20	20	20	20	20
690	20	20	20	20	20	20	20	20
790	20	20	20	20	20	20	20	20

UA (10)

Length (cm)	90	100	110	120	150	200	250	300	350
290	10	10	10	10	10	10	10	10	10
390	10	10	10	10	10	10	10	10	10
490	10	10	10	10	10	10	10	10	10
590	10	10	10	10	10	10	10	10	10
690	10	10	10	10	10	10	10	10	10
790	10	10	10	10	10	10	10	10	10

Cutting Instructions and STICKS file

Table 9 Cutting instructions for week beginning 11/12/2017

Docket Grade	Lengths	SED	LED	Knot	Customer	Destination	Stencil	Priority	Loads
S30	6.1	30	80	7cm	Max Birt	Pokeno	S30		
S25	6.1	25-30	80	7cm	Max Birt	Pokeno	S		
S20 RL	4.9/5.5/6.1	20	42	7cm	CHH FORT	FORT	S20	Max	3
A	3.74	34	70	10cm	Export	PRTMTM	A		
M20	3.77	24	40	10cm	Big Tuff Pallets	Manukau	M20		
K	3.74	24	50	10cm	Export	PRTMTM	K		
KM	3.74	16	30	10cm	Export	PRTMTM	KM or K		
KI	3.74	28-60	U/L	20cm	Export	PRTMTM	KI		
UA	3.0 - 8.0	10	40	U/L	OJI Kinleith	Kinleith	Gang #		

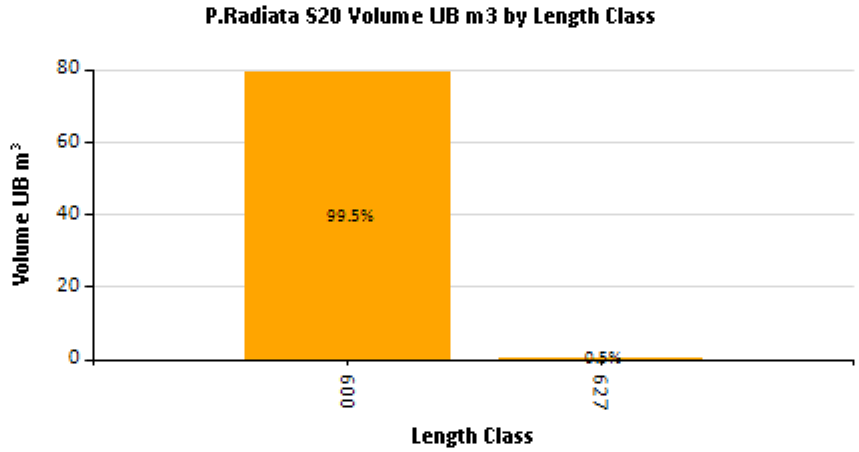
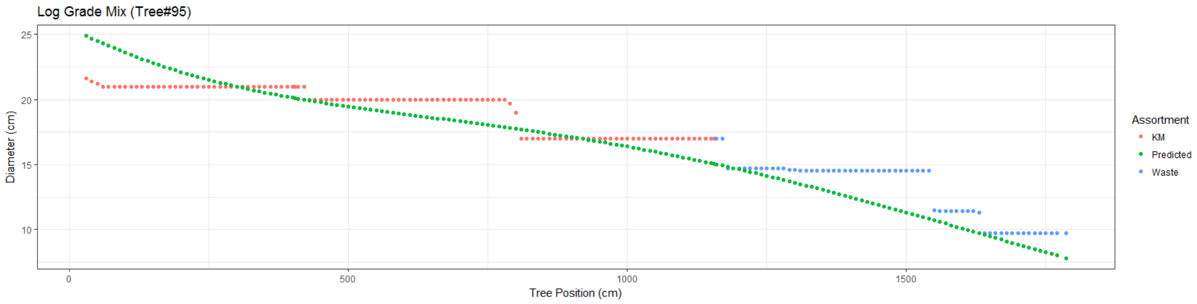
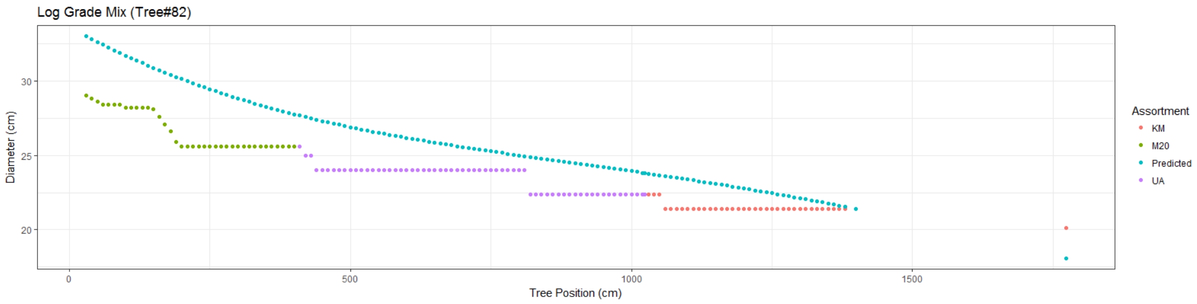
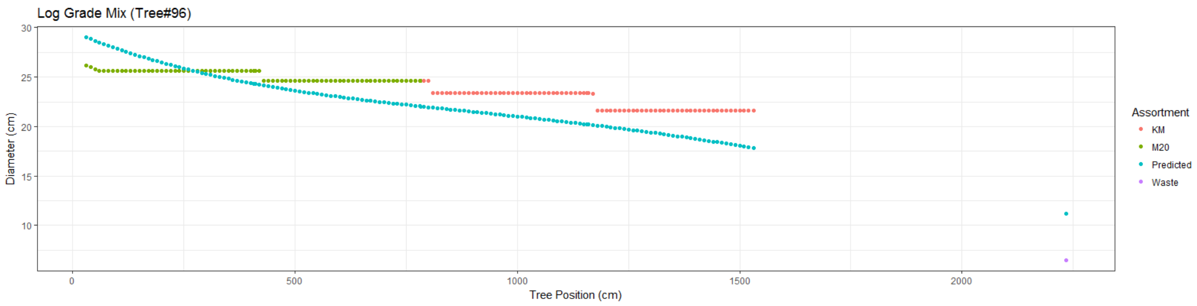


