The effect of the number of log sorts on mechanised log processing productivity and value recovery in landing-based cable yarder harvesting operations

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Abstract

The New Zealand forest industry produces a diverse range of log grades and sorts to meet domestic and export market demands and to maximise returns to the forest grower. An implication for the supply chain is the number of log grades and sorts a harvesting operation is expected to produce from one species, radiata pine (*Pinus radiata*). The number of log grades and sorts can impact on landing size and layout requirements, value recovery, log-making complexity, machine utilisation and quality control requirements.

A study was conducted to investigate if the number of log sorts affects mechanised log processing productivity and value recovery. This would determine if any gross value gains derived from producing a higher number of sorts are offset by losses in log processing productivity. Two landing-based mechanised log processors at cable yarder harvesting operations were studied using different cutting scenarios producing five, nine, twelve and fifteen log sorts. The study collected data from over 26 hours of mechanised processing which included the processing of 578 stems at an average piece size of approximately 1.6 m³. Machine utilisation results showed processors spending 84% of total time on productive tasks and that 49% of total time was spent on the primary productive tasks of log processing.

Quadratic regressions were used to model log processing productivity trends which showed piece size and cutting scenario as significant predictor variables (p-value < 0.01). There was a significant difference between cutting scenario with five log sorts and the cutting scenarios with twelve and fifteen log sorts (p-values < 0.05), as well as a significant difference between the nine and fifteen log sort cutting scenarios (p-value < 0.01). There was not enough evidence to suggest productivity was different between cutting scenarios producing five and nine log sorts. Based on this analysis, it was likely that the null hypothesis that the number of log sorts does not affect log processing productivity should be rejected. At a piece size of 2 m³, the productivity model estimated processing productivity was 10% higher producing nine log sorts compared to producing fifteen log sorts.

A linear regression model showed a strong relationship between gross value recovery, piece size and cutting scenario (p-value < 0.01). Gross value recovery increased as the number of log sorts increased. A significant model suggested it is likely null hypothesis 2, that the number of log sorts does not affect gross value recovery, should be rejected. There were only some differences in variances between cutting scenarios which were statistically significant. Both the average results and regression estimates showed the five log sort cutting
scenario recovering 94% of the value of the cutting scenario with fifteen log sorts. Incremental gains in value recovery as the number of log sorts increased were marginal, which appeared to be due to log prices for many major log grades trading in a close range in relation to historic price trends.

Regression trends for productivity and gross value recovery indicated that the most optimal cutting scenario, in terms of processing value outturn per productive machine hour, was the cutting scenario producing nine log sorts. This suggests that declines in processor productivity offset gains in gross value recovery when producing twelve and fifteen log sorts. Market sensitivity analysis suggested that differentials in log prices impact on the number of log sorts which optimise the value outturn per productive machine hour from log processing.
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1 Introduction

New Zealand’s log supply chain handles a wide range of log products to meet domestic and export market demands and to maximise returns to the forest grower. Managing such a wide array of products through the supply chain requires intensive processing, handling and logistics systems. Individual log products are referred to as ‘log sorts’, which is defined as a log grade of a given length. The number of log sorts produced by the industry can potentially impact productivity and costs through the supply chain. The New Zealand forest industry tends to produce a relatively higher number of log sorts compared to other softwood log producing nations in Scandinavia and North America. This research focuses on harvesting operations and the impact of the number of log sorts on mechanised log processing.

The higher number of log sorts produced by the New Zealand forest industry is driven by customer requirements and the potential to achieve greater value recovery (Cossens 1991). Domestic wood processors give consideration to a wide range of quality specifications and define log grades and sorts to reflect their requirements. Traditional specifications such as diameter, branch size, sweep and defects have been combined with more modern specifications such as wood stiffness, strength, density extractives content and spiral grain (Walker 2000). Another key driver of the increase in log sorts is expanding log export markets which receive a wide range of log products. Logs are now being exported to many Asian countries, with major destinations being China, South Korea, Japan and India (NZFOA 2012).

Harvesting crews in New Zealand are typically allocated a cutting instruction, or cutplan, which outlines a set of log sorts to be produced over a given timeframe. An important component of log processing operations is the ability of the operator to maximise value recovery (Cossens 1991). The trend in the New Zealand forest industry is to increase the number of log sorts to meet the specifications set by log buyers and to obtain the maximum possible gross value from an extracted stem at the processing site (Murphy and Marshall 2003). However, a higher number of log sorts can also increase log-making complexity, the number of pieces handled, log length variation and the additional time to segregate extra log sorts which can impact on production costs (Cass et al. 2009; Parker et al. 1993).
An individual forest estate can produce over thirty different log sorts at any given time and a single harvesting crew can produce around five to twenty log sorts from a single species, which is radiata pine (Visser 2013). Logs are typically processed and sorted on landings within the forest. A small proportion of stems are transported to central processing yards (CPY), or super-skids, to handle the production of a wide range of log products on a larger scale (McKerchar & Twaddle 1987).

Logs are either processed motor-manually, with a team of skid workers and a log maker, or in a mechanised operation, by an excavator with a processing head, before being sorted and fletted into log stacks according to sort. Log processing on landings requires experienced operators to log-make, which determines the value recovery from extracted stems, and space to sort logs into separate stacks. The processing and sorting components of landing-based harvesting operations can comprise a significant portion of harvesting costs.

A log grade is defined by a set of specifications as required by the customer relating to characteristics such as diameter, maximum branch size, maximum sweep and allowable defects (Whiteside & Manley 1986). There are five major log types produced, which are pruned logs, structural, utility, industrial and pulp. Each log type contains multiple grades and sorts which are specified for domestic or export markets, or both (Table 1).
Table 1: Description of typical New Zealand log types, grades, sorts and specifications

<table>
<thead>
<tr>
<th>Log Type</th>
<th>Market(s)</th>
<th>Log grades</th>
<th>Lengths/sorts (m)</th>
<th>SED (cm)</th>
<th>Max. branch size (cm)</th>
<th>Sweep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pruned logs</td>
<td>Export</td>
<td>P30, P35</td>
<td>3.7, 3.9, 4.0, 6.0</td>
<td>30+</td>
<td>0</td>
<td>SED/4</td>
</tr>
<tr>
<td></td>
<td>Domestic</td>
<td>P35, P40</td>
<td>3.75, 4.0, 4.4, 5.0, 5.5, 6.1</td>
<td>35+</td>
<td>0</td>
<td>SED/4</td>
</tr>
<tr>
<td>Structural</td>
<td>Domestic</td>
<td>S20, S30, S35</td>
<td>4.9, 5.5, 6.1</td>
<td>20+</td>
<td>7</td>
<td>SED/4</td>
</tr>
<tr>
<td>Utility</td>
<td>Export</td>
<td>A, AO</td>
<td>3.7, 3.9, 4.0, 4.1, 5.1, 5.2, 5.4, 7.8, 8.0, 12.0</td>
<td>30+</td>
<td>12</td>
<td>SED/4</td>
</tr>
<tr>
<td></td>
<td>Export</td>
<td>K, KS, KM</td>
<td>3.7, 3.9, 4.0, 4.1, 5.1, 5.2, 5.4, 7.8, 8.0, 12.0</td>
<td>16-30</td>
<td>12</td>
<td>SED/4</td>
</tr>
<tr>
<td></td>
<td>Domestic</td>
<td>L30, L40</td>
<td>4.1, 4.7, 5.0</td>
<td>30+</td>
<td>14</td>
<td>SED/4</td>
</tr>
<tr>
<td>Industrial</td>
<td>Export</td>
<td>KI</td>
<td>2.7, 3.1, 3.7, 3.9, 4.0, 4.1</td>
<td>26+</td>
<td>20</td>
<td>SED/3</td>
</tr>
<tr>
<td>Pulp logs</td>
<td>Export</td>
<td>Pulp</td>
<td>4.0, 6.0, 8.0</td>
<td>10+</td>
<td>Unlimited</td>
<td>Unlimited</td>
</tr>
<tr>
<td></td>
<td>Domestic</td>
<td>Pulp</td>
<td>3.0-8.0</td>
<td>10+</td>
<td>Unlimited</td>
<td>Unlimited</td>
</tr>
</tbody>
</table>

