Master's Thesis

StanForD as a data source for forest management: a forest stand reconciliation implementation case study

Author: Goetz Roth

This thesis is submitted as part of the requirements for the Degree of Master of Forest Science at the School of Forestry, University of Canterbury

Primary Supervisor: Prof Dr. Rien Visser

Assistant Supervisor: Prof Dr. Glen Murphy

Date: 28 July 2016

Abstract

The New Zealand forest industry is in a state of change from motor-manual chainsaw processing towards fully mechanised harvesting operations. This is driven predominately by changes in the health and safety legislation and increased efficiency targets. Through the use of advance harvesting machinery with built in computer systems and standardised compatible data collection software (called StanForD), all mechanised processing operations are able to produce near real-time production data. This data stream enables forest management to work with datasets containing detailed information of all harvesting production. StanForD data will therefore enable the development of new ways of forest management.

The study objective was to research the use of StanForD data in a forest stand reconciliation scenario. StanForD production volumes were compared against a weight docketing system and inventory yield predictions on four harvesting sites. These studies were conducted in a clearfell harvesting crew with an experienced harvester operator over the duration of approximately one year.

The data collection included all relevant production files from the harvester; .PRI (production data), APT (harvester cutting instruction) and KTR (harvester head calibration data) files. The forest management company supplied load delivery dockets, conversion factors and inventory data. The inventory data was processed to estimate the yields of the harvested stands. PLE[1] ($p \leq 0.05$) boundaries by grade group and total volume were calculated. The estimated yields with its PLE boundaries were compared against the volume recorded by the harvester and the data retrieved via the docketing system.

The results show the harvester data, when compared with the inventory data, was within the PLE limits for seven out of 15 grade groups. Small utility was the only grade correctly predicted at all sites. Pulp wood hasn't been predicted correctly at any site in comparison to the harvester data. The docket data was for five out of 15 grade groups within the PLE limits. For the total volume the harvester data was two out three sites within the PLE limits. The docket data failed on all three sites to be within the PLE boundaries on total volume. These results show both reconciliation methods, docketing system and harvester data based system have failed to confirm the yield predictions repetitively.

Comparison of the harvester data against the docketing data, showed the harvester had lower recorded volumes for pulp, export pulp and an systematic over-measurement for the higher grades compared to the docket data at all sites. Subsequent to data collection, the reason for the lower harvester volume measurements on the lower quality grades was identified to be operators not correctly recording harvest data. As possible causes for the over measurement, missing bark function and the use of estate wide conversion factors were identified. The study showed higher grades, despite the schematic differences, were recorded more accurately than lower quality grades.

Taking all results in account, using harvester data remains a valuable data source for the future; especially for aspects such as reconciliation. More emphasis on operator training on the harvester computers systems is likely to increase the data quality collected by the harvester.

(PLE – Proximate Limits of Error)[1] PLE refers to the confidence limits expressed as a percentage of the estimated Mean. E.g. a PLE of 10% at 95% probability level implies that the true mean is likely to lie within 10% of the

Acknowledgement

I'd like to thank Interpine Group Ltd for supporting my studies and enable me to travel to Europe to visit different StanForD users including SkogForsk to learn more about the use of StanForD internationally. Many thanks go to Jeremy Gibson and his company Forest PHD for letting me use the STICKS software suit to analyse my datasets and I would also like to thank Jeremy directly for answering all my questions. Furthermore I thank my supervisors Dr. Rien Visser and Dr. Glen Murphy for their advice.

Table of Contents

Table of Figures

List of Tables

1. Introduction

The focus of this master's thesis is on an evaluation of the commercial use of data collected from harvesting machines (using StanForD – **Sta**ndard for **For**est and **D**ata Communication) in the New Zealand forest industry as well as assessment of what is the status quo in regards to On-Board Computer (OBC) setup and optimizer use. The New Zealand forest industry is in a state of change from manual processing with chainsaws towards fully mechanised harvesting operations, driven predominately by changes in the health and safety legislation and increased efficiency targets. Interest in the possibility of capturing data from mechanised harvesting operations has therefore increased rapidly over the last few years. However there is no history around the use of StanForD data as a data source within the New Zealand forest industry (Geerkens, 2010). Attempts to incorporate such data into business terminated early because of a lack of knowledge around StanForD, slow delivery of files and lack of trust in the accuracy of the data.

Currently some forest companies, having moved to mechanised processing, are willing to evaluate the implementation of StanForD based analysis systems as part of their business processes. The reasons for doing so are diverse and range from managing value recovery, a production monitoring and woodflow planning, and using the data for forest stand reconciliation. While no information on successful integration of StanForD data into a New Zealand forestry business exists, in Australia Hancock Victoria Plantation (HVP) has implemented the use of the daily delivered harvesting data from their mechanised operations into their woodflow planning system.

StanForD was developed and continues to be maintained by SkogForsk in Sweden (SkogForsk, 2014). Baar (2006) comprehensively described how a successful implementation of the "Scandinavia Model" - meaning the use of harvesting data along the wood supply chain - could be implemented into a Radiata pine regime in Australia (Barr, 2006).

Another setup, whereby the StanForD data is part of the daily business routine, is that developed by the company SDC in Sweden (SDC, 2015). The company is Sweden's independent forestry data hub for the industry. It publishes electronic cutting lists for the contractor and collects electronic production files, it therefore manages the woodflow across several entities entirely based on the StanForD data.

This study evaluated the feasibility of using StanForD data in a harvesting production environment within a New Zealand forest company. Specifically, the study undertook research on the use of StanForD data for harvest stand reconciliation. Four harvesting sites were studied. The data collected from the harvesters' On-Board-Computer (OBC) system were compared against two other sets of data; (1) data obtained via the company's reconciliation methods based on pre-harvest yield analyses ,and (2) analysis of docket information on the harvest stand level. The study also investigated potential issues and problems that might delay or prevent usage of harvester data in New Zealand radiata pine (*Pinus radiata* D.Don) plantation forest management.

1.2 Literature Review

There is no standardised methodology for a forest harvest stand reconciliation available that is used nationwide. The general approach for a reconciliation of a pre-harvest inventory yield analysis against the load docket system (including the breakdown by grade or aggregated grade groups) is common practice, but the exact forest stand reconciliation process will differ slightly from company to company. This literature review therefore illustrates the current sources of data in use to reconcile harvest stands, touches on the history and the developments of StanForD and reviews previous work around StanForD as a data source for research. It also highlights the newest findings around harvester head measurement accuracy, an important aspect of data integrity.

1.3 StanForD File Format

The **St**andard for **For**est machine **D**ata and Communication was developed in the late 80's by Skogforsk, the forestry research institute of Sweden. Its development continues to be supported by an international panel of forestry companies and manufacturers (SkogForsk, 2014). StanForD is today the quasi standard for all forest harvesting computers around the world. Since 2012 the "classic" standard with its text based encoding has stopped being further developed. The replacement is the newer file format *StanForD2010* (SkogForsk, 2014). The main difference between the two formats is the move from text encoding to an .xml format. There are only a few StanForD2010 compliant machines working in New Zealand forests today. All machines used as part of this project were running the "classic" StanForD system. All discussion from this point on in the thesis relate to the classic StanForD system.

StanForD contains around twenty file types. Only five file types should be of interest to New Zealand forest managers in relation to harvesting (see also Olivera & Visser 2014 and Olivera, Visser, & Morgenroth).

.APT: The "cutting strategy", it includes price and grade matrices and builds the base information on contractor, organisation, contract, harvest data and site. Furthermore it includes settings on bark equations, color coding for log grade marking and optimization.

.PRI: The production individual file. This file records cut lengths, small end diameter, cut description volume and when equipped with a Global Navigation Satellite System (GNSS) receiver, the spatial coordinates of the cut log products.

.PRD: The production file gives a summary of the log count and the volume grade mix. The file doesn't record individual logs.

.STM: In addition to the information in the .PRI files includes all harvester head diameter measurements down the stem in 10cm intervals for each log.

.KTR: A .KTR file records all calibration and control checks executed on to the harvester head. All files include a timestamp and calibration result. The file can be crucial to processor head accuracy.

This study was conducted using .APT, .PRI, .KTR files.

The idea of using the available data from mechanised harvester for woodflow planning and production analysis goes back to Scandinavia in the late 80's (Sondell, 1989). However it took two decades to progress from a vision to reality. Several milestones had to be passed on the way. In the 90's the data was still only used for controlling the bucking optimization. Development changed from the year 2000 and the use of the harvesting data in a production environment for planning and logistics started to became reality, finally leading to a widely accepted planning tool within the Scandinavian forestry (Moeller, Arlinger, Hannrup, Larsson, & Barth, 2011).

The data captured by the harvester and used for business decisions has almost entirely been part of company internal projects. There is no official literature available on the use of the data for reconciliation of the stand volume estimates against a pre harvest inventory analyses in a harvesting production environment. Neither has there been a reconciliation of the harvester data against the load dockets; this requires conversion of load weights to load volumes.

Most published papers focus on a certain aspect of mechanised harvesting in regards to the data collected, for example; the economic impact of the length measurement and diameter measurement errors (Marshall, Murphy, & Boston, 2006). Published papers on the value of StanForD production data for actual forest management are rare. Walsh (2012) assesses the capability of a harvester's optimizer to increase value recovery in comparison to a machine running no optimizer. The field measurements were conducted in a closed environment with a sample size of two 100-tree plots with a full assessment of each tree. An interesting finding was the yields by product, measured by the harvester and customer weighbridges, gave a very similar result of +-5%. The study doesn't state what factors were used for the conversion of tonnes to volume at the weighbridge. The study also quantified the effect of a harvester on value recovery. The value recovery by the harvester was higher than predicted via a PHI inventory. Furthermore the study showed a small but significant improvement in value recovery when using the harvester optimiser over manual decisions making, see Figure 1. The Figure shoes the volume distribution by grade for Inventory, Control plot (harvest optimizer turned off), Simulated plot (harvest optimizer turned on). A constraint can be seen as the simulated plots are based on simulated stems files cut via a harvester simulator.

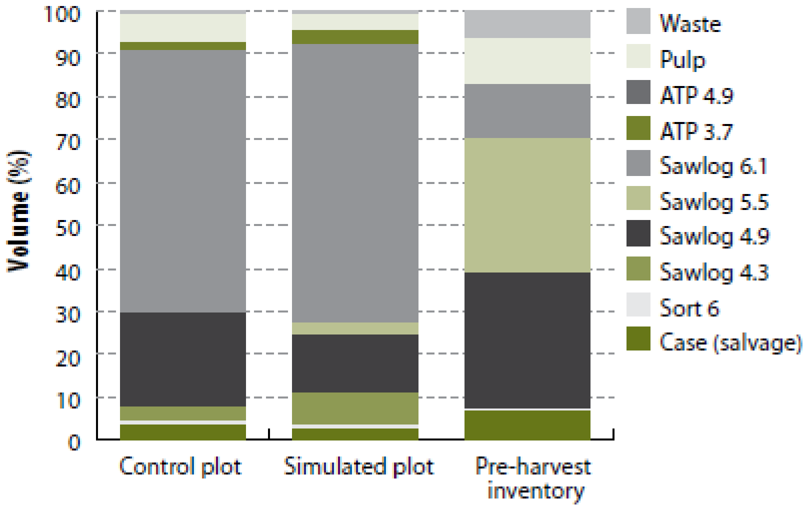


Figure 1 - Walsh, D. (2012). Quantifying the value recovery improvement using a harvester optimiser. CRC for Forestry - University of Tasmania.

1.4 Processing Head Accuracy and Calibration

When thinking about basing business decisions around the results of collected harvester data it is important to look into the measurement accuracy of a modern harvester. The measurement equipment on a processing head in New Zealand forests differs slightly between different manufacturers. All processing heads use a measuring wheel to determine length, which runs along the stem when feeding the log through the processors feed rollers. The measuring wheel is coupled to an encoder (Fig – 1) which generates a fixed number of pulses when the wheel is moving. These recordings are translated into distance (commonly 0.5cm/pulse) through an OBC (Makkonen, 2001). The start of a measurement is triggered either by a saw cut or via a find-end-sensor. Diameter measurements are taken by pulse encoders or potentiometers within the shoulder of the delimbing knives. These sensors determine the stem diameter through pulses generated according to the opening angels of the delimbing knives. The processing head makes contact with the stem at three points. Some heads even measure the deflection and include ovality in the diameter assessment (Standgard & Walsh, 2012). Both length and diameter measurements can be measured inaccurate in the field due to a number of external factors.