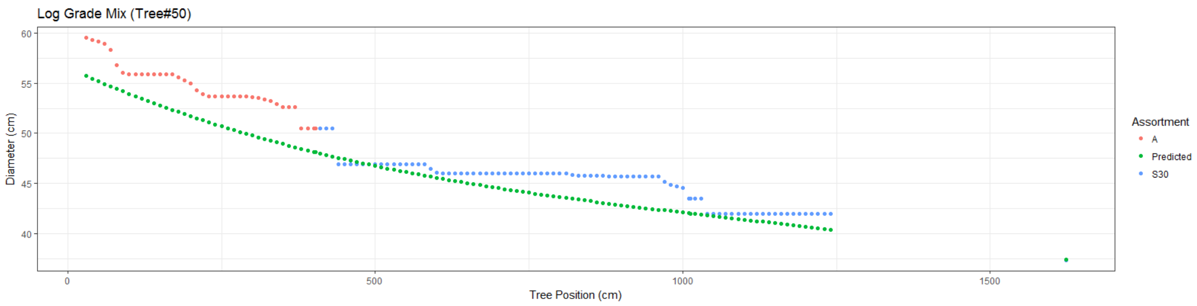
Figure 25 Volume of S20 cut (week beginning 11/12/2017)

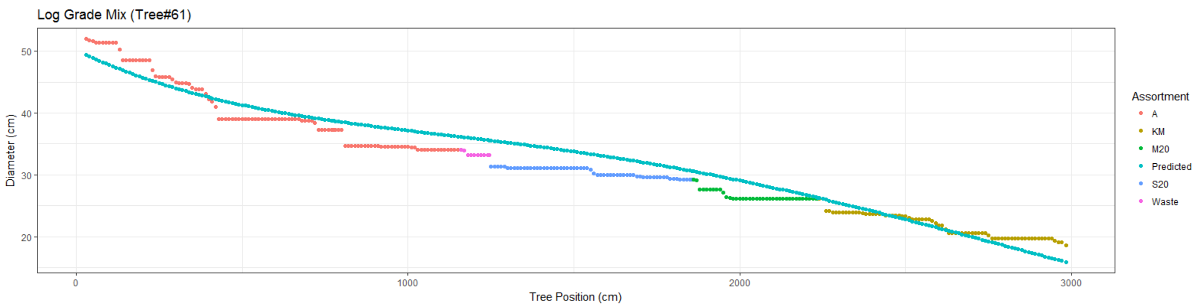
Taper Function Predictions











Taper Function Code

```
stems <- read.csv('Stems.csv')
logs <- read.csv("Logs.csv")
sections <- read.csv('Sections.csv')

sections$StemLength <- stems$EndHeightcm[match(sections$StemNo,stems$StemNo)]

#Create Diameter Position Classes (1m Classes)
#This may need to be extended if trees are larger than 35m
#Lines were writen using excel to auto fill in values.
sections$DPClass[sections$DiamPos<100]<- "0"
sections$DPClass[sections$DiamPos>=100&sections$DiamPos<200]<- "100"
sections$DPClass[sections$DiamPos>=200&sections$DiamPos<300]<- "200"
sections$DPClass[sections$DiamPos>=300&sections$DiamPos<400]<- "300"
#Volume function 118
b1 <- 0
b2 <- 0.25934
b3 <- 0
b4 <- 0.00134
b5 <- 0
#Tree volume formula
stems$PredTreeVol <- (b2*((stems$InDBH/10)^2)*stems$InHeight/10000)+(b4*stems$InHeight)

#Predicted Diamter along stem
sections$PredTreeVol <- stems$PredTreeVol[match(sections$StemNo,stems$StemNo)]
sections$DiamPosTree <- sections$DiamPos+30
sections$TFX <- ((sections$TreeHeight-(sections$DiamPosTree/100))/sections$TreeHeight)

# Taper calculaton
#Taper function 115
c1 <- 1.1714
c2 <- -3.5452
c3 <- 26.708
c4 <- -44.31
c5 <- 22.686
c6 <- 0
c7 <- 0
c8 <- 0
c9 <- 0
k <- 0.00007854
#Taper volume formula
sections$PredDiam <- sqrt((sections$PredTreeVol/(k*sections$TreeHeight))*
                            (c1*sections$TFX+c2*sections$TFX^2+c3*sections$TFX^3+c4*
                               sections$TFX^4+c5*sections$TFX^5+c6*sections$TFX^c7))


sections$StemNo <- as.factor(sections$StemNo)
sections$HDiamCM <- sections$DiamUBmm/10
sections$error <- (sections$HDiamCM-sections$PredDiam)
library(ggplot2)
#Graph of errors by tree
ggplot(sections,aes(DiamPosTree/100))+
  geom_point(aes(y=error,colour=StemNo))+
  ylab("Error (cm)")+ xlab("Stem position (m)") +
  ylim(-20,20)+
  ggtitle("Stem diameter error (Harvester-Predicted)")+
  theme_bw()

#Same as above but without the colours but a 0 line
GPlot1 <- ggplot(sections,aes(DiamPosTree/100))+
  geom_point(aes(y=error))+
  ylab("Error (cm)")+ xlab("Stem position (m)") +
  ylim(-20,20) +
```

```
#Graph of harvester vs predicted with a line with slope of 1
GPlot2 <- ggplot(sections,aes(HDiamCM))+
  geom_point(aes(y=PredDiam))+