Source: MPI (2010); Rayonier Matariki pers. comm.

Over a period of expansion into log export markets, log prices for major domestic sawlog and export log grades have converged to a large degree. This price convergence has occurred over a period of rapidly increasing demand for logs in export markets. In 2012, over half of New Zealand’s log production in cubic metres of roundwood equivalent (m³ RWE) was exported (Figure 1) which was largely due to expanding markets in China. Of the total log export volume in 2012, over 65% was supplied to China.

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Historic log prices show a trend of convergence between major export grades since around 2008 (Figure 2). Export A and K grades averaged an approximate 5% price differential in 2012, compared to around 12% in 2008 when only 30% of log exports were supplied to China. The price for A and K grade has also become similar to prices for major domestic structural grades. Average prices for S1/S2 domestic structural sawlogs over the twelve months to November 2013 are around 5% less than lower quality export A grade and only around 2% higher than export K grade. This represents a significant change from 2008, when prices for S1/S2 were approximately 21% higher than A grade prices and 35% higher than K grade. The convergence of log prices will reduce incremental value gains from producing a large number of log sorts.

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Intensive handling, logistics and administration systems are required to manage the supply chain effectively. Each log sort is identified and handled through the supply chain and each export log sort is stored separately at port facilities until ship loading. The number of log sorts being handled through the supply chain impact efficiency and costs and there is limited research on this topic. Figure 3 shows the flow of log sorts through different components of the supply chain and key elements of each component.

Source: MPI (2013)

Figure 2: Historic monthly New Zealand log prices

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A thorough understanding of how the number of log sorts can affect productivity and costs through the supply chain could assist managers to make optimal decisions and improve efficiency. Harvesting represents one of the most significant supply chain costs for forest managers and a logical starting point to consider the effect of the number of log sorts on the supply chain. Figure 4 shows handling and storage requirements for producing a diverse range of log sorts at a landing-based cable yarder harvesting operation.

This study quantifies the effect of the number of log sorts on mechanised processing productivity in landing-based cable yarder operations. As the number and type of log sorts is a key driver of value that can be recovered from individual trees, the effect of the number of
log sorts on value recovery was also monitored. Another outcome of this study was to estimate the number of log sorts which optimises the value outturn from mechanised log processing per productive machine hour.

Section 2 includes a review of literature and Section 3 outlines the research questions and the tested null hypotheses. Section 4 details the methodology applied to the study to gather data to answer the research questions. Section 5 presents results and analysis followed by a discussion and conclusions in Section 6.
2 Literature review

This section considers relevant literature and topics related to studying the effect of the number of log sorts on harvesting operations. The literature review includes information on the following sub-sections:

- Log grades and sorts;
- Harvesting production studies;
- Mechanised processing productivity;
- Software for mechanised log processing;
- The effect of the number of log sorts on harvesting operations and value recovery; and
- The human operator factor.

2.1 Log grades and sorts

Although the New Zealand forestry industry has broadly adhered to a standard set of log grades, variations are often required to meet specific domestic and export market specifications. Continued development of export markets has led to wider variety of log sorts due to subtle differences in lengths, which can reflect on the separate sales agreements made between forest managers, log marketers and customers in China, South Korea, India and Japan (pers. comm. Rien Visser). Forest managers generally have internal systems for allocating stands and cutting instructions to harvesting contractors to meet operational and market requirements.

In manual and mechanised processing operations, log making is where decisions are made that directly contribute to the realisation of value from the forest. Log makers are required to select a suitable combination of log grades to be cut to maximise the potential value of the stem. In New Zealand, it is not unusual for log makers to make selections from a list of 15 to 20 sorts, when an average sized stem would produce around four to six logs. Errors made during the log making process can result in value loss from the forest stand (Parker et al. 1993).

Log grades in New Zealand were standardised in the 1980s when the Forest Research Institute developed a set of log grade specifications that could be used for both assessing the standing resource and for log sale purposes (Whiteside & Manley 1986). Twaddle (1986) discussed the potential consequences of the New Zealand forestry industry adopting this new
set of log grades and analysed the feasibility and cost of log sorting based on the new grades. Conclusions showed that no additional costs would be incurred unless market demands led to a wider variety of log sorts.

### 2.2 Harvesting production studies

Harvesting production studies, or time and motion studies on mechanised forest harvesting and processing are undertaken for various reasons, with a fundamental reason being an investigation into the factors affecting work productivity and operation costs (Björheden 1988). Factors affecting harvest system productivity can include terrain, forest stand characteristics, working conditions and machine operators (Visser & Spinelli 2011). An understanding of factors affecting productivity can inform improvements and developments in forest operations. Models can be developed from time and motion study results which can simulate key operational variables in different scenarios. These models can be used for purposes such as production and wood-flow planning and predicting harvesting productivity from different operational configurations.

A variety of methods are used to collect time and motion study data. A typical data collection technique uses pre-programmed work study software on a handheld field computer. A common method for collecting time study data is to use SIWORK3 software developed by the Danish Institute of Forest Technology for field computers (Glode 1999; Rolev 1988; Spinelli et al. 2002). Work cycle elements can be pre-defined and loaded into SIWORK3 for each machine. Detailed time and motion studies can also be effectively carried out by analysing video footage of forest operations (Björheden 1988; Nurminen et al. 2006).

Time and motion studies on forest harvest operations collect detailed data on defined work activities which generally form part of a production cycle. Cycle times are divided into time elements which are typical of the operations being studied. Time spent on work activities which are dependent on one or more external factors can be isolated to enable analysis of productivity relationships (Spinelli & Visser 2008). Time spent on significant work activities can then be coupled with operational inputs or outputs to form results.