Length inaccuracy can be due to:

1.) Measuring wheel penetrates bark differently depending on bark hardness
2.) Stem roughness can cause measuring wheel to travel extra distance along the stem
3.) Bark slipping under the measuring wheel and therefore blocking the wheel from spinning
4.) Uneven stem shape causes measurement wheel to loose contact with the stem

Errors 1 and 2 can be counteracted through regular calibration as they are most likely due to temperature, machine maintenance or forest stand characteristics. Errors 3 and 4 can be caught by the operator if possible (FPInnovations, 2015) and immediately react and move head back to the last cut, zero the saw and reprocess the log.

Diameter inaccuracy can be due to:

1.) Wrong diameter measurement due to log ovality
2.) Bark hardness can cause the delimbing knifes to cut deeper into the bark and cause a wrong diameter measurement
3.) Poor delimbing quality can result in knot whorls that are too big and cause diameter measurements to be over estimated

Calibrated and well maintained equipment will help to limit these errors (FPInnovations, 2015).

The accuracy of harvesting heads has improved over the decades (Leitner, Stampfer, & Visser, 2014). A good calibration policy will ensure an accurate measurement and can eliminate missing calibration as one of the biggest drivers of measurement error (Strandgard & Walsh, 2008). Regular calibration has been shown to increase the processor measurements accuracy in a trial in sitka spruce (*Picea sitchensis*) in Ireland (Nieuwenhuis & Dooley, 2006). A recent New Zealand study on a Waratah 625C in P. radiata found a 98% length accuracy to within +-5cm (Saathof, 2014). This accuracy level is similar (98%) to a recent study in Chile (Carey & Murphy, 2005). When looking at the diameter measurement accuracy, a Swedish study showed that 73% of the diameter measurements were within the margins of +-4mm (Sondell, Moeller, & Arlinger, 2001). An Australian report, summarising multiple studies on diameter accuracy of +- 4mm, showed a range of 20% to 95% (Standgard & Walsh, 2012). Canadian researchers state that an accuracy of 90% to within +- 5cm for length and an accuracy of 75% within 8mm for diameter is achievable (FPInnovations, 2015).

Another factor influencing the accuracy of the measurements is the decision on the right bark equation. Most modern harvesters have four built-in bark thickness models, which are defined within StanForD (SkogForsk, 2012). It is not possible to import a customized bark equation. In Australia, where CTL (cut to length) operations are common, the use of the linear *double bark thickness model* is common (Zacco, 1974).

$$\boldsymbol{Double\ Bark\ Thickness\ Model}:$$

$$\boldsymbol{dbt = b0 + b1 * DOB}$$

$$Whereb0\ and\ b1user - defined\ coefficient$$

$$dbt\ double\ bark\ thickness\ (mm)$$

$$DOB\ Diameter\ Over\ Bark\ (mm)$$

(Zacco, 1974)

Although it is commonly used this model has been identified as a poor fit for radiata pine as the linear model doesn't represent the substantially thicker bark found at the lower trunk level in mature radiata pine stands but still represents the best the best fitting function (Strandgard & Walsh, 2011)**.** A wrongly used bark equation can result in log rejects due to false small end diameter prediction and therefore result in a significant loss of value (Marshall, Murphy, & Lachenbruch, 2006).

Harvester head volume calculation:

Most manufacturer's software that use StanForD calculate the volume based in 1 dm or 1 cm section. How exactly the diameters are used is not strictly defined. Depending on the manufacturer the measurement can be based on SED and LED, mid diameter or the function for a cut cone. An unpublished study conducted by SkogForsk didn't show a significant difference in the calculated volume between manufacturers on the same sample (Arlinger, personal communication, 2016). An important aspect on volume calculation is; the measured LED can't be smaller than the SED. If that is the case the OBC will set LED=SED.

Cylinder $\boldsymbol{Volume\ Equation\ used\ in\ Timbermatic\ H-09}$:

$$V_{b.k.} = \frac{\pi}{4} \cdot d_{b.k.}^{2} \cdot l \cdot 10^{-4}$$

$$l = length\ in\ (m)$$

$$d_{\ b.k.} = mid\ diameter\ under\ bark\ in\ (cm)$$

1.5 Pre-harvest inventory

The harvest stands selected for this study had a pre-harvest inventory (PHI) completed. Pre-harvest inventories are an important part of New Zealand forest management processes. This inventory allows the forest company to refine their tactical planning for the next 1-2 years. The main focus of PHI's are to specify the target markets for stands to be harvested, to reschedule long term harvest plans, and to predict the grade, volume and financial output of stands. The defined sample intensity, i.e. the amount of inventory plots within a stand, largely depends on company internal inventory policy. The literature defines a common operational target sample intensity for a PHI Inventory of around +-4% of the total harvesting area. The exact sample size depends on stand variation, stems/ha, target precision and inventory budget (Interpine Group, 2014)**.** A target PLE (Probable Limit of Error) for TRV (Total Recoverable Volume) of around 10% is recommended. PLE is the expression of the confidence limits in percentage around the estimated mean within a 95% probability level (Maclaren, 2000).

$$\boldsymbol{PLE\ Formulae}:$$

$$PLE \ = (\pm 100 t S_{\bar{x}})/\bar{x}$$

$$t \quad = \ student's\ value\ at\ the\ required\ probability\ level\ and\ degrees\ of\ freedom$$

$$\bar{x} \quad = \ the\ sample\ mean$$

$$S_{\bar{x}} \quad = \ the\ standard\ error\ of\ the\ mean$$

(Gordon, 2005)

All inventory plots measured in the study were based on a systematic sampling method with a circular bounded 0.04 to 0.07 ha plot layout. The manual around the plot establishment and measurement can be requested from Interpine Group Ltd, Rotorua. The sample size, plot type and plot layout for this study have been subject to the forest management's decision around their inventory work program. The sample strategy has not been reviewed as part of this study. The field measurement was conducted by trained field mensuration teams, holding appropriate New Zealand Qualifications Authority (NZQA) inventory modules.

It is important when looking into the different data sources error for reconciliation, to accept that no system is perfect. Therefore the following summarises the literature around the estimation of inventory and data analysis accuracy.

Field mensuration errors can occur due to:

1) Use of the wrong measurement tool
2) Lack of adequate training
3) Carelessness
4) Difficulty in assessing the hard-to-measure features like branching

In particular branching has been reported to be difficult to assess (Murphy, Wilson, & Barr, 2006)**.**

Field grouping errors can occur when:

1) Heights and diameter are rounded into broad classes

Sampling errors can occur when:

1) The wrong sample size is used
2) The wrong plot shape and plot size are used
3) Plots are not distributed correctly
4) Subsets of the population are not represented.

Examples of *Process errors* can occur in the analysis of the collected data due to:

1) Application of wrong stem taper models
2) Application of wrong bark thickness models

(Canavan, 2002)

An evaluation of the two sources of error; sampling intensity (sampling error) and stem quality (mensuration error) showed that both can have a large impact on estimated net value recovery. Furthermore the use of an unsuitable model (e.g. branch model) for processing the collected data (process errors) has enormous potential for false value estimates (Murphy & Acuna, 2011).

Murphy, Wilson, & Barr (2006) refer to three unpublished studies undertaken in New Zealand and Australia between 1979 and 2000 which compared actual and predicted log yields. The predicted volume of saw logs and higher grade log product was within 8% to 41% of the actual. For pulp volumes the pre-harvest estimates were within 12% to 57% of actual.

It is important to point out that the author’s proposed research objective is not to test the accuracy of forest management pre-harvest yield prediction system. The primary focus lies in the evaluation of the mechanised processing data against the current reconciliation process.

1.6 Weighbridges, Scaling and Conversion Factors

The only data for the reconciliation of harvest stand volumes against pre-harvest inventory estimates comes from the weighbridges located at domestic mills and seaports. The process of weighing the wood is the most frequently used method to determine the harvested volume in New Zealand. To obtain the weight, each logging truck delivering the logs from the forest has to pass a weighbridge or loader based-scales prior to unloading and again when leaving the site. The subtraction of unloaded from loaded weights will give the net weight of the logs of one load. All weights in this study were taken by a weighbridge. For reconciliation purposes it is of importance to convert the weight back to cubic volume as cubic volume is the unit used when estimating the yield for the harvest area. To do so it is common practice to develop and apply weight/volume conversion for each log grade. The samples for obtaining the conversion factors are collected using stratified random sampling (Ellis & Crawley, 2014). All samples are scaled and calculated via the 3D Log Scaling Method (Ellis, 1982).

$$\boldsymbol{3D\ Formula}:$$

$$V = exp(1.944 * In(L)) + 0.03 * d0 - 0.039 + 0.885 * In((d1 - d0)/L)) \\ + 0.079 * d02 * L$$

$V\ is\ the\ log\ volume\ (dm3)$
$In\ is\ the\ natural\ logarithm$
$exp\ is\ the\ antilog\ of\ natural\ logarithm$
$L\ is\ the\ log\ length\ (m)$
$d0\ is\ the\ small - end\ diameter\ (cm)$
$d1\ is\ the\ large - end\ diameter\ (cm)$

In the forest where the study was undertaken rolling average conversion factors are applied. The factors get updated continuously as newer samples are collected and older samples are discarded (Ellis & Crawley, 2014)**.** The conversion factor is a division of the 3D scaling sample volume (under-bark) by sample weight (over-bark).

$$\boldsymbol{Conversion\ Factor}:$$

$$CF = sumV / sumW$$

$CF\ is\ conversion\ factor\ from\ sample$
$sumV\ is\ sum\ of\ volumes$
$sumW\ is\ sum\ of\ weights$

The volume to weight ratio is subject to errors due to variation in moisture content, wood density and the relative amount of foreign material within the load when weighing (Smith, 1978). The author was not able to obtain the error limits associated with the conversion factors for the harvest areas included in the study.

2. Research Question and Hypothesis

The literature review shows that there has been a substantial amount of work related to the use of harvester data. However research where StanForD data is used for wood flow management is rare. In New Zealand no research has been conducted on the use of StanForD as a forest management tool. Therefore the focus of this work is to report on and evaluate the practical implementation of StanForD in a forest stand reconciliation scenario.

To evaluate the quality of StanForD data collected in the forest today the following research questions were asked:

1. How does the pre-harvest inventory analysis compare against the harvest data collected via the processor on a stand level?

$H_0 \neq$ The Pre-harvest prediction of volume and grade mix won't differ from the results obtained via the StanForD data collected during the harvest and the collected harvester data will be within the PLE.

2. How does the converted volume and grade mix from weighbridge and log scaling compare against the harvest data collected via the processor on a stand level?

$H_0 \neq$ The Volume and Grade mix collected via StanForD in a mechanised processing operation won't differ from the results obtained in a reconciliation based on weights, log scaling and conversion factors.