  ylab("Predicted diameter") + xlab("Harvester diameter") +
  ggtitle("Predicted vs Measured Diameters")+
  theme_bw()
GPlot2 + geom_abline(intercept = 0,slope = 1,colour = "Red",size = 1.5)

library(plyr)
sections2 <- na.omit(sections)
sections2$DPClass <- as.numeric(sections2$DPClass)
sections2 <- sections2[order(sections2$DPClass),]

attach(sections2)
#Graph of average error along stem
#(the values @ stem positon <28 or so are unreliable due to small sample size)
barplot(tapply(error,DPClass/100,mean),
        ylim=c(-2,2),
        ylab="Error (cm)",
        xlab="Stem position (m)",
        main="Average diameter error (Harvester-Predicted)")
detach(sections2)

#gives you the values of the errors
ddply(sections2,.(DPClass),summarise,Error=mean(error))

#The "Average" Maramarua Tree
library(plyr)
BelTree <- ddply(sections,.(DPClass),summarise,Diameter=mean(DiamUBmm),SD=sd(DiamUBmm),IQR=IQR(DiamUBmm))
BelTree$DPClass <- as.numeric(BelTree$DPClass)
BelTree$Height <- mean(stems[["InHeight"]])
IQR(BelTree$Diameter)


BelTree$DBH <- mean(stems[["InDBH"]],na.rm=T)
BelTree$DBH <- BelTree$DBH/10


#Tree volume calculation
#Volume function 118
b1 <- 0
b2 <- 0.25934
b3 <- 0
b4 <- 0.00134
b5 <- 0
#Tree volume formula
BelTree$PredTreeVol <- (b2*(BelTree$DBH^2)*BelTree$Height/10000)+(b4*BelTree$Height)
```

```
#Predicted Diamter along stem
BelTree$DiamPosTree <- BelTree$DPClass+30
BelTree$TFX <- ((BelTree$Height-(BelTree$DPClass/100))/BelTree$Height)
#Taper calculator
#Coefficients which will change according to forest
#Taper function 115
c1 <- 1.1714
c2 <- -3.5452
c3 <- 26.708
c4 <- -44.31
c5 <- 22.686
c6 <- 0
c7 <- 0
c8 <- 0
c9 <- 0
k <- 0.00007854
#Taper volume formula
BelTree$Predicted <- sqrt((BelTree$PredTreeVol/(k*BelTree$Height))*
                            (c1*BelTree$TFX+c2*BelTree$TFX^2+c3*BelTree$TFX^3+c4*
                               BelTree$TFX^4+c5*BelTree$TFX^5+c6*BelTree$TFX^c7))
BelTree$error <- BelTree$Diameter/10-BelTree$PredDiam
BelTree$Harvester <- as.numeric(BelTree$Diameter)



ggplot(BelTree,aes(DPClass/100))+
  geom_point(aes(y=Predicted,colour="Predicted")) +
  geom_point(aes(y=Harvester/10,colour="Harvester")) +
  ylim(0,50) +
  xlab("Stem Position (m)") + ylab("Stem Diameter (cm)") +
  ggtitle("Average Maramarua stem") +
  scale_color_discrete(name="Diameter Type") +
  theme_bw()
```