### 2.3 Mechanised processing productivity

Mechanised log processing has become increasingly common in New Zealand and worldwide. Major drivers of the shift towards fully mechanised systems include productivity
and cost improvement goals, overcoming labour shortages and improving worker safety (Pasicott & Murphy 2013). Forest industry companies and researchers have looked at many aspects of mechanised harvesting operations to gain an understanding of the key drivers of production efficiency and the factors affecting productivity.

Landing-based mechanised processing productivity can be influenced by many factors. Tree size has been found to have a significant effect on productivity and the unit cost of production (Holtzcher & Lanford 1997). As tree size increases, the unit cost of production decreases. Other influencing factors include, tree form (Evanson & McConchie 1996), landing layout, the number of products to be produced and sorted (Cass et al. 2009) and the performance of the human operator (Murphy & Vanderburg 2007). The effect the number of log grades and lengths on log processing productivity is not as well understood and there is limited available public information and research in this area in New Zealand.

As most studies conclude piece size has a significant effect on processing productivity, various regression functions have been used to describe the relationship over a range of piece sizes. Some non-linear functions have been considered an appropriate regression trend for mechanised productivity relationships, while linear and power regression functions can be considered too aggressive and mono-directional (Visser & Spinelli 2011). Quadratic functions reflect a peak in productivity and a subsequent decline at larger piece sizes beyond the optimum operating point of a mechanised processing head. This is due to exceptionally large trees being difficult to process. Productivity curves can also be specific to cutting patterns. In European and North American production studies, productivity curves are commonly separated by the number of log sorts produced (Cass et al. 2009; Nurminen et al. 2006; Spinelli et al. 2002).

Mechanised processors operating on cable yarder landings generally have multiple responsibilities in addition to the primary task of processing logs. Other responsibilities can include clearing the yarder chute as stems are extracted, managing processing waste to a designated part of the landing as part of environmental requirements and pre-sorting logs for the loader. This differs from ground-based mechanised processing operations, where the processor can usually focus completely on cutting logs and maximising production and value recovery.

Studies have shown mechanised processing to be most productive working a single day shift. A comprehensive study based on over 30,000 machine hours maintained by a
Chilean forestry company found unit productivity of mechanised processing of radiata pine to fall by up to 30% beyond one nine hour shift (Pasicott & Murphy 2013). While overall production volumes increase from working extended or double shifts, unit harvesting costs increase due to productivity decline.

Productivity studies have been carried out in New Zealand on both mechanised cut-to-length and full tree length extraction operations. Many Scandinavian productivity studies focus on the commonly used cut-to-length harvesting systems. Tree length extraction to a landing or skid site, where log processing takes place, is generally used in steeper terrain in New Zealand where cable yarders are required. Evanson and McConchie (1996) compared mechanised processor productivity on landings in ground-based and cable yarder operations. Productivity was similar for both harvesting types using Waratah HTH 234 processing heads averaging around 77 m³ per productive machine hour (PMH). Evanson and Riddle (1994) evaluated the productivity of a Waratah HTH 234 hydraulic tree harvester in a landing-based radiata pine cable yarder operation and estimated productivity to be around 82 m³ PMH.

2.4 Software for mechanised processing

Modern harvesters and processors are equipped with on-board computers to assist the operator with log-making. Mechanisation of log making provides a format for the use of advanced measurement and monitoring technologies which can predict cutting patterns and potentially optimise the merchandising of stems into logs (Marshall 2005). Major forest machine manufacturers have included automatic tree processing functions, or ‘bucking algorithms’ to assist operators with maximising tree value.

On-board systems can forecast the profile of a stem and suggest a cutting pattern according to the diameter at the base of the current stem and cutting priorities. Stem profiles are forecast based on taper measurements recorded from previously processed stems. Forecasting contrasts to optimising the stem, where optimising incorporates a full stem scan prior to cutting, which is more time consuming and impractical. This requires precise measurements by the processing head and an accurate stem quality description by the operator as inputs (Marshall & Murphy 2004).

The standard for managing, formatting and communicating data collected by mechanised harvesters and processors is StanForD, which was recently updated as StanForD 2010. StanForD was developed in Scandinavia and is used globally by major manufacturers of forestry machines (Skogforsk 2011). StanForD provides a platform for recording
production data and detailed descriptions for individual stems and logs. Software loaded on machine computers also has capability for automatically recording productivity, machine movement time, machine location with global positioning systems (GPS) and fuel consumption (Skogforsk 2011).

Incorporating modern data management and communication technology into mechanised harvesting and processing provides potential for monitoring performance on a large scale at a detailed level. In combination with volume data, detailed time study information can be collected automatically. For example, a production study in north western Russia collected productivity data from 38 single grip wheeled harvesters cutting 1.4 million m³ under bark at an average piece size of 0.31 m³ under bark (Gerasimov et al. 2012). Purfürst (2010) evaluated the performance of 32 harvester operators using StanForD files containing data based on 0.65 million m³ of logs which was collected over a period of three years.

Standardised and automated computer systems present opportunities for forest managers and harvesting contractors to centralise and analyse large amounts of production data. Many harvesters and processors in New Zealand are equipped with on-board computers and log-making software which generate StanForD files. This technology and data capture could potentially be used to analyse harvesting operations and operators on a large scale.

2.5 The effect of the number of log sorts on harvesting operations

There is limited research and information available on the effect of the number of log sorts on mechanised harvesting productivity or other parts of the wood supply chain in New Zealand. Studies have been undertaken in Europe and North America, where the number of log sorts is usually much less than in New Zealand, which consider the impact and economic feasibility of increasing the number of log sorts. The increased time and machine capacity to undertake log sorting can add cost, which is partly due to the resulting decline in productivity (Cass et al. 2009). Murphy and Marshall (2003) suggested that producing and handling a larger number of log sorts could result in productivity decreases and cost increases, which can affect the economics of a harvesting operation.

Parker et al. (1995) studied the effect of the number of log grades on log making errors in New Zealand in a manual operation without the added time pressure of normal operational conditions. Results showed log making errors increased when more than ten
grades were included in the cutting strategy. Log making mistakes can reduce the recoverable volume and value recovery from the stem, as out of specification logs often need to be downgraded and re-cut on a landing or by customers.

The size and layout of a landing is an integral part of a harvesting operation, particularly on cable yarder landings in steep terrain where extraction, processing and truck loading takes place. Landing size in New Zealand harvesting operations is correlated with the number of log sorts and daily production (Raymond 1987; Visser 2010). Landing size was found to have doubled since the 1980s, with a key driver being an increasing number of log sorts over time.

Log sorting is usually carried out by a hydraulic knuckleboom loader on cable yarder landings which organises, or fleets, processed logs by grade and sort into stacks. Raymond (1988) conducted a study on loader productivity on a small landing of approximately 1,600 m² for a cut to length operation with ten log sorts. The study found around 42% of the loaders productive time is spent sorting and stacking logs, with other time mostly spent loading trucks.

In the US South, Cass et al. (2009) evaluated the impact of producing different log sorts against the typical tree-length stem production system, where whole stems are loaded on to trucks. Crew production was found to be impacted by producing and sorting multiple log sorts. Weekly production declined when more than nine log sorts were produced and average net revenue was found to decline when more than four log sorts were produced. This overall loss in revenue was attributed to the extra processing and handling of log sorts which reduced productivity and increased the harvesting cost.