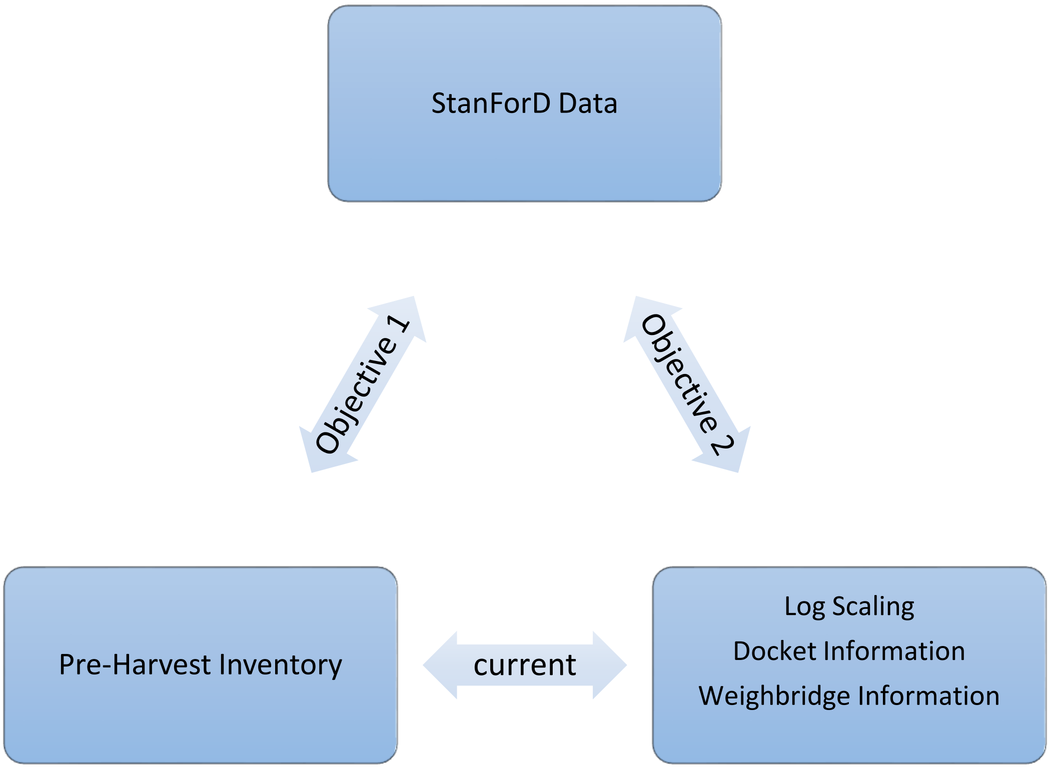


Figure 2 - StanForD as a data source for harvest stand reconciliation

3. Methodology

3.1 Research Scope

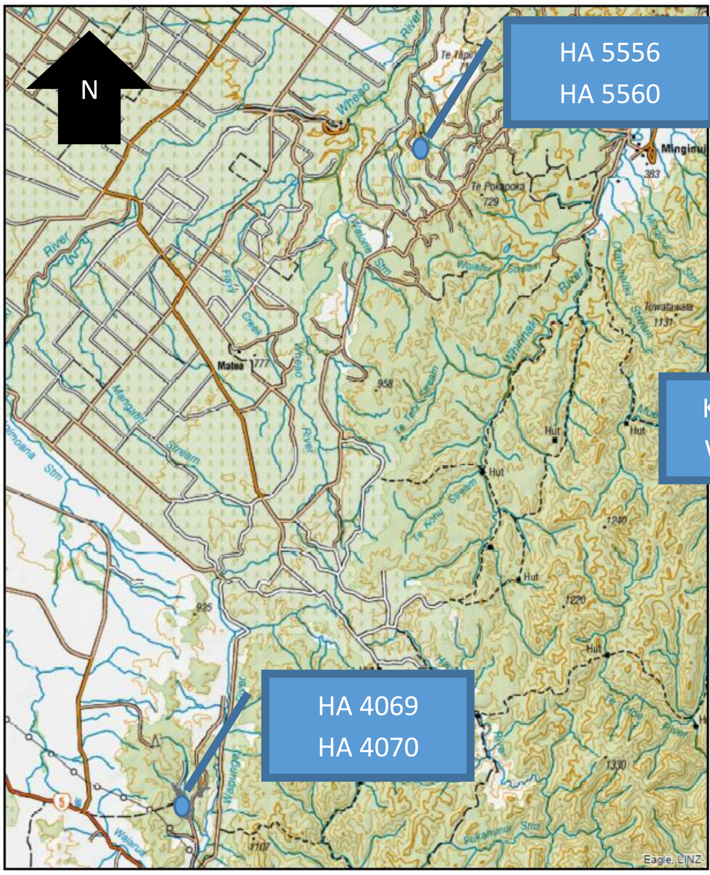
To meet the defined objectives the study included a field work and data analysis component. The data for this study was collected in the forest estate managed by Timberlands Ltd. The field work took place in Whirinaki and Kaingaroa forests. The study sourced its information from pre-harvest inventory prediction, load dockets, and daily harvester production. Four ground-based harvesting operations with mechanised felling and landing-based mechanised processing were studied. The field work was conducted in cooperation with the logging crew 038 Volcanic Plateau Logging. The harvesting equipment was a SATCO SAT325 felling and delimbing head with a Dasa 5 On-Board-Computer on a Tigercat 855L carrier for felling and delimbing (*Figure 3)* and a Waratah 625C with a Timbermatic H09 On-Board-Computer on a Sumitomo SH 330LC-5 carrier *(Figure 2)* for processing on the landing. StanForD data was only collected from the Waratah machine. The data collection started on the 10/09/2015. An initial meeting on site was held one week prior to the start of the field work. Participants present were the harvesting supervisor, harvesting crew owner and processor operator. It was not within the scope of the proposed research to analyse the quality of the forest management company's current reconciliation process, nor to assess the quality of harvesting operation's log making activity.

Figure 3 - Sumitomo SH 330LC-5 with Waratah 625C Processor

Figure 4 - Tigercat 855L with SATCO SAT325 Processor

Figure 5 - Waratah 625C (left) and SAT325 (right)

5.2 Site and Stand Characteristics



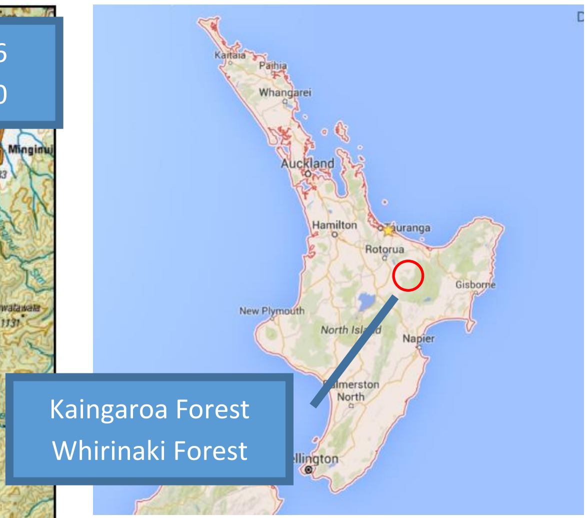


Figure 6 - Location of Kaingaroa forest and Whirinaki forest

Figure 7 - Study site location within estate

Kaingaroa Forest is located between Rotorua and Taupo on the volcanic plateau of New Zealand’s central North Island, see Figure 6. The flat terrain and pumice soils create a “waterproof” forest for year round harvesting, of approximately 4 million m³ per annum of radiata pine and small volumes of Douglas fir (Kaingaroa Timberlands, 2016).

The stands chosen for the study were of similar characteristic. The blocks were of steep rolling terrain. The stands were planted between 1983 and 1985 and all four stands were pruned. Table 1 contains information handed out to the harvest crew prior to harvest as part of the harvest prescription.

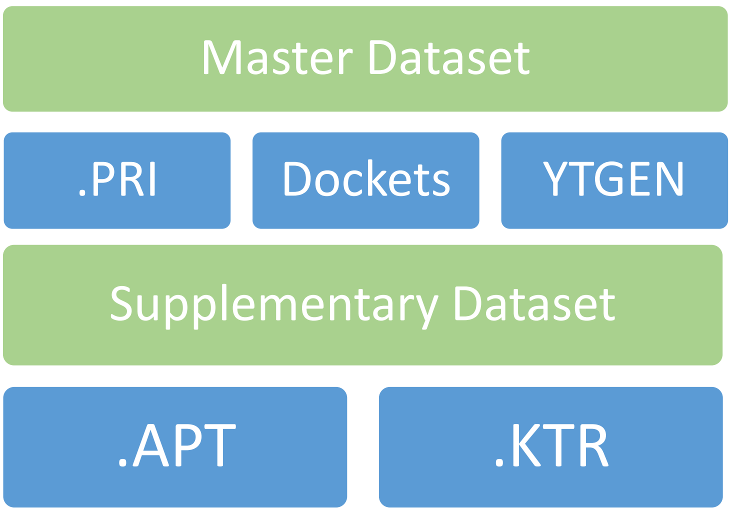
Table 1 - Harvest area description

Harvest Area	Time of Harvest	Season	Forest	Terrain	Establishment Year	Area (ha)
5556	18/08/2015 - 10/09/2015	Winter To Early Spring	Whirinaki	Rolling Steep	1983	16.1 ha
5560	09/10/2015 – 30/10/2015	Spring	Whirinaki	Flat Rolling Steep	1985	13 ha
4069	30/11/2015 - 15/12/2015	Spring To Early Summer	Kaingaroa	Rolling Steep	1985	47.7 ha
4070	15/12/2015 – 16/03/2016	Summer To Early Autumn	Kaingaroa	Rolling Steep	1985	50.5 ha

5.2 Data Collection

The data for this study was delivered from three different parties; the processor operator, the resource management team and woodflow management team. The Master Dataset included 3 sources of information; the .PRI files, the truck docket information, and YTGEN pre-harvest inventory output as seen in Table 2. The Master Dataset was used for the main data analysis. The Supplementary Dataset was used to support the analyses and include .KTR calibration files and .APT cutting strategy files.

Table 2 – Studied data sources



5.3 .PRI, .APT, .KTR Files

First and foremost it was of immense importance to collaborate with an operator having an "*advanced*" level of understanding of their harvester OBC systems. The benchmark for operator capabilities was therefore defined as:

1. Knowledge of how to save and reset the .PRI daily
2. Confidence in calibrating the processor head
3. Ability to edit APT files on the OBC

Crew 038 was recommended as a suitable partner for the fieldwork component. After an initial meeting with the crew, the author was confident 038 will be able to reliably deliver data to meet the benchmark as above. The high importance of the operator's level of technical know-how around this machine will be discussed in depth in the Discussion part of the thesis.

PRI Files:

The PRI files were saved, reset and delivered on a daily basis. Files were downloaded via an USB stick by the operator and sent to the author via an email attachment. The volume collected by the harvester was grouped into the same grade groups as those used for the PHI assessment, see Table 3.

Table 3 - Grade groups and grades

Grade Group	Grade
Appearance	Z2Y
Industrial	SKX
Large Structural	S30
	S35
Large Utility	13
	SOM
Large Prune	P30
	P35
Pulp	AG
	RBAM
	RBAS
	RUA
	RUH
Small Utility	15
	SMM
	SSM

Table 4 shows an example from the PRI output as used in this study. The table displays the products produced out of a single harvested stem. Each stem has a unique stem number (StemNo) which helps to maintain data integrity and to avoid duplication. Furthermore it includes recorded diameter, length and volume for each cut product. The legend below the table provides a detailed description of each column.

Table 4 - Example output from PRI

FileSaveDate	StemNo	Log No	Grade	Length cm	Length Class cm	TopDiam OBmm mm	DiamClass mm	VolumeOB m3
18/08/2015	35459	1	S30	491	490	437	420	0.791
18/08/2015	35459	2	S30	612	610	391	380	0.778
18/08/2015	35459	3	13	390	390	369	340	0.438
18/08/2015	35459	4	S30	550	550	321	320	0.519
18/08/2015	35459	5	15	589	490	256	250	0.397

LEGEND:

File Save Date = Date Stamps showing the date of file saving. Important to distinguish produced volume by date

Stem No = A running value unique for a harvesting site.

Log No = Numbering for each product cut out of the stem.

Grade = Describes the grade for each log

Lengthcm = Actual measurement of each log's length

LengthClasscm = Class defined in the APT. Each actual cut length is hereby associated to a class

TopDiamOBmm = Actual measurement of each log's SED

DiamClassmm = Class defined in the APT. Each actual cut diameter is hereby associated to a class

VolumeOBm3 = Volume over bark as calculated by the OBC.