References

Barrington, M. (2018, August 16). Lessons from Tolaga Bay erosion disaster. *New Zealand Herald*.

Bloomberg, M. (2018). Environmental Interactions in Forestry : Soil Erosion. Christchurch, Canterbury.

Charlotte, B. (2018). New Zealand, Canterbury.

Crawley, D. (May 2007). Measuring radiata pine and forecasting yields. *New Zealand Tree Grower*.

Dick, A. (2005). Log value recovery in a woodlot context. *New Zealand Tree Grower*.

Dunlop , J. (1995). Permanent Sample Plot System (User Manual). *New Zealand Forest Research Institute Ltd, FRI Bulletin No. 187.*

Ellis, J. C. (1993). Measurement of roundwood in New Zealand. *Ministry of Forestry Statistical release*, 16-20.

Gordon , A. T., Wakelin, S. J., & John , A. T. (November 2005). *Using Measured and Modelled Wood Quality Information to Optimise Harvest Scheduling and Log Allocation Decisions.* Rotorua, New Zealand: ATLAS technology.

Herries, D. (2018). *Plotsafe* . Retrieved from Interpine Innovation : http://www.interpine.nz/plotsafe/

Kilkki , P., Saramaki, M., & Varmola , M. (1984). *A simultaneous equation model to determine taper curve.* Silva Fennica.

Leitner, T., Visser, R., & Stampfer, K. (2014). Analysing log length measurement accuracy of harveter and processor heads. *Austrian Journal of Forest Science 131*, 129-146.

Marchi, E., Visser, R., Chung, W., Abbas, D., Nordfjell, T., Mederski, P. S., . . . Laschi, A. (2018). *Sustainable Forest Operations (SFO): A new paradigm in a changing world and climate.*

Marshall , H., & Murphy , G. (2004). *Econoic Evaluation of Implementing Improved Stem Scanning Systes on Mechanical Harvesters/Processors.* Corvallis, Oregon, USA: Oregon State University.

NZFOA. (2007). *New Zealand Environmental Code of Practice for Plantation Forestry.* New Zealand: FITEC.

Powrie, J. (2017). *What is Forest Value Recovery?* Retrieved from Forest Value Recovery: http://www.forestvaluerecovery.com/

Prandi, F., Magliocchetti , D., Poveda , A., Andreolli, M., Devigili, F., & De Amicis, R. (2017). *Project Overview.* Retrieved from Slope Project.

Roth, G. (28/7/2016). *StanForD as a data source for forest management: a dorest stand reconciliation implementation case study.* Canterbury: Geotz Roth.

Saathof, D. A. (2014). *An Investigation of the Measurement Accuracy and Productivity of a Waratah HTH 625c Processor Head.* University of Canterbury .

Sabatia, C. O. (20 August 2016). *Use of upper stem diameters in a polynomial taper equation for New Zealand radiata pine: an evaluation.* New Zealand Journal of Forestry Science.

Silcock, P. (May 2007). *Rationalisation of volume.* Plantation Management Cooperative.

Strandgard, M. |. (2012). Accessing measurement accuracy of harvester heads in Australian Pine Plantations. In M. |. Strandgard. Retrieved from Cooperative Research Centre for Forestry.

Thomas Leitner, R. V. (2014). Analysing log length measurement accuracy of harvester and processor heads. *Austrian Journal of Forest Science*, 129-146.

Tolan, A. (2018, 1 18). 2015-2016 Maramarua Reconciliation .

Xialou, T., Perez-Cruzado, C., Fehrmann, L., Álvarez-González, J. G., Lu, Y., & Kleinn, C. (Jan 22 2016). *Development of a Compatible Taper Function and Stand-Level Merchantable Volume Model for Chinese Fir Plantation.* PLoS One.