In Finland, primary wood processors are increasing requirements for defined quality and log making precision, which has led to an increase in the number of log sorts since the 1990s (Nurminen et al. 2009). This has led to concerns relating to whether the gains achieved with better defined log specifications are offset by increased production and logistics costs. An activity-based costing system has been developed to allocate costs to products according to the actual time and machine requirements for production and transport.

A time study of mechanised cut-to-length operations in Finland found that stem size, tree species and the number of log assortments affected log processing productivity (Nurminen et al. 2006). Operations included in the study mostly produced only one or two
different log sorts, or wood assortments, per stem. Producing an additional log sort slowed the processing of Scots pine stems by 3% to 10%, Norway spruce by 3% to 11% and silver birch stems by 2% to 9%. Stem size was small relative to New Zealand radiata pine at around 0.3 to 0.8 m³ per stem.

2.6 The effect of the number of log sorts on value recovery

Gross value recovery (value of logs processed from a stem prior to incurring any production costs) from extracted trees generally improves as the number of log sorts increases due to the wider variety of potential merchandising cutting patterns. Various studies have assessed trees for theoretical optimal value recovery, which is the maximum possible gross value to be obtained from a given cutting pattern and sample of trees (Cossens 1991; Murphy & Marshall 2003; Parker et al. 1998). In these studies optimal gross value recovery can be estimated by conducting a detailed measurement of stems to note size, form, taper and quality features. Measurements are then analysed with an optimiser to compute log making decisions which derive maximum gross value from the sample.

Murphy and Marshall (2003) found at least 95% of theoretical optimal value can be recovered with five or fewer log sorts depending on market complexities and pricing. Beyond five log sorts, incremental gains in gross value substantially diminished. A net value recovery trend was conceptualised, taking the impact of increased production costs into account as the number of log sorts increased. It was expected the net value trend would reach a peak at an optimum number of log sorts for a logging crew for a given set of conditions. This also assumed increased decision making complexity for log makers would lead to mistakes and lower productivity as the number of log sorts increased.

Studies have been conducted on the quality and accuracy of mechanised log making and how this impacts value recovery. Cossens (1991) found mechanised processing to recover 1.2% less value in comparison to manual log making. There has been a strong financial interest in improving the accuracy of mechanised log making which has included the development of various on-board computer calculations to assist with log making decisions. Marshall (2005) looked at the economic impacts of measurement errors on value recovery in mechanised harvesting operations. Operational data included in the study showed potential value loss of 3% to 23% due to measurement errors.

Value loss from mechanised log-making can occur due to inaccurate measurements and failure to capture volume of higher value products which leads to material being
downgraded into lower value products, such as pulp wood (Boston & Murphy 2003). Evanson (1995) considered mechanised log making accuracy from a sample of machines and sites across New Zealand and found most processors processed within length tolerances for around 90% of logs and within small end diameter (SED) tolerances for 95% of logs. Evanson and McConchie (1996) found a sample of two Waratah tree harvesters to have length measuring accuracy of ± 5 centimetres for 93% of logs. Variable results for mechanised log making can also relate to operator ability and technique, the type of processor, the degree of production pressure and stem characteristics.

### 2.7 Human operator factor

A key variable affecting mechanised harvesting productivity and processing accuracy is the performance of the human operator. Many of the new and advanced technologies applied in mechanised harvesting systems require a human operator to handle and manage them. In comparison to equipment, a human operator could be considered much more variable in terms of specifications, capabilities and limitations (Murphy & Vanderburg 2007). The physical, mental and emotional demands placed on a human operator could impact on productivity, safety and value recovery. Studies from other industries have shown the detection of defects to decline as an inspection task becomes more complex (Harris & Chaney 1969). This theory can be considered highly relevant to manual or mechanised log processing, where the log-maker or operator is expected to identify multiple stem quality and shape characteristics in an intensive work environment.

A processor operator is both a machine operator and a log maker, who is required to select the best possible option from a list of log sorts to maximise value while meeting crew production targets. The operation of a harvester or processor is regarded as an intensive and complex work task which includes cyclic repetition of work activities. Gellerstedt (2002) study found operators having 3,400 to 3,700 inputs per hour in mechanised thinning operations in Sweden. The study concluded that further automation of machine operations are required to reduce operator workload of mechanised harvesting machines. Studies on log-makers have strongly recommended frequent rests and job enrichment initiatives to mitigate tediousness (Parker et al. 1993).

Studies have been conducted on the physical workload of forestry machine operators. Results for processor operators show mental and physical fatigue increasing over the work day (Kirk 1998). Worker fatigue has been identified as a major driver of workplace accidents.
in many industries and it needs to be carefully managed in forestry due to the physically and mentally demanding nature of the work (Lilley et al. 2002). Harvester productivity can decline due to operators working extended hours or working a night shift (Nicholls et al. 2004).

The human operator factor must be taken into account when conducting harvesting production studies. Productivity estimates and models need to be based on large sample sizes to overcome the variation caused by operator performance, which can be as high as 20% to 50% (Murphy et al. 2005; Murphy & Vanderburg 2007; Nurminen et al. 2006; Visser & Spinelli 2011). Purfürst (2010) analysed harvester production data in Germany from 16 new operators and defined a learning period of approximately eight months before maximum productivity was achieved. Although learning curves varied significantly by operator, most new operators had doubled their output by the end of the learning phase. This demonstrates the training phase of a new operator is expensive and good experienced operators are a strong driver of harvest system productivity.

In addition to collecting large sample sizes, production studies should be conducted in conditions reflecting normal operations to mitigate the “Hawthorne Effect”, where productivity tends to increase during trials due to increased personnel interaction and supervision of work tasks (Karsten 2013). Technological developments in processor on-board computers could mitigate the Hawthorne Effect, as large amounts of data can be collected without significantly interfering with normal operations.
3 Research questions and hypotheses

The literature review shows there has been a substantial amount of research into different aspects of mechanised harvesting production over the last twenty to twenty-five years. However, while the research presented in the literature review is relevant, there is a limited amount of previous work which quantifies the impact of producing a large number of log sorts on the productivity of harvesting operations in the New Zealand forest industry. Recent trends in log prices further emphasise the need for research in this area, as a large number of log products of varying quality are selling for similar prices. The key issue is that some or all of the gains in value arising from producing a relatively extensive product range could be offset by the required production and handling costs through the supply chain.

While research has been conducted on the impact of the number of log sorts on manual log-maker errors and value recovery in New Zealand, there is no published work relating to the effect on mechanised processing productivity. This research focused on the impact of the number of log sorts on mechanised log processing productivity and tested the null hypothesis that the number of log sorts does not affect mechanised log processing productivity.