APT:

The APT file was compared against the cutting instruction handed out to the crew. The focus was to duplicate the paper instruction in Table 5 in the APT file in Table 6. The scope of the work did not include any changes to the value matrix, oversize allowance or cutting windows within the APT. Table 5 provides an example of a cutting instruction as handed out by the harvest supervisor to the harvest operator. Table 6 shows the matrix style cutting instruction as used in the APT file for one log grade (P35 grade). Besides the value matrix the APT consists of additional information like settings of length tolerance for a product, and bucking condition (e.g. log can only be found at the butt of the stem).

Table 5 - Example cutting instruction handout

Priority	$/tonne	Docket Grade	Docket Length Code	Min SED	Max LED	Lengths	Max Knot Size (cm)
1		P35	IL	35	85	5.55,6.2	0
2		P35	IM	35	85	4.4,5.0	0
3		S35	M	35	85	4.9,5.5,6.1	7
4		S30	M	30	60	4.9,5.5,6.1	7
5		13	5.9	32	100	5.90	12
6		13	3.9	32	100	3.90	12
7		15	5.9	23	60	5.90	12
8		15	3.9	23	60	3.90	12
9		SSM	S	16	60	3.7,4.3,4.9,5.5,6.1	12
10		RUA	S	10	40	3.7-5.5	99
11		RUH	S	40	85	3.7-5.5	99
12		RBAM	B	10	85	1.8-3.6	99

Table 6 - Example APT style cutting instruction

Species:	Pine
Assortment:	P35
Product Group:	Prune
Buck:	Butt log only
Max Diam mm:	900
Max Len cm:	625
Len -cm:	-2
Len +cm:	1

Qualities Q1

Length/Diam	350(0)	370(0)	390(0)	410(0)
440(0)	900	900	900	900
500(0)	950	950	950	950
555(0)	1000	1000	1000	1000
620(0)	1000	1000	1000	1000

KTR:

The KTR files were collected for every control measurement carried out by the operator. The files were sent together with the daily PRI via email to the author. A total of 184 length checks were conducted for the four harvest areas. Figure 8 shows that the operator carried out control checks at least once a week with two exceptions, calendar week 43 of 2015 and calendar week 9 of 2016 when checks were not carried out. The diameters were also calibrated but, due to a software issue (fixed after the study was completed), were not recorded in KTR file. Figure 9 shows the distribution of length differences prior to adjustment. A positive value represents an over measurement from the processor head and vice versa.

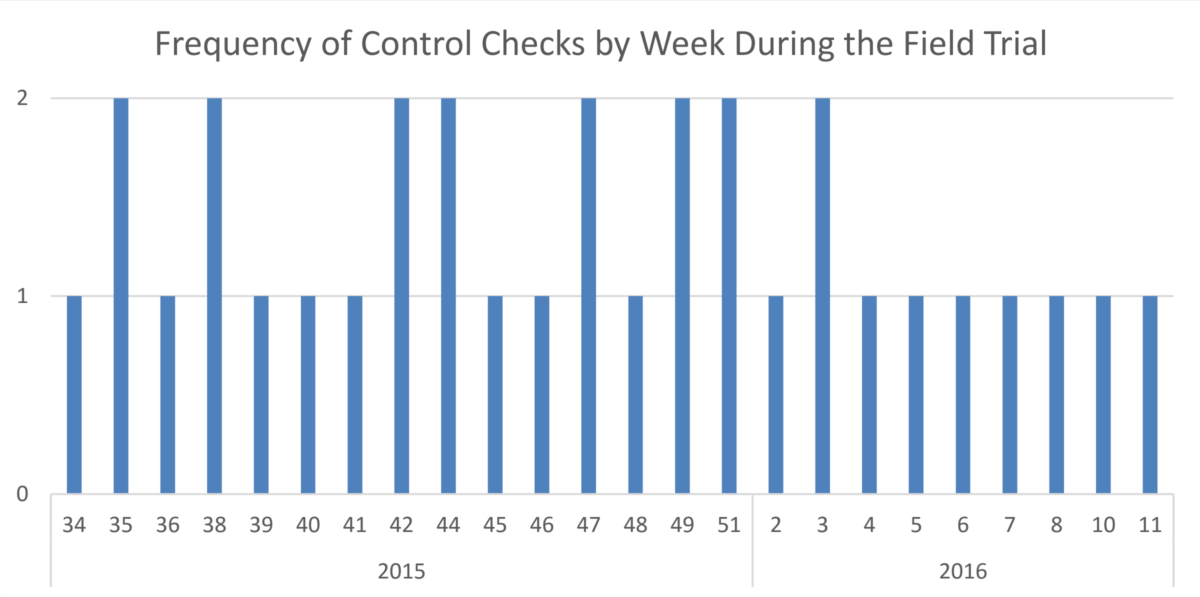


Figure 8 - Calibration frequency report showing number of calibrations by week

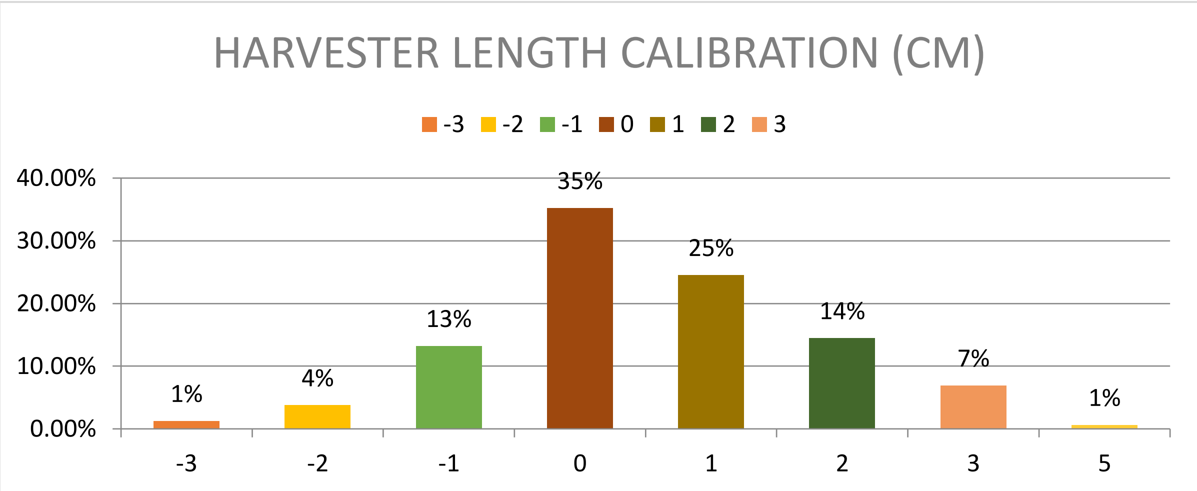


Figure 9 - Length adjustment required after control measurement

5.4 Pre-harvest Inventory

As part of the research the inventory data was analysed. To meet the research objectives the inventory data was supplied by the forest management in two formats:

1. Completed reconciliation on a stand level as an Excel spreadsheet. The analysis was conducted using a generic cutting instruction. All possible grades were simulated regardless of whether they were produced or not. This dataset is called: **Market independent yield**.
2. The raw YTGEN .ytf file which allowed simulation of the actual grades produced. This output is called: **Market dependent yield**.

For the yield analysis simulation the software YTGEN was used. The yield analysis used the breakage and taper models and the grade specifications of the forest management company. The yield output and grade aggregation was based on the same grade groups that were used by the forest management company for the reconciliation, see Table 3.

To meet the research objectives, harvester data and the converted docket weights were compared against the inventory. By including the actual docket information a comparison of harvester data results against the existing reconciliation system based on docket weights was possible. Furthermore it can highlight whether QC staff on-site up- and/or downgraded volume between processing and fleeting.

To quantify the results a comparison against the yield mean and the inventory PLE was carried out. The PLE by grade group and total was calculated via the following method:

$$\mathit{Calculation\ of\ PLE\%}$$
$$PLE\% = CI\ (95\%)/\,Volume$$

With the calculated PLE percentage the upper and lower limits of the true mean were calculated ($p \leq 0.05$) as shown in Table 12 to Table 17. These results allowed the following comparisons:

- Market dependent yield by grade group against harvester volume by grade group
- Market dependent yield total against harvester recorded volume total
- Market independent yield total against harvester recorded volume total
- Market dependent yield by grade group against docket volume by grade group
- Market dependent yield total against converted docket weights total
- Market independent yield total against converted docket weights total

5.5 Load Dockets, Weights and Conversion Factors

The docket information was supplied by the forest management woodflow team, exported from their internal docketing system within "FIPs" (Forest Information and Planning System). All docket information was delivered on a weekly basis. All conversion factors were based on sampling across the grade groups and calculated on a five quarter-year rolling average. The sample loads came from across the whole estate. All relevant weighbridges were calibrated each Friday.

To meet the research objective an analysis of harvester data against the converted docket weights was conducted. To qualify the results of following comparisons were carried out:

- Total volume for harvester against converted dockets
- Harvester volume against converted dockets by harvest area
- Harvester volume against docket information by grade group
- Harvester volume against docket information by grade and by site
- Harvester volume against docket information by common grade group across all sites

5.6 Bark Function

No bark function was applied in the harvester in this study. Therefore all measurements were taken over bark and the calculated volume represents the over bark volume. There is a clear limitation of not using a bark function, the reasons were the following:

- No bark function was in use at the time of the study (in fact no harvester in the whole estate is running a bark function)
- The available literature didn't describe well enough the variables to use for a bark function in pinus radiata
- A landing based operation with multiple tree handling (Felling → Delimbing → Shovelling→ Skidding → **Bucking**) could cause a significant and unpredictable bark loss prior to bucking, see Figure 10.
- In StanForD available bark function aren't the best fit for the bark characteristic of radiata pine.

Figure 10 - Stems at landing prior to bucking at HA 5556

The lack of a bark function will cause the harvester to over measure the solid volume. The question is by how much? It is believed that regardless of spatial location and stem part, an average of the stem volume consists of 13% bark. The 13% represent the volume of a log with zero bark loss (Murphy & Cown, 2015). Depending on the type of harvesting operation a further reduction of the bark percentage can be made. For a landing based operation the remaining bark volume can be reduced by 75% (Murphy & Logan, 2015). To account for difference in seasons and therefore the strength of the bond between stem and bark a reduction of further 3% percent can be conducted for volume harvested in spring (Murphy & Pilkerton, 2011). As the study moved from winter 2015 into early autumn 2016 the bark percentage of remaining bark volume on total volume will vary in the range of:

$$\boldsymbol{Bark\ Percentage\ of\ Total\ Volume:}$$

$$Winter\ and\ Summer = 13\%\ X\ 0.25 = 6.5\%$$

$$Spring = (13\%\ X\ 0.25) - 3\% = 3.5\%$$

6. Results

The following section shows the results and analysis of the research. All four harvesting areas were used to produce these results. The results will focus on answering the research question and the objectives of the thesis.

The results are presented in three parts:

- Description of the data collected from harvester, dockets and inventory independently
- Comparison of harvester production data against pre harvest inventory
- Comparison of harvester data against weights from load dockets

6.1 Description of Harvester, Docket and Inventory Results

Table 7 provides a summary of the total volume measured or predicted by different methods for the four harvest areas. More detail is provided in Sections 6.1, 6.2 and 6.3.

Table 7 - A summary of all volume from all sites and all sources

Measurement or Prediction Method	**Harvest Area Identification Numbers**			
	5556	**5560**	**4069**	**4070**
m^3 Harvester	13,382	9,812	19,287	28,920
m^3 Dockets	11,313	8,819	20,661	30,895
m^3 Market Dependent Yield	12,912	N/A	25,556	28,547
m^3 Market Independent Yield	12,419	N/A	23,809	29,013

6.2 Harvester Data

The harvester processed a total of 72,979 m^3 across the four study sites. 71,402 m^3 was recorded as productive volume. Productive volume is the total volume of all recorded logs which have a grade name in the PRI file. A total of 776 m^3 was recorded below the dimensions acceptable for any grade. This was assumed to be unclassified waste as the lengths and diameters were below those of any of the possible grades, example Figure 11. All logs with diameter smaller than 95 mm and/or length smaller than 180 cm are waste cuts, these are smaller than the minimum specified dimensions for binwood.

This leaves 801 m^3 of unclassified volume which could not be waste. The hereby recorded logs could have fitted into one or more grade classes but the logs did not get recorded as a particular grade. To associate the volume to a certain grade requires both dimension data and quality information. Since quality information is not recorded and dimensions can overlap several grades it was impossible to reallocate the 801 m^3 of unclassified volume to particular log grades. Unclassified volume is reported separately in the tables below.

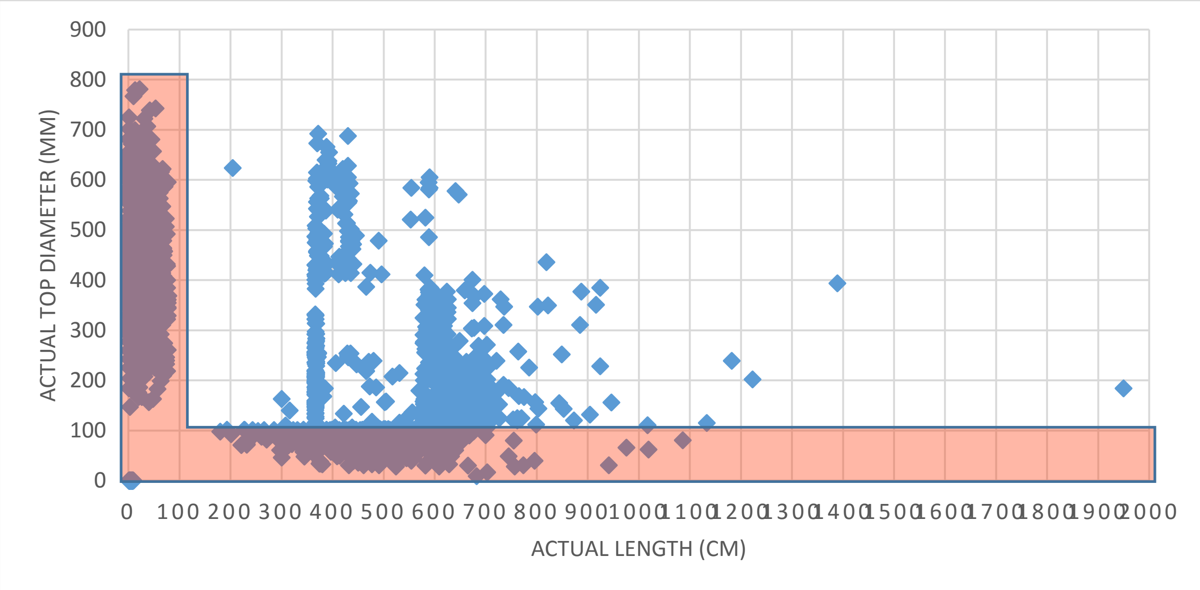


Figure 11 – Diameter and length characteristic of logs that were unclassified in HA 4069.

Table 8 describes the volume produced by the harvester for each site by grade group. The graphs include productive volume as well as waste and unclassified volume.

Table 8 - Volume recorded by the harvester

Harvest Area	Grade Group	Volume m^3	Harvest Area	Grade Group	Volume m3
5556	Large Prune	1,353	5560	Large Prune	1,868
	Large Structural	5,863		Large Structural	3,731
	Large Utility	2,623		Large Utility	1,762
	Small Utility	2,735		Small Utility	1,926
	Pulp	808		Pulp	525
	Waste	148		Waste	54
	Unclassified	40		Unclassified	44
4069	Large Prune	1,769	4070	Large Prune	5,823
	Large Utility	9,135		Large Utility	14,183
	Small Utility	4,952		Small Utility	6211
	Industrial	935		Appearance	23
	N/A	N/A		Industrial	485
	Pulp	2,496		Pulp	2,195
	Waste	234		Waste	340
	Unclassified	327		Unclassified	390

6.3 Weighbridge Data

The weekly collected weighbridge information was converted from tonnes to cubic metres on a grade group level. The total volume of converted volume was 72,340 m^3. The conversion factors used are shown in Table 9.

Table 9 - Conversion factor averages across all sites

Grade Group	Conversion Factors (tonnes per m^3)
Prune	1.048
Large Structural	0.981
Large Utility	0.981
Small Utility	0.986
Appearance	1.048
Industrial	0.938
Pulp	0.938

The Table 10 below shows the volume collected via the docket information system after it has been converted to cubic meters for all four sites. The volume information is separated by site and grade group.

Table 10 - Volume collected via the load dockets

Harvest Area	Grade Group	Volume m^3	Harvest Area	Grade Group	Volume m3
5556	Prune	989	5560	Prune	1,493
	Large Structural	4,977		Large Structural	3,359
	Large Utility	2,233		Large Utility	1,541
	Small Utility	2,123		Small Utility	1,728
	Pulp	992		Pulp	737
4069	Prune	1,564	4070	Prune	5357
	Large Utility	8,066		Large Utility	13,635
	Small Utility	4,791		Pulp	4041
	Industrial	1,531		Small Utility	6550
	Pulp	4,709		Industrial	1312

6.1.3 Inventory Data

The inventory data was, as discussed in section 5.2.1 processed in two separate formats:

1. As the standardized yield run conducted by the forest management. Hereby a standard grade list was used and not the actual grades produced at site. It is called the ***market independent yield***.
2. As a separate yield run conducted using only the actual products cut by the harvester. It is called the ***market dependent yield***.

HA5560 was partly harvested by a ground based crew (Crew 038) and later finished with a hauler crew which was not participating in the study. No inventory data was analysed for harvest area HA 5560, so no inventory information can be presented.

Total recoverable volume for the three sites, excluding HA5560, was estimated to be 67,015 m^3 for the market dependent yield. The combined market independent yield was estimated to be slightly less at 65,241 m^3 across all three sites. Table 11 shows the estimated volume by grade group.

Table 11 - Market independent and Market dependent yield in m^3

Harvest Area	Grade Group	Market Independent Yield (m3)	Market Dependent Yield (m3)
5556	Prune	1,642	1,337
	Large Structural	3,421	6,486
	Small Structural	1,008	N/A
	Large Utility	1,339	1,444
	Small Utility	932	2,650
	Large Framing	2,861	N/A
	Appearance	19	N/A
	Large Industrial	63	N/A
	Pulp	1,134	995
4069	Large Prune	2,988	4,200
	Small Prune	542	N/A
	Large Structural	2645	N/A
	Small Structural	1695	N/A
	Large Utility	2,371	11,005
	Small Utility	2,109	4,979
	Large Framing	2,929	N/A
	Small Framing	970	N/A
	Appearance	101	N/A
	Large Industrial	1732	981
	Pulp	5,151	4,392
	RWaste	576	N/A
4070	Large Prune	5,206	5,381
	Small Prune	857	N/A
	Large Structural	4,615	N/A
	Small Structural	2,326	N/A
	Large Utility	2,810	12,040
	Small Utility	2,096	5,838
	Large Framing	4,144	N/A
	Small Framing	788	N/A
	Appearance	163	N/A
	Large Industrial	1,782	506
	Pulp	4,226	4,782

N/A = Grades excluded from market dependent yield estimation which haven't been produced at site

The graphs below describe the estimated product outrun based on the type of cutting instruction used. Figure 12 represents the Market Independent Yield and shows the product outturn estimated using a standardized cutting instruction used by the forest management company. Figure 13 shows the Market Dependent distribution of the grade outcome using a cutting instruction based on the actual produced products.

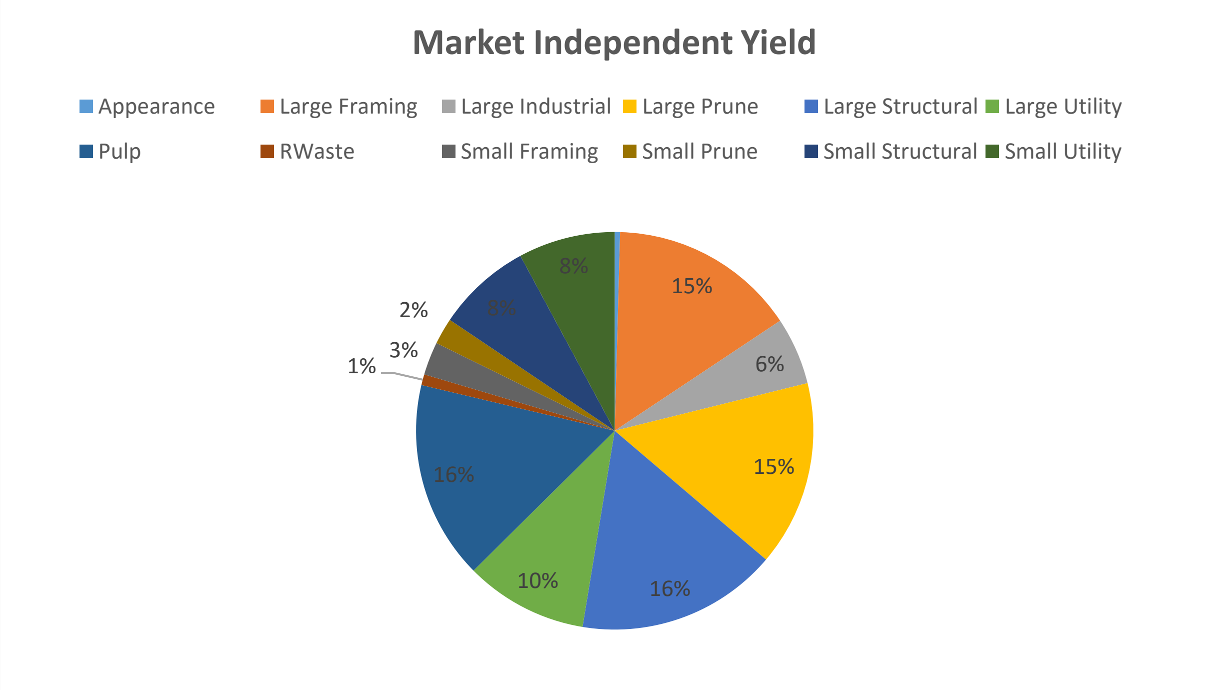


Figure 12 - Predicted yield by grade group for all harvest site run on standardized cutting instruction

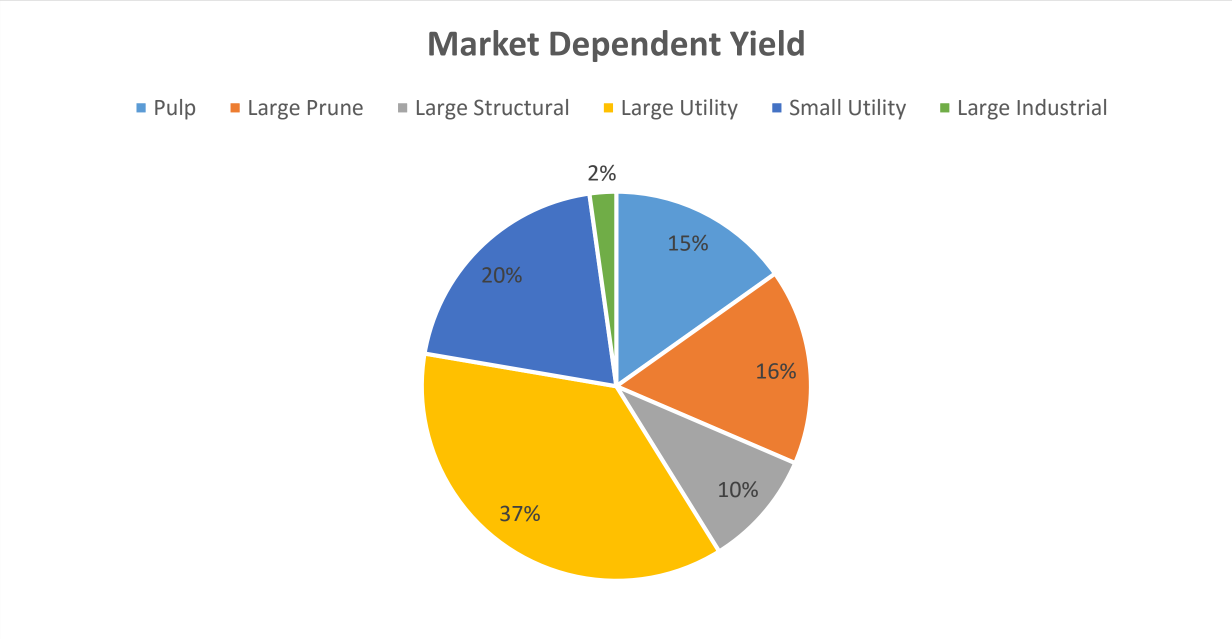


Figure 13 - Predicted yield by grade group for all harvest site run on a cutting instruction representing the actual product outturn

6.4 Comparison of Forest Inventory Data

The results of this comparison are presented in two parts; 6.2.1 focusing on harvester data versus Inventory PLE. 6.2.2 investigates if the docket information produced a different result than from the harvester data. Both sections include the results by grade group and total.