As the number of log sorts has implications for value recovery, this research also investigated the impact on gross value recovery, with gross value recovery being defined as the market value of processed stems prior to incurring any production, handling or transport costs. This tested a second null hypothesis, that the number of log sorts does not affect gross value recovery. Productivity and value recovery analysis was also combined to give an indication of the most optimal number of log sorts for processing, in terms of the value outcome per productive machine hour.

Overall, this research aimed to answer the following questions:

I. Does the number of log sorts affect mechanised log processing productivity in landing-based cable yarder harvesting operations?
   o This tested null hypothesis 1: the number of log sorts does not affect mechanised log processing productivity in landing-based cable yarder harvesting operations.

II. A) Does the number of log sorts affect gross value recovery in landing-based mechanised log processing operations?
o This tested null hypothesis 2: the number of log sorts does not affect gross value recovery in landing-based mechanised log processing operations.

B) How many log sorts should be produced to optimise processing value outturn in landing-based mechanised log processing operations?
4 Methodology

A field study was conducted to collect data on the implementation of a range of cutting instructions on mechanised processing operations. To meet the objectives of the study, two mechanised processing operations were observed with each using four different cutting instructions. The four cutting instructions were defined as ‘cutting scenarios’ which differed in the type and number of log sorts. For the purposes of this study, a log sort was defined as a log grade of a given length. The four cutting scenarios contained five, nine, twelve and fifteen log sorts. Two key types of data were collected from each cutting scenario to estimate productivity and value recovery:

1. Processed volume by stem, log and log grade; and
2. Time and motion observations on the processor for each stem.

Processed volume and time and motion data was subsequently aligned to derive productivity and value recovery estimates. Figure 5 shows an outline of the study and the types of data collected from processors and time and motion studies.

Figure 5: Study design and data collection techniques
4.1 Site and stand characteristics

The field study was carried out in Onewhero forest, approximately 75km South of Auckland in the North Island of New Zealand (Figure 6). Harvesting in Onewhero forest was managed by Rayonier Matariki Forests and carried out by logging crews from Davis logging. This site was chosen for the study as there were two harvesting crews located in close proximity to each other. Both crews were operating the same mechanised processor and were able to use the same cutting instructions. While the inclusion of two crews was considered sufficient within the scope of a Masters and the project budget, it is recognised that studying more crews across different regions would improve the representativeness of results.

![Map of Onewhero Forest](image)

Source: Land Information New Zealand (2013)

**Figure 6: Location of Onewhero Forest**

Plantations in the harvest settings were predominantly planted in 1987 and were 26 years of age at the time of harvest. Pruning was variable, with most stands being pruned up to four to six metres. Topography was predominantly rolling hill country with a series of steep valleys and long leading ridges. Most of the Onewhero plantation is located in the altitudinal range between 200 and 400 metres, with some below 200 metres on the North side where terrain slopes down towards the Waikato River. Tree size tended to be smaller on ridges in comparison to trees located in gullies.
The steep and variable topography in Onewhero suited cable yarder harvesting operations. Cable yarding distances extended to a maximum of around 400 metres in both harvest settings. Steep gullys or ‘guts’ were located throughout the harvest settings which presented challenges for yarder drivers and choker-setters (breaker-outs). Conditions were generally wet or overcast during the study period. Figure 7 shows the two study sites and the nature of the working environment for cable yarding harvesting operations.
Site 1

Site 2

Figure 7: Study sites within Onewhero Forest
Pre-harvest inventory data for each sample plot located within the harvest settings were provided by the forest manager and stand attributes were estimated as at June 2013 using YTGen inventory processing software. A larger piece size was estimated for site 2, with an average of 2.4 m³ per stem compared to 2.1 m³ per stem at site 1. Table 2 lists stand characteristics for the harvest settings included in the study.

Estimated stand attributes between individual sample plots showed stocking varying from 171 stems per ha to 440 stems per ha at site 1 and from 142 stems per ha to 369 stems per ha at site 2. This could partly explain the range in estimated piece size between plots, which varied from 1.4 m³ per stem to 2.6 m³ per stem at site 1 and from 1.9 m³ per stem to 3.3 m³ per stem at site 2. A similar level of inter-plot variability was also evident in the estimated total recoverable volume (TRV) at each site, which ranged from 337 m³ per ha to 805 m³ per ha.

**Table 2: Estimated stand attributes of study sites**

<table>
<thead>
<tr>
<th>Stand attributes</th>
<th>Site 1 Average</th>
<th>Inter-plot range</th>
<th>Site 2 Average</th>
<th>Inter-plot range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piece size (m³/stem)</td>
<td>2.1</td>
<td>1.4 – 2.6</td>
<td>2.4</td>
<td>1.9 – 3.3</td>
</tr>
<tr>
<td>Height (m)</td>
<td>36.6</td>
<td>34.1 – 38.5</td>
<td>35.5</td>
<td>33.5 – 37.9</td>
</tr>
<tr>
<td>Stocking (stems/ha)</td>
<td>276</td>
<td>171 - 440</td>
<td>239</td>
<td>142 – 369</td>
</tr>
<tr>
<td>TRV (m³/ha)</td>
<td>587</td>
<td>349 – 805</td>
<td>565</td>
<td>337 - 746</td>
</tr>
<tr>
<td>Pruned %</td>
<td>13%</td>
<td>2% - 31%</td>
<td>12%</td>
<td>0% - 27%</td>
</tr>
<tr>
<td>Structural %</td>
<td>18%</td>
<td>0% - 53%</td>
<td>14%</td>
<td>3% - 30%</td>
</tr>
<tr>
<td>Utility/Industrial %</td>
<td>49%</td>
<td>32% - 64%</td>
<td>54%</td>
<td>38% - 76%</td>
</tr>
<tr>
<td>Pulp %</td>
<td>20%</td>
<td>7% - 43%</td>
<td>20%</td>
<td>7% - 48%</td>
</tr>
</tbody>
</table>

Source: Rayonier Matariki (2013), MPI (2013)

A cutting strategy was developed from the generic Ministry of Primary Industries (MPI) log types, grades and sorts to estimate log type recovery at each site. Log type recovery estimates show an expected 12% to 13% average outturn of pruned logs, 14% to 18% of domestic structural sawlog, 49% to 54% of export utility and industrial grades and 20% of pulp grade logs. Estimates of log type outturn varied significantly between inventory plots, indicating variable tree quality within each of the harvest settings.

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4.2 Harvesting operations and work methods

The cable yarding operations comprised of a Madill 124 swing yarder operating a scab skyline system (site 1) and a Madill 171 tower yarder operating a live skyline shotgun system with a motorised carriage (site 2). The swing yarder at site 1 operated with a grapple where possible. However, two to three breaker-outs working with three strops for extraction was the preferred option over the study period. Processing was undertaken with Caterpillar 330DL excavators each fitted with a Waratah HTH626 processing head. Both crews averaged a daily production of around 240 tonnes of logs, which tended to vary on a daily basis according to the performance of the extraction phase of the operations.

Processing areas were located adjacent to the haulers and processed logs were pre-sorted for fleeting. Each processor operator had over five years mechanised and ten years log making experience. At each operation, the processor had multiple responsibilities which included:

- Clearing the hauler chute (whilst ensuring safety of breaker outs);
- Managing processing waste;
- Delimbing trees;
- Log processing; and
- Pre-sorting logs for the loader.