6.5 Comparison of Forest Inventory Data against Harvester Data

To identify if there is a difference in the predicted yield and the data collected by the harvester the following hypothesis was prepared:

$H_0 \neq$ The Pre-harvest prediction of volume and grade mix won't differ from the results obtained via the StanForD data collected during the harvest.

The harvester produced a total of 61,295 m^3 productive volume. The total estimated market dependent yield was 67,015 m^3.
Market dependent yield by grade group against harvester volume by grade group:
As Table 12 shows, the volume recorded by the harvester was seven times inside the PLE boundaries and eight times outside the PLE range. The difference between market dependent yield and harvester volume by grade group varied from 16 m^3 to 2,587 m^3. For those times where the harvester yields were outside the PLE limits, on two occasions the volume recorded by harvester was more than PHI yield estimate and on six occasions it was less.

Table 12 - Market dependent yield/PLE and harvester data by grade group

		PHI Market Dependent Yield (m^3)			Harvester Yield (m^3)	
HA	**Grade Description**	**Mean Volume**	**Lower Limit Total**	**Upper Limit Total**	**Recorded Volume**	**Difference**
5556	Prune	1,337	1,131	1,543	1,353	-16
	Large Structural	6,486	5,962	7,010	5863	*623
	Large Utility	1,444	1,166	1,723	2,623	*-1,179*
	Small Utility	2,650	2,278	3,021	2,735	-85
	Pulp	995	823	1,166	808	*187
4069	Prune	4,200	3,277	5,123	1,769	*2,431
	Large Utility	11,005	9,885	12,125	9,135	*1,870
	Small Utility	4,392	3,386	5,398	4,680	-288
	Large Industrial	981	779	1,183	935	46
	Pulp	4,979	4,420	5,538	2,496	*2,483
4070	Prune	5,381	4,318	6,445	5,823	-442
	Large Utility	1,2040	10,847	13,233	14,183	*-2,143
	Small Utility	5,838	5,153	6,522	6,211	-373
	Large Industrial	506	318	694	485	21
	Pulp	4,782	3,673	5,892	2,195	*2,587

(*) Recorded harvester volume outside PLE boundaries

Market dependent yield total against harvester recorded volume total:
Referring to Table 13 the total volume on stand level, the harvester volume was twice inside and one time outside the PLE boundaries. The difference for the volume outside the PLE was 6,564m^3. For the times the harvester volume inside the PLE the difference was 470m^3 and 41m^3

Table 13 - Market dependent yield/PLE and docket totals

HA	Grade Description	YTGEN m^3			Harvester m^3	
		Mean Volume	**Lower Limit Total**	**Upper Limit Total**	**Recorded Volume**	**Difference**
5556	All Grades	12,912	12,060	13,764	13,382	-470
4069	All Grades	25,579	24,126	27,032	19,015	*6,564
4070	All Grades	28,547	26,927	30,167	28,506	41

(*) Recorded harvester volume outside PLE boundaries

Market independent yield total against harvester recorded volume total:
When comparing the market dependent yield totals against harvester information and docket information we are getting the following results as shown in Table 14: The Harvester recorded the volume twice inside the PLE and once outside the PLE. The difference for the value outside the PLE was 4,652m^3.

Table 14 - Market independent yield/PLE and harvester totals

HA	Grade Description	YTGEN m^3			Harvester m^3	
		Mean Volume	**Lower Limit Total**	**Upper Limit Total**	**Recorded Volume**	**Difference**
5556	All Grades	12,606	11,762	13,451	13,382	-776
4069	All Grades	23,667	22,323	25,012	19,015	*4,652
4070	All Grades	29,038	27,411	30,664	28,506	532

(*) Recorded harvester volume outside PLE boundaries

6.2.2 Comparison of Forest Inventory Data against Docket Data

To investigate the results for a docket based reconciliation, the same analysis as in 6.2.1 was conducted with the docket data replacing the harvester data.

Market dependent yield by grade group against docket volume by grade group:
The volume collected via the dockets in Table 15 was on five occasions inside the PLE boundaries and 10 outside for the market dependent yield run. The difference between market dependent yield and the converted docket weights reached from 21m^3 to 2,727m^3. On five grade groups the yield estimate was higher than the volume recorded by harvester. On three instances the volume estimated was lower than the volume recorded via the docket information.

Table 15 - Market dependent yield/PLE and docket data by grade group

HA	Grade Description	YTGEN m^3			Docket m^3	
		Mean Volume	**Lower Limit Total**	**Upper Limit Total**	**Recorded Volume**	**Difference**
5556	Prune	1,337	1,137	1,543	989	*348
	Large Structural	6,486	5,962	7,010	4,977	*1,509
	Large Utility	1,444	1,166	1,723	2,233	*-789
	Small Utility	2,650	2,278	3,021	2,123	*527*
	Pulp	995	823	1,166	1,134	-139
4069	Prune	4,200	3,277	5,123	1,494	*2,706
	Large Utility	11,005	9,885	12,125	8,278	*2,727
	Small Utility	4,392	3,386	5,398	4,930	-538
	Large Industrial	981	779	11,83	1,463	*-482
	Pulp	4,979	4,420	5,538	5,215	-236
4070	Prune	5,381	4,318	6,445	5,357	-466
	Large Utility	12,040	10,847	13,233	13,635	*-548
	Small Utility	5,838	5,153	6,522	6,550	*339
	Large Industrial	506	318	694	1,312	*827
	Pulp	4,782	3,673	5,892	4,041	*1,846

(*) Recorded docket volume outside PLE boundaries

Market depended yield total against converted docket weights total:
As Table 16 shows, for the total volume on stand level the docket volume was on three sites outside the PLE. The difference for the volumes outside the PLE was 1,599m^3 4,918m^3 and 2,348m^3

Table 16 - Market dependent yield/PLE and docket totals

HA	Grade Description	YTGEN m^3			Docket m^3	
		Mean Volume	**Lower Limit Total**	**Upper Limit Total**	**Recorded Volume**	**Difference**
5556	All Grades	12912	12060	13764	11313	*1,599
4069	All Grades	25579	24126	27032	20661	*4,918
4070	All Grades	28547	26927	30167	30895	*-2,348

(*) Recorded docket volume outside PLE boundaries

Market independent yield total against converted docket weights total:
For the docket information, as Table 17 shows, the recorded total volume was on all three sites outside the PLE. The difference hereby was 1,293m^3, 3,006m^3 and 1,857m^3.

Table 17 - Market independent yield/PLE and docket totals

HA	Grade Description	YTGEN m^3			Docket m^3	
		Mean Volume	**Lower Limit Total**	**Upper Limit Total**	**Recorded Volume**	**Difference**
5556	All Grades	12606	11762	13451	11313	*1,293
4069	All Grades	23667	22323	25012	20661	*3,006
4070	All Grades	29038	27411	30664	30895	*-1,857

(*) Recorded docket volume outside PLE boundaries

6.6 Comparison of Docket Information against Harvester Data

To analyse the difference in the docket information and the data collected by the harvester the following hypothesis was prepared:

$H_0 \neq$ The Volume and Grade outcome collected via StanForD in a mechanised processing operation won't differ from the results obtained in a reconciliation based on weights, log scaling and conversion factors.

The analysis included data from the harvesting areas 5556, 5560, 4069 and 4070.

To meet the research objective an analysis of harvester data against the converted docket weights was conducted. To qualify the results the following comparisons were carried out:

- Total volume for harvester against converted dockets
- Harvester volume against converted dockets by harvest area
- Harvester volume against docket information by grade group
- Harvester volume against docket information by grade and by site
- Harvester volume against docket information by common grade group across all sites

Total volume of harvester against converted dockets:
The total of productive harvester volume was 71,407 m^3, the total volume of converted docket volume was 71,787 m^3. The difference between harvester and docket measurement was 380 m^3. There was more volume recorded in the docketing system than recorded as productive volume by the harvester.

Total harvester volume against converted dockets by harvesting area:
Following up on Table 18 the converted docket volume was twice higher than the recorded harvester volume; for HA4069 the difference was 1,374 m^3, for HA4070 the difference was 1,973 m^3. Twice the volume recorded by the harvester was higher. The difference was; for HA5556 2,070 m^3 and for HA5560 892 m^3.

Table 18 - Total volumes collected by harvest area

Harvest Area	Docket m^3	Harvester m^3	Difference m^3	Difference in %
4069	20,661	19,292	1,369	-7%
4070	30,895	28,922	1,973	-6%
5556	11,313	13,382	-2,070	18%
5560	8,919	9,812	-892	10%

Harvester volume against docket information by grade group:
The results in Table 19 include all grades cut by the harvester. For four grade groups the harvester recorded more volume than the docketing system. For two grade groups, the converted docket volume was higher. Pulp and Industrial were under measured by the harvester. For the industrial grade only half of the volume on the dockets got recorded by the harvester. For the pulp grades over 40% were not present in the harvester data. The four grades over measured by the harvester, the volume difference reached from 4% to 15%. Small and Large Utility with a difference of 4% and 9% represented 68% of all harvester volume. 89% of the volume recorded by the harvester were within 4% to 15% difference.

Table 19 - Docket and harvester volume by grade group

Grade Group	Docket m3	Harvester m3 (% of total Volume)	Difference	Difference %
Industrial	2,843	1,420 (2%)	1,423	-50%
Large Structural	8,336	9,594 (13%)	-1,258	15%
Large Utility	25,475	27,703 (39%)	-2,228	9%
Pruned	9,403	10,813 (15%)	-1,411	15%
Pulp	10,479	6,024 (8%)	4,455	-43%
Small Utility	15,191	15,825 (22%)	-633	4%

Harvester volume against converted docket weights by grade group and harvest area:
As Figure 14 shows, the harvester recorded, on 13 times, more volume than the docket for a particular grade group by harvest area. Six times the dockets recorded more volume than the harvester. The grades affected by an under measurement from the harvester were the Pulp and Industrial grades. These grades have been under measured by the harvester on each harvesting area. The Industrial grade has therefore been under measured on 2 sites and Pulp on four sites. As Table 20 highlights for the under measured groups the difference between harvester measurement and docket was between 2% and 10%. The difference from the harvester over measured grades reached from 0% to 8%.

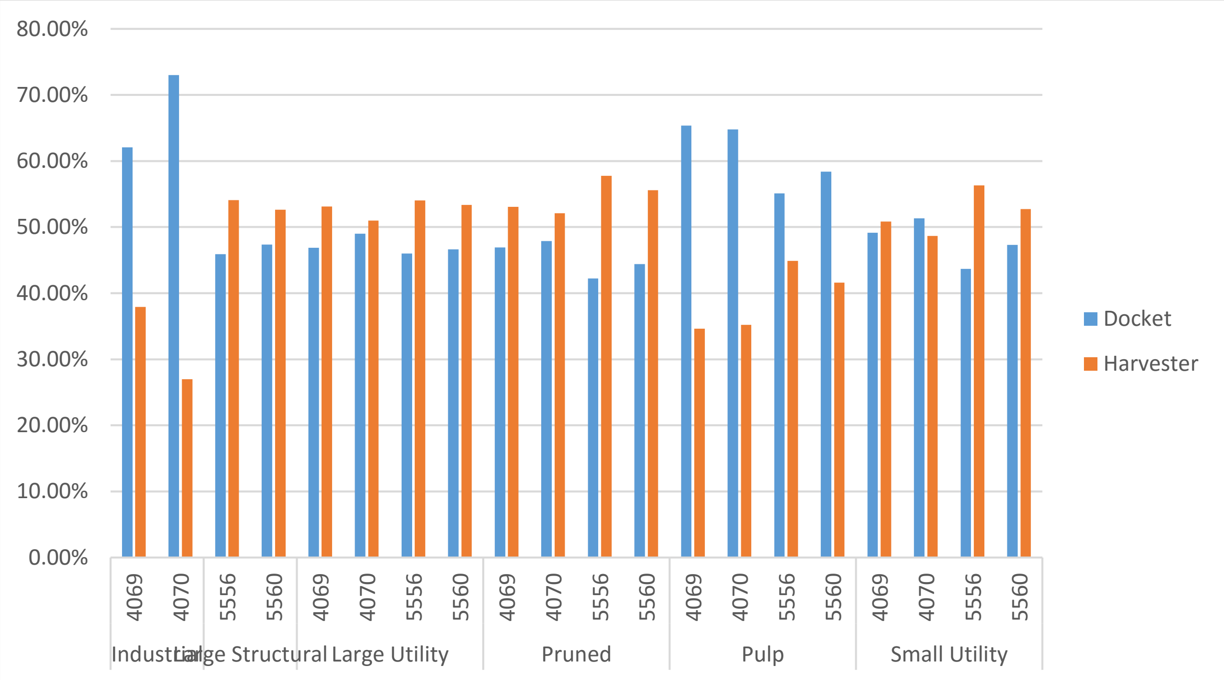


Figure 14 - Total volume distribution collected via docket and harvester by grade group and site

Table 20 - Harvester and docket volume showing the percentage of volume within each grade group by site

Grade	Harvest Area	Docket Volume in %	Harvester Volume in %	Volume Difference in %
Industrial	4069	62%	38%	24%
Industrial	4070	73%	27%	46%
Large Structural	5556	46%	54%	-8%
Large Structural	5560	47%	53%	-5%
Large Utility	4069	47%	53%	-6%
Large Utility	4070	49%	51%	-2%
Large Utility	5556	46%	54%	-8%
Large Utility	5560	47%	53%	-7%
Pruned	4069	47%	53%	-6%
Pruned	4070	48%	52%	-4%
Pruned	5556	42%	58%	-16%
Pruned	5560	44%	56%	-11%
Pulp	4069	65%	35%	31%
Pulp	4070	65%	35%	30%
Pulp	5556	55%	45%	10%
Pulp	5560	58%	42%	17%
Small Utility	4069	49%	51%	-2%
Small Utility	4070	51%	49%	3%
Small Utility	5556	44%	56%	-13%
Small Utility	5560	47%	53%	-5%

Harvester volume against docket information by grade group common across all sites:
Table 21 and Table 22 shows the mean, standard deviation and standard error for all commonly produced grade groups across all sites. All volume produced by the harvester is hereby within the limits of the standard deviation. The smallest differences in the mean between docketed and harvester volume by percentage are Small Utility followed by Prune and Large Utility. The largest difference in the mean is grade group pulp.

Table 21 -Mean, Standard Deviation and Standard Error for harvester volume by grade in percentage for common grades

By Grade	Harvester		
Grade Group	**Mean**	**Standard Deviation**	**Standard Error**
Large Utility	40.89%	10.62%	5.31%
Pruned	19.71%	8.68%	4.34%
Pulp	10.17%	2.60%	1.30%
Small Utility	29.22%	6.23%	3.11%

Table 22 - Mean, Standard Deviation and Standard Error for docket volume by grade in percentage for common grades

By Grade	Docket Information		
Grade Group	**Mean**	**Standard Deviation**	**Standard Error**
Large Utility	37.88%	7.96%	3.98%
Pruned	17.26%	7.83%	3.91%
Pulp	16.83%	5.28%	2.64%
Small Utility	28.03%	5.32%	2.66%

7. Discussion

The core goal of this study was to evaluate current implementation of harvesting data as a decision making tool of today.
The comparison of harvester production against the forest inventory estimates resulted in a similar outcome to the system based on dockets. Dockets and harvester data, have failed to meet the inventory grade prediction on a consistent level.

On a grade group prediction level the collected harvester data was within the PLE limits seven out of 15 times for the market independent yield. Small utility was the only grade which was predicted within the PHI PLE at all sites. Pulp on the other hand failed to be within the PLE limits at all sites. The reason for the missing volume of pulp is seen as operator error in regards to how the pulp wood has been handled. In percentage and compared with a previous study (Murphy, Wilson, & Barr, 2006) the differences between harvester data and yield prediction for higher grade logs and pulp was higher.

The docket data was five out of 15 times within the PHI PLE limits. The only grade correctly predicted at all sites was Pulp.

The pruned log yield has been predicted correctly for the harvester information on two sites 5556 and 4070 via harvester and docket information.

The total market dependent predicted volume the harvester volume fell within the PLE two out of three times and for converted docket weights 0 out of 3 times. The 2 times the PHI PLE level of accuracy was achieved by the harvester the difference between prediction and actual volume was 4% (HA 5556) and 0.1%. (HA 4070) These two numbers are well within the limits of an acceptable prediction (Petr & Jindrich, 2007).

Because of the limited number of sample sites (3) we can't conclude a positive or negative result for harvester data as a data source for reconciliation. It has to be pointed out for the one time the harvester total was outside the PHI PLE (HA4069) on the market dependent yield the difference between predictions and actual was exceptionally high 6,564 m^3. The estimated output of pruned logs was especially different, 2,431 m^3. The docket data confirms the difference with a total of 2,706 m^3 under predicted. The high difference in both systems, docket based and harvester based, indicates the possibility of a wrong estimation of recoverable pruned yield rather than inaccurate harvester data or inaccurate docket data. The question arises, "did the inventory data represent the reality accurately?"

A key finding of this research is constant under measurement of volume for pulp and the industrial (export pulp) grades via the harvester. What caused the under measurement of pulp and industrial? The difference for the industiral grades represented by SKX seems to be too high, caused by measurement variation, up to 46% less volume measured by the harvester than recorded on the dockets. A hint could be that both grade groups, pulp and export pulp represent the lowest end of the qualities, like largest possible knots. Does the way the operator handles these logs effect the way they're getting measured and recorded from the harvester? Indications are the operator comments when asked about a difference in handling cutting pulp:

“In those frost flats some pulp was not recorded as I had to cut it back from the crutch to get it through the head”

“The other thing also, which is an error on my part by not giving the computer correct info, is if I shoot a bit of pulp through (I know its pulp and just random cut it) but don't hit Quality 6 pulp button and it still big enough for a small saw log it will record it as a saw log even though I’ve cut it as pulp simply because I didn't tell the computer that it was pulp”

“I have seen when I shoot pulp logs through the head and I don't hit the pulp assignment button it will say its something else (ie SKX , 13,15) depending on diameter”

Furthermore the operator has seen downgrades to fill pulp loads on trucks:

When looking into the reason for over-measured volume the most obvious factor is, no bark function has been applied in the harvesting machine. The effect on the total volume has been discussed in section 5.2.3 and is seen to reduce the volume across all grades sites between 3.5% (Summer) and 6.5% (Winter). These bark reductions, when applied, would bring all the higher grades closer to a match with the docket information.

Another reason for an over measurement could be the conversion factors applied. Do they represent the reality for the harvested areas when samples come from across the entire estate? An indication of the influence of the conversion factors might be the fact that the differences in percentage highlighted in Table 20 seem to be paired around the location where the harvesting took place. HA5560 and 5556 are in close neighborhood within Whirinaki and 4069 and 4070 in Kaingaroa, this means the smallest differences between docket volume and havester for a certain grade group are always in the neibouring stands. Are the conversion factors causing this phenomenon? Another factor which can cause a difference between the harvester volume by grade group and the volumes from the docketing system is related to what happens after the log is cut: A) Does the operator always place the log as recorded by the harvester computer in the correct stack? B) Do the QC staff downgrade logs after they have been recorded and stacked? C) Do logs get downgraded when being loaded?

And indication for C) was described by the operator:

“Some (higher quality logs) may have been rejected into RUH or RUA or I have seen in the past pulp loads topped off with these logs”.

What effect do A, B and C have on the volume recorded by grade group? A further study on an operational level should be conducted to quantify this source of error.

When looking at the actual numbers it is obvious the difference between the total volume of <1% is very small. When looking into each grade group, the volume difference reached from 2% to 16% for the overmeasured grades. Within the overmeasureed grades 49% of the docket volume and 52% of the harvester volume were within the <=5% volume difference band. <=10% volume difference represented 76% docket volume and 82% harvester volume. Overall the overmeasurment seems to be systematic. If the reason for this can be identified, the harvesting data will potentially be as good as the weighbridge system for future forest reconciliation management.

The study also highlighted the importance of a “good” APT file. A good apt will limit any data errors due to unclassified volume. Unclassified volume in this study occurred when the operator cut grade manually with length and diameter dimensions which aren’t covered in the APT matrix. The right setting on oversize allowance and cut window are of immense importance as an overlap can cause a log to be recorded as unclassified even if within the matrixes boundaries. With the right knowledge on building an APT the errors source of wrongly recorded grades or marked as unclassified volume can be minimized.

The APT file and operational issues causing harvester data errors can be minimized by improving the knowledge base of all actors involved with training. Therefore, forest companies have to increase their knowledge on building APT files and have to stop leaving it up to the contractor to interpret the one line paper style cutting instruction in the field. But not only the values in the cutting instruction matrix matter, the companies have to know how to use the StanForD features like oversize and cutting allowance to record the data correctly. On the contractor side, training has to be conducted to assure the operator is knowledgeable on the OBC and how to change the basic settings, like for example loading new harvesting sites. Furthermore the whole crew has be made aware of the harvester data’s value. Examples are dropped logs have to be re-recorded to minimize double recordings and pulp wood needs a top cut to get recorded, logs recorded by the harvester should be fleeted as the recorded grade. The recommendation therefore is to improve the training of forest company staff and contractor/operator on harvester computer systems and harvester data management. This will allow the forest industry in conjunction with emerging StanForD reporting systems like STICKS[1] to take the full advantage of the harvester data as a data source for the forest management of tomorrow.

STICKS [1] is a cloud based software product which allows user to upload and report on StanForD data.

The five points below highlight some of the areas where further research in regards to the use of StanForD would be beneficial:

- Effect on recorded volume due to operational errors outside the known limits of harvester head accuracy.
- Comparison of harvester volume against a different measurement systems volume like scanner volume.
- Research on the monetary value lost or gained by using harvester volume data for payment purposes.
- Interrogate the use of harvester data for spatial tracking felling operation. See example in Appendix 1
- Investigate the possible use of harvester data for bush stock takes and the possibility of replacing manual counting and guessing of wood available for fleeting. See example in Appendix 2

8. Conclusion

This study’s aim was to describe the use of harvester data as an additional data source for forest stand reconciliation. For that four clear fell harvesting operations have been monitored with the help of StanForD data and compared to pre harvest inventory and weight dockets.

Based on the results the research question can be answered as followed:

How does the pre-harvest inventory analysis compare against the harvest data collected via the processor on a stand level?

The inventory prediction can’t be matched repetitively with the harvesting data. No clear pattern is visible. The docket based reconciliation has a similar result and frequently fails to confirm the prediction. The hypothesis: “*The volume and grade outcome collected via StanForD in a mechanised processing operation won’t differ from the results obtained in a reconciliation based on weights, log scaling and conversion factors”* can’t be confirmed.

How does the converted volume and grade mix from weighbridge and log scaling compare against the data collected via the processor on a stand level?