Site 1 encompassed a complete extraction, processing and stacking operation and Site 2 was a two stage operation where logs were processed at the hauler and then transported by forwarder to another landing. Both processors followed a similar work method, where the first work priority was to clear stems from the hauler chute and then delimb stems before placing them in a surge pile. During hauler cycles, the processor would move over to the surge pile and process delimbed stems. Figure 8 shows the two processors observed in the study.
Figure 8: Processors operating at each site during the study
The processor at site 1 operated in a more confined space in comparison to site 2. At site 2, the processor worked in conjunction with the hauler and a forwarder without space constraints. At site 1, the processor was operating in a limited space between the swing yarder and the loader. The processor was also required to clear the yarder chute immediately due to the steep drop-off from the landing causing safety concerns for the breaker-outs.

Each processor was fitted with an on-board computer to run Waratah TimberRite measuring and control system software. A profile of each stem and processed logs were recorded in stem files which were downloaded from the processor. Stem files recorded by the processors followed the StanForD Nordic standard for collecting stem and log information from mechanised processing.

### 4.3 Preparation of cutting instructions

Cutting instructions for each cutting scenario were prepared off-site on Silvia desktop software and then loaded on-site into the TimberRite system. TimberRite applies a predictive log-making function according to the priorities set out in cutting instructions. The operator has an option to accept the cutting prediction or override the prediction with a manual cut selection based on observations of stem characteristics. Working in conjunction with the forest manager, log grades and sorts were selected from the range of possible products able to be supplied to domestic and export markets at the time of data collection. To prepare the four cutting scenarios with 5, 9, 12 and 15 log sorts, longer length log sorts were retained as a priority and at least one sort for each log type (log types being pruned, structural, industrial, utility and pulp) were retained if possible.

The cutplan with the fewest log sorts (5) only included domestic pruned, two export K grades, export KI grade and a pulp grade. To reduce this scenario to five sorts, the maximum small end diameter (SED) range of export K grade 3.9 metre and 5.9 metre lengths were expanded beyond the usual upper SED limit of 30 centimetres to 50 centimetres. This effectively combined A grade and S30 volume as K grade volume. Expanding the K grade SED range was possible as A grade length requirements were the same as K grade in export log markets at the time of the study. This allowed for minimal disruption to normal landing operations, as A grade sized logs could be sorted from K grade logs following the processing phase.

Table 3 lists the log grades and sorts included in each cutting scenario and their respective size and quality specifications. Pruned P35 log grades were produced at the
different lengths of 4.4, 5.0 and 5.5 metres. These P35 lengths were defined as one log sort to reflect how the lengths were fleteed on the landing and loaded out on trucks. The domestic structural grade (S30) was divided into two log sorts, with S30 4.9 metre and 5.5 metre lengths being one sort and 6.1 metre being another. This also reflected how the lengths were fleteed on the landing and loaded out.

Table 3: Log grades and sorts included in the study by scenario

<table>
<thead>
<tr>
<th>Cutting priority</th>
<th>Grade</th>
<th>Lengths/sorts (m)</th>
<th>Min. SED (cm)</th>
<th>Max. branch size (cm)</th>
<th>Indicative price (NZ$/m² AMG/AWG)</th>
<th>Log sort scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P35</td>
<td>4.40/5.00/5.50</td>
<td>35</td>
<td>0</td>
<td>145</td>
<td>Y Y Y Y Y</td>
</tr>
<tr>
<td>2</td>
<td>P35</td>
<td>3.75</td>
<td>35</td>
<td>0</td>
<td>145</td>
<td>Y</td>
</tr>
<tr>
<td>3</td>
<td>S30</td>
<td>6.10</td>
<td>30</td>
<td>7</td>
<td>112</td>
<td>Y Y Y</td>
</tr>
<tr>
<td>4</td>
<td>S30</td>
<td>4.90/5.50</td>
<td>30</td>
<td>7</td>
<td>112</td>
<td>Y Y Y</td>
</tr>
<tr>
<td>5</td>
<td>AO</td>
<td>3.90</td>
<td>45</td>
<td>10</td>
<td>110</td>
<td>Y</td>
</tr>
<tr>
<td>6</td>
<td>A</td>
<td>5.90</td>
<td>30</td>
<td>10</td>
<td>110</td>
<td>Y Y Y</td>
</tr>
<tr>
<td>7</td>
<td>A</td>
<td>3.90</td>
<td>30</td>
<td>10</td>
<td>110</td>
<td>Y Y Y</td>
</tr>
<tr>
<td>8</td>
<td>K</td>
<td>5.90</td>
<td>22</td>
<td>10</td>
<td>105</td>
<td>Y Y Y Y*</td>
</tr>
<tr>
<td>9</td>
<td>K</td>
<td>3.90</td>
<td>22</td>
<td>10</td>
<td>105</td>
<td>Y Y Y Y*</td>
</tr>
<tr>
<td>10</td>
<td>K</td>
<td>3.77</td>
<td>22</td>
<td>10</td>
<td>105</td>
<td>Y</td>
</tr>
<tr>
<td>11</td>
<td>KM</td>
<td>3.95</td>
<td>16</td>
<td>8</td>
<td>102</td>
<td>Y Y Y</td>
</tr>
<tr>
<td>12</td>
<td>KI</td>
<td>3.90</td>
<td>26</td>
<td>20</td>
<td>93</td>
<td>Y Y Y Y</td>
</tr>
<tr>
<td>13</td>
<td>KI</td>
<td>3.15</td>
<td>26</td>
<td>20</td>
<td>93</td>
<td>Y Y</td>
</tr>
<tr>
<td>14</td>
<td>Pulp (small)</td>
<td>3.00 - 8.00</td>
<td>10</td>
<td>Unlimited</td>
<td>48</td>
<td>Y Y Y Y</td>
</tr>
<tr>
<td>15</td>
<td>Pulp (large)</td>
<td>3.00 - 8.00</td>
<td>30</td>
<td>Unlimited</td>
<td>48</td>
<td>Y Y</td>
</tr>
</tbody>
</table>

*In the 5 sort scenario, the SED was expanded for K grade 3.9m and 5.9m to combine A and K grade specifications

The order of cutting priorities reflects the TimberRite log-making priority matrix which was based on log price relativities at the time of the study. Indicative log prices were sourced from the June 2013 Agrifax log price publication and these prices were aligned with the order of cutting priorities. These log prices were applied to the processed volume data to estimate gross value recovery by cutting scenario.

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4.4 Time study

All activities associated with the operation of a mechanised processor on a cable yarding landing were considered for inclusion in the time study. Time study data was separated into three groups:

1. Productive time – primary tasks
2. Productive time – other tasks
3. Non-productive time

Productive time was separated into time spent on the ‘primary tasks’ and ‘other tasks’. Primary tasks included the time taken for the processor to move towards the surge pile, pick up a stem and process the stem into logs. Productive time attributed to ‘other tasks’ included tasks undertaken by the processor that contributed to normal landing operations. These ‘other tasks’ included clearing the chute at the yarder, managing processing waste, pre-sorting logs for the loader and delimming. Delimming could not be included as a primary task as it was undertaken in batches as stems were collected from the chute, which was prior to stems being placed in the surge pile for later processing.