The harvesting data constantly under measures the pulp and pulp export qualities. Reasons for this have shown to be of an operational nature:

- No care is taken to assure the right recordings of lower grade logs in OBC
- Different log types can be used to fill truck loads

The difference between the harvesters over-measured volume seem to be related to:

- Missing bark function within harvester
- The use of estate wide conversion factors
- The log recorded in the harvester is not necessary the grade as what the log is fleeted (QC downgrades)

The hypothesis: “*The volume and grade outcome collected via StanForD in a mechanised processing operation won’t differ from the results obtained in a reconciliation based on weights, log scaling and conversion factors”* can’t be confirmed. The quality of the recorded data seems to decrease along the stem. Pruned and the high quality saw logs are recorded more accurately than industrial and pulp.

References

Arlinger, J., SkogForsk (2016). personal communication.

Barr, B. (2006). *Key Elements For the Successful Integration of In-Forest Optimisation Into Australia.* Clayton South: J. W. Gottstein Memorial Trust Fund.

Canavan, S. (2002). *The Presence and Characterization of Measurement Error in Forestry.* Oregon State University.

Carey, P., & Murphy, G. (2005). Mechanised Versus Manual Log-Making in two Chilean Pinus Radiata Stands. *New Zealand Journal of Forestry Science, 35*(1), 25-34.

Deadman, M., & Goulding, C. (1979). *A Method for Assessment of Recoverable Volume by Log Types.* Rotorua: Fores Research Institute.

Ellis, J. (1982). A three-dimensional formula for coniferous log volumes in New Zealand. *FRI Bulletin, 20*.

Ellis, J., & Crawley, D. (2014). *Practical log scaling guide.* Tauranga: C3 Limited.

FPInnovations. (2015, June 8). *Harvesting Operations.* Retrieved from FP Innovations Homepage: https://fpinnovations.ca/ResearchProgram/Pages/research-program-forest-operations-harvesting.aspx

Geerkens, N. (2010). Harvest Optimisation: A case study of Hancock Forest Management's introduction of optimisation systems for their Northland harvesting crews. *Wood Supply Chain Optimisation 2010* (pp. 69-78). Rotorua: Forest Industry Engineering Association.

Gordon, A. D. (2005). Forest Sampling and Inventory. In *NZIF Forestry Handbook* (pp. 133-135).

Interpine Group. (2014). YTGEN Training Course. Interpine Group.

Kaingaroa Timberlands. (2016). Retrieved from Kaingaroa Timberlands: http://www.kaingaroatimberlands.co.nz/kaingaroa_forest

Leitner, T., Stampfer, K., & Visser, R. (2014). Analysing log length measurment accuracy of harvester and proccessor heads. *Austrian Journal of Forest Science, 3*, 129-146.

Maclaren, J. P. (2000). How many plots are required? In J. P. Maclaren, *How much wood has you woodlot got?* (pp. 28-31). New Zealand Fores Research Institute Limited.

Marshall, H., Murphy, G., & Boston, K. (2006). Evaluation of the economic impacts of length and diameter measurement error on mechanical harvesters and processors operating in pine stands. *Canadian Journal of Forest Research, 36*, 1661-1673.

Marshall, H., Murphy, G., & Lachenbruch, B. (2006). Effects of bark thickness estimates on optimal log merchandising. *Forest Product Journal, 56*, 87-92.

Moeller, J., Arlinger, J., Hannrup, B., Larsson, W., & Barth, A. (2011). Harvester data as a base for management of forest operations and feedback to forest owners. *Innovation in Forest*

Engineering - Adapting to Structural Change (pp. 31-35). White River - South Africa: Department of Forest and Wood Science - Stellenbosch University.

Murphy, G., G.E. Murphy & Associates (2016). Via E-Mail.

Murphy, G., & Acuna, M. (2011). Ranking of four contributions to error in stand-level Douglas-fir log supply and value recovery estimation. *Canadian Journal of Forest Research*, 2040-2050.

Murphy, G., & Logan, O. (2015). Radiata pine bark removal associated with two on-landing, log processing methods. *Forest Products Journal*.

Murphy, G., & Pilkerton, S. (2011). Seasonal Impacts of Bark Loss on Simulated Payloads, Bark Delivery, and Transport Costs for Freshly Harvested Logs. *Forest Products Journal*.

Murphy, G., Wilson, I., & Barr, B. (2006). Developing methods for pre-harvest inventories which use a harvester as the sampling tool. *Australian Forestry, 69*(1), 9-15.

Nieuwenhuis, M., & Dooley, T. (2006). The Effect of Calibration on the Accuracy of Harvester Heads. *International Journal of Forest Engineering*, 25-33.

Olivera, A., & Visser, R. (2014). *Making the most of your harvester data: Opportunities with integration of GNSS and StanForD files.* New Zealand: Future Forest Research.

Olivera, A., Visser, R., & Morgenroth, J. ((in review)). Automaic GNSS enabled harvester data collection as a tool to evaluate factors aftfecting harvester productivity in an Eucalyptus sp. harvesting operation in Uruguay. *International Journal of Forest Engineering*.

Petr, S., & Jindrich, N. (2007). *ANALYSIS OF VOLUME DIFFERENCES IN MEASURING TIMBER IN FORESTRY AND WOOD INDUTRY.* Brno: Department of Forest and Forest Products; Technology Faculity of Forestry and Wood Technology; Mendel University of Agriculture an Forestry Brno.

Saathof, D. (2014). *Assessing Measurment Accuracy and Productivity of a Waratah 625c Proccessing Head.* Christchurch: New Zealand School of Forestry - University of Canterbury.

SDC. (2015, June 8). *About SDC*. Retrieved from SDC Homepage: http://www.sdc.se/default.asp?id=1232

SkogForsk. (2012, May 18). Retrieved from http://www.skogforsk.se/contentassets/b063db555a664ff8b515ce121f4a42d1/appendix1_eng_120418.pdf

SkogForsk. (2014, June 8). *SkogForsk/Projects/StanForD* . Retrieved from SkogForsk Homepage: http://www.skogforsk.se/english/projects/stanford/

Smith, V. (1978). Minimum Total Cost: An Improved Weigh Scaling Strategy. *New Zealand Journal of Forest Science, 8*(2), 269-276.

Sondell, J. (1989). *Introducing Computerized Bucking.* Spanga - Sweden: Forskningsstiftelsen Skogsarbeten.

Sondell, J., Moeller, J., & Arlinger, J. (2001). *Third-generation merchandising computers.* Sweden: SkogForsk.

Standgard, M., & Walsh, D. (2012). *Assessing measruement accuracy of harvester heads in Australian pine plantations.* CRC for Forestry.

Strandgard, M., & Walsh, D. (2008). *Maintaining harvester measurement accuracy to maximise value recovery.* Australia: CRC for Forestry - University of Melbourne - University of Tasmania.

Strandgard, M., & Walsh, D. (2011). Improving harvester estimates of bark thickness for radiata pine. *Southern Forests, 72*(2), 101-108.

Walsh, D. (2012). *Quantifying the vlaue recovery improvement using a harvester optimiser.* CRC for Forestry - University of Tasmania.

Zacco, P. (1974). *The bark thickness of saw logs.* Sweden: Swedish Royal College of Forestry.

Appendix 1

Harvest progress tracking with the harvesters internal GPS:

PRI files can include, additionally to log measurement, the coordinates of every log produced. The limitations are, a log needs a bottom and a top cut to record data. In a fell and delimb scenario with landing based processing even a harvesting machine with a fully StanForD compliant OBC won't produce under normal circumstances a PRI with coordinates. During the trial SATCO and the author developed a work around by making changes in the OBC software and replacing the recoding trigger second cut with the process of tiling the head up right. This enabled the machine to produce PRI files containing spatial data, see Figure 15.

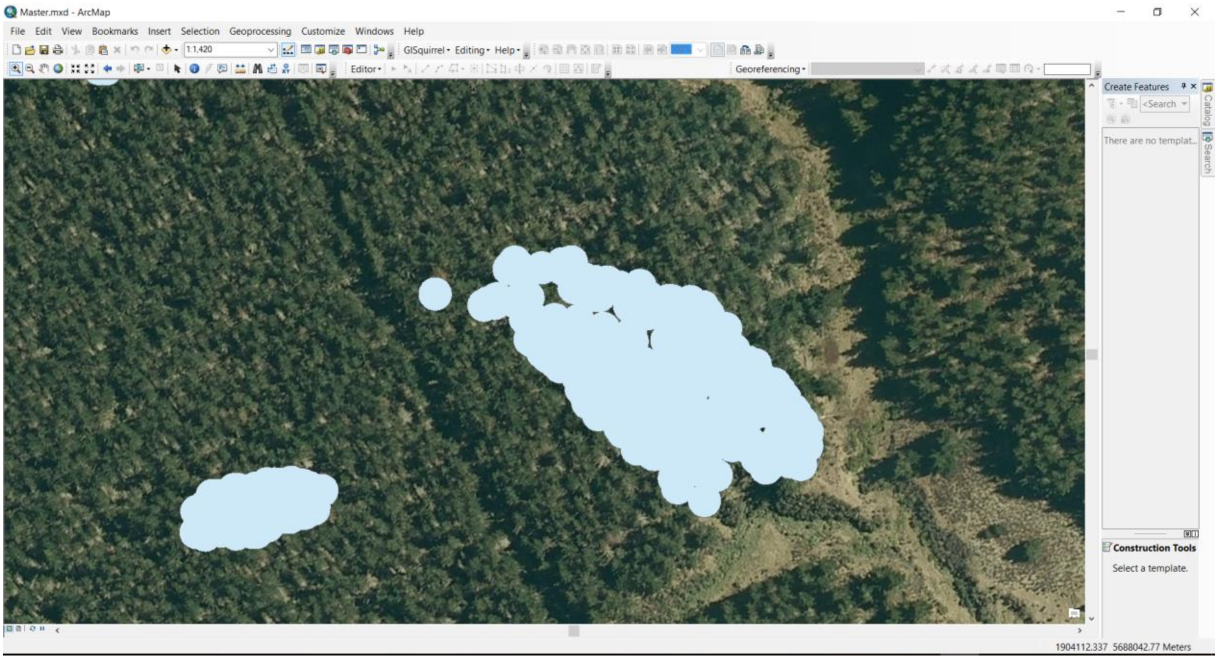


Figure 15 - Spatial data of trees harvested with the SATCO harvester and buffered on eight meter for average boom length

The spatial data will allow improvement of harvest and woodlfow management and is inexpensive and near real time. An example would be an implementation as a planning tool for contractors to estimate area left before felling machine is running out of work and therefore can be shifted without losing time. It should be noted that StanForD2010 won't have the limitation of the second cut for recordings anymore.

Appendix 2

Use of harvester data bush stock monitoring and replacing a manual counting by QC staff at end of the working day:

A comparison of the manual bush stock count taken at the end of each shift and the log count from the PRI files for the grade P35 on harvest area 5556 has been carried out. By adding the number of processed logs to previous day's stock and subtracting current days stock the number of uplifted logs could be calculated. To see the accuracy of the harvester count the total number of logs for grade P35 on harvest area 5556 was compared against the count of all logs uplifted. The result is 1340 logs within the PRI file and 1335 logs summarized all uplifted logs. The 5 missing logs were still at the landing when harvest crew moved. This result indicates the type of precision harvester data as a counting tool can achieve.

Table 23 - Harvester log count for P35 in HA 5556 and result of log count and calculated uplift

Date	Number of Logs Recorded by the Harvester	Number of Logs Recorded manually at the end of each shift	Logs Uplift
18/08/2015	17		
19/08/2015	97	99	15
20/08/2015	75	90	84
21/08/2015	131	82	139
24/08/2015	85	147	20
25/08/2015	88	109	126
26/08/2015	93	118	84
27/08/2015	60	107	71
28/08/2015	28	94	41
31/08/2015	92	111	75
1/09/2015	71	92	90
2/09/2015	104	134	62
3/09/2015	75	197	12
4/09/2015	71	233	35
7/09/2015	62	283	12
8/09/2015	144	216	211
9/09/2015	13	192	37
10/09/2015	34	72	154
11/09/2015		52	20
14/09/2015		13	39
15/09/2015		5	8
Summary	1340		1335

Table 24 - Logs counted by processor, by QC and the calculated uplift