Non-productive time included idle machine time and delays due to breakdowns, maintenance and repairs. Scheduled breaks and lunch were not included in the time study. Table 4 lists the definitions and classifications of work activities applied in the time study.
Table 4: Work activity definitions for the time study

<table>
<thead>
<tr>
<th>Work phase and activity</th>
<th>Descriptions used for time studies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Productive time - Primary</strong></td>
<td></td>
</tr>
<tr>
<td>Positioning and pickup</td>
<td>Begins when the processor starts to move to the surge pile and ends once a stem has been picked up and is positioned by the feeder rollers for making the first cut.</td>
</tr>
<tr>
<td>Processing – cross-cutting</td>
<td>Starts when the first cut is made (usually to remove the sloven), continues while the stem is bucked into logs and ends when the last cut is made and the last log is dropped onto the sorting pile.</td>
</tr>
<tr>
<td><strong>Productive time - Other tasks</strong></td>
<td></td>
</tr>
<tr>
<td>Clear chute</td>
<td>Begins when the processor moves towards the yarder to collect extracted stems and finishes when the stems are placed in the surge pile or when the processor begins to delimb the stems prior to placing them in the surge pile.</td>
</tr>
<tr>
<td>Delimming</td>
<td>Delimming was usually undertaken as stems were cleared from the chute, prior to the stems being placed in the surge pile for later processing. Delimming began when the feeder rollers started moving the stem and finished when the stem was placed in the surge pile.</td>
</tr>
<tr>
<td>Waste management</td>
<td>Time spent picking up and moving logging waste into designated areas according to slash management arrangements.</td>
</tr>
<tr>
<td>Log sorting</td>
<td>Time spent picking up and moving processed logs into sorting piles for the loader (pre-sorting).</td>
</tr>
<tr>
<td><strong>Non-productive time</strong></td>
<td></td>
</tr>
<tr>
<td>Sitting idle</td>
<td>Time spent sitting with the engine idling, not carrying out any particular tasks. This could be due to the operator talking on the phone or radio, or while there are no stems to process as the operator waits for more stems to be extracted by the hauler.</td>
</tr>
<tr>
<td>Other delays</td>
<td>Time when the processor was not operational due to breakdowns, maintenance and repairs.</td>
</tr>
</tbody>
</table>

4.5 Data collection

The study was conducted over a period of two weeks in June 2013. Data was collected on each cutting scenario during two separate data collection sessions at each operation. Data collection sessions were scheduled randomly on different days to mitigate any effect of the day of the week on production. For example, the harvesting crews could potentially be more productive on Mondays than Fridays. Sample units were defined as a stem or piece of a stem which was processed into at least one log. This aligned with how the
TimberRite processor software created individual stem files. The target sample size was to collect data on 60 to 80 samples for each scenario at each operation, which equated to a minimum of 120 samples for each cutting scenario and a minimum of 480 samples in total.

Time and motion data was collected on an Android smartphone using SIWORK3 work study software developed by the Danish Institute of Forest Technology. Work activity definitions for the time study were pre-programmed into SIWORK3. A DOS emulator, DOSBox, was installed on the Android smartphone to run the software. Each data collection session commenced once the cutting instruction had been loaded into the TimberRite software and an individual observation was made in SIWORK3 for each sample.

Processing volume data was collected by downloading stem files (.stm) and production files (.prd) from the Waratah on-board computer on to a USB memory stick at the conclusion of each data collection session. Stem files included volume, dimensional and grade information about every stem and processed log. Production files provided a higher level summary of the volume of processed stems and logs. Time study data and volume data was aligned for each sample by matching up time study observations with the respective stem file data.
5 Results

This section presents results and analysis based on the field study data. Data from both of the studied sites was used to produce these results. The results are presented in five parts:

1. Machine utilisation – a summary of time study data showing the average amount of time spent on each defined work activity by the processors;
2. Processor volume data – a summary of the volume data collected by the Waratah TimberRite log making software;
3. Processing productivity – an alignment of time study and volume data to show productivity in each cutting scenario;
4. Productivity relationships – identification of productivity relationships and statistical analysis to test null hypothesis 1; and
5. Value recovery – log grade outturn and average gross value recovery by cutting scenario, identification of gross value recovery relationships and statistical analysis to test null hypotheses 2, the determination of the most optimal cutting scenario and market sensitivity analysis.

Parts one through to four addresses the research question to investigate the effect of the number of log sorts on mechanised processing productivity. Part four also tests null hypothesis 1 that the number of log sorts does not affect mechanised log processing productivity. Part five address the research questions to investigate the effect of the number of log sorts on gross value recovery (null hypothesis 2) and to determine the number of log sorts which optimises the value outturn from processing by taking account of both productivity and value recovery.

5.1 Machine utilisation

The time study comprised of a total of 26.1 hours of observed processor activities, of which 12.8 hours (approximately 49%) was spent on the primary task of picking up and processing logs. Overall, machines were utilised for 84% of the time study, which included other productive tasks such as clearing the yarder chute (16%), delimming (10%), waste management (5%) and log sorting (4%). Around 16% of total time was considered as non-productive, which included time spent with the machine sitting idle or delayed by maintenance or repairs. Idle time tended to only occur due to long cable yarding distances or
when tailhold cable position was shifted. Table 5 lists the average and total time spent on each work activity per stem during the time study.

Table 5: Summary of the processor time spent on each defined work activity

<table>
<thead>
<tr>
<th>Time element</th>
<th>Avg. time per sample unit (min)</th>
<th>Total sample (hours)</th>
<th>Proportion of time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Productive time – Primary tasks</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positioning and pick up</td>
<td>0.29</td>
<td>2.8</td>
<td>11%</td>
</tr>
<tr>
<td>Processing</td>
<td>1.03</td>
<td>9.9</td>
<td>38%</td>
</tr>
<tr>
<td><strong>Productive time - Other tasks</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delimbing</td>
<td>0.27</td>
<td>2.6</td>
<td>10%</td>
</tr>
<tr>
<td>Clear chute</td>
<td>0.43</td>
<td>4.2</td>
<td>16%</td>
</tr>
<tr>
<td>Waste management</td>
<td>0.14</td>
<td>1.3</td>
<td>5%</td>
</tr>
<tr>
<td>Log sorting</td>
<td>0.11</td>
<td>1.0</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Non-productive time - Delays</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sitting idle</td>
<td>0.25</td>
<td>2.4</td>
<td>9%</td>
</tr>
<tr>
<td>Other delays</td>
<td>0.18</td>
<td>1.8</td>
<td>7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.71</strong></td>
<td><strong>26.1</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

Productive time comprised of an average 0.29 minutes for the processor to position the processor and pick up each sample and 1.03 minutes to process the sample. This equated to an average pick up and process time of around 1.32 minutes. Around 0.95 minutes per sample was spent on other tasks such as clearing the hauler chute, managing harvesting waste or pre-sorting logs for the loader. If non-productive time is included with productive time, it took a total of 2.71 minutes to process each sample.

Around 13.3 hours and 12.9 hours of time study data was collected at site 1 and site 2, respectively (Table 6). Machine utilisation by site shows each processor spent a similar proportion of time picking up and processing stems (47% to 50%). On average, the operator at site 2 processed stems 0.14 min, or 10%, faster than the operator at Site 1. This could be due to many factors such as less variable tree form and a larger working space at site 2 relative to site 1, or differences in operator performance.
Table 6: Time study data collected by site

<table>
<thead>
<tr>
<th>Time element</th>
<th>Site 1</th>
<th>Site 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg. (min)</td>
<td>Total (hours)</td>
</tr>
<tr>
<td><strong>Productive time – Primary tasks</strong></td>
<td>1.39</td>
<td>6.7</td>
</tr>
<tr>
<td>Positioning and pick up</td>
<td>0.33</td>
<td>1.6</td>
</tr>
<tr>
<td>Processing</td>
<td>1.06</td>
<td>5.1</td>
</tr>
<tr>
<td><strong>Productive time - Other tasks</strong></td>
<td>0.93</td>
<td>4.5</td>
</tr>
<tr>
<td>Deliming*</td>
<td>0.23</td>
<td>1.1</td>
</tr>
<tr>
<td>Clear chute</td>
<td>0.43</td>
<td>2.1</td>
</tr>
<tr>
<td>Waste management</td>
<td>0.10</td>
<td>0.5</td>
</tr>
<tr>
<td>Log sorting</td>
<td>0.17</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Non-productive time - Delays</strong></td>
<td>0.44</td>
<td>2.1</td>
</tr>
<tr>
<td>Sitting idle</td>
<td>0.23</td>
<td>1.1</td>
</tr>
<tr>
<td>Other delays</td>
<td>0.21</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.32</strong></td>
<td><strong>13.3</strong></td>
</tr>
</tbody>
</table>

Both of the processors spent around 16% of time at respective haulers clearing the chute, which was carried out on an as required basis and operators would stop processing to attend to the yarder chute. Delimming, which comprised 8% to 12% of total time, was carried out as stems were collected from the chute. Delimbed stems were then placed in the surge pile ready for later processing.

During periods of longer cable yarding distances, which often extended out to 300 to 400 metres, the processor was able to focus most of its time on processing the surge pile. On occasions when the surge piles had been completely processed and hauler cycles were slow, operators used these opportunities to carry out other important tasks such as managing waste (4%-6%) or log sorting (2%-4%). Non-productive time was similar at both sites, comprising around 16% of the total observed time.

5.2 Processor volume data

Volume data was downloaded from the processor on-board computers and extracted using Silvia desktop software. A total of 578 stems and 1,957 processed logs made from 2,769 saw cuts were included in the sampling across both sites. The number of samples was similar at each site, with 288 observations at site 1 and 290 at site 2. These observations include broken parts of stems and tree tops which were treated as individual stems if they were processed into at least one log. Table 7 lists a summary of the sample volume and other attributes by site.
Table 7: Summary of processed stems and log characteristics by site

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations (n)</td>
<td>288</td>
<td>290</td>
<td>578</td>
</tr>
<tr>
<td>Total volume (m³)</td>
<td>419</td>
<td>500</td>
<td>920</td>
</tr>
<tr>
<td>Avg. piece size (m³)</td>
<td>1.5</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Max. piece size (m³)</td>
<td>4.8</td>
<td>4.6</td>
<td>4.8</td>
</tr>
<tr>
<td>Min. piece size (m³)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Avg. base diameter (cm)</td>
<td>36.4</td>
<td>38.4</td>
<td>37.4</td>
</tr>
<tr>
<td>Avg. length (m)</td>
<td>14.8</td>
<td>15.9</td>
<td>15.4</td>
</tr>
<tr>
<td>Total saw cuts</td>
<td>1307</td>
<td>1462</td>
<td>2769</td>
</tr>
<tr>
<td>Avg. saw cuts</td>
<td>4.5</td>
<td>5.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Total logs</td>
<td>946</td>
<td>1011</td>
<td>1957</td>
</tr>
<tr>
<td>Avg. logs</td>
<td>3.3</td>
<td>3.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Although a similar amount of observations was made at each site, a higher volume was sampled at site 2 due to a larger average piece size of 1.7 cubic metres compared to 1.5 cubic metres at site 1. A total processed volume of 920 cubic metres was sampled. There was a large range in piece size, from 0.1 to 4.8 cubic metres, due to variable tree size and breakage during felling and extraction. The average base, or large end, diameters and lengths recorded by the processor were 37.4 centimetres and 15.4 metres, respectively. These may appear low. However, field observations noted a majority of stems had suffered some degree of breakage.

An average of 4.8 saw cuts was required to process each sample to produce an average of 3.4 logs. Overall, 2,769 saw cuts were required to produce 920 cubic metres of logs, which equates to approximately 3.0 saw cuts per cubic metre of logs. The average number of saw cuts and logs per sample was similar at each site.

Figure 9 and Figure 10 show the data distribution of piece size and stem length samples, which illustrates the wide range of sample data due to variable tree size and stem breakage. The box shows the 25th and 75th percentile containing the median value, while the whiskers show the minimum and maximum values. Two piece size values at site 1 were considered as outliers, which were defined as a value exceeding 1.5 times the interquartile range. When the samples were converted to productivity in terms of cubic metres per productive machine hour (see Section 5.3), these piece size outliers followed the general productivity trend and were retained in the data. The distribution of the raw piece size and length data is skewed towards lower values due to the incidence of broken stems and pieces.
Figure 9: Box and whisker plot of piece size by study site

Figure 10: Box and whisker plot of stem length by study site

Table 8 shows a summary of volume data by cutting scenario. Between 122 and 163 observations were collected for each scenario. Average piece size was similar for cutting scenarios with five, nine and twelve sorts at around 1.5 to 1.6 cubic metres per piece. The cutting scenario with fifteen sorts had a larger average piece size of 1.8 cubic metres, which
was largely due to the variable size of stems within the harvest setting. The differences in piece size by cutting scenario reinforced the requirement for undertaking statistical analysis to estimate the productivity for each cutting scenario at the same piece size.

<table>
<thead>
<tr>
<th>Cutting scenario (No. of log sorts)</th>
<th>No. of samples</th>
<th>Total volume (m³)</th>
<th>Avg. piece size (m³/piece)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>122</td>
<td>174</td>
<td>1.5</td>
</tr>
<tr>
<td>9</td>
<td>130</td>
<td>198</td>
<td>1.6</td>
</tr>
<tr>
<td>12</td>
<td>163</td>
<td>255</td>
<td>1.6</td>
</tr>
<tr>
<td>15</td>
<td>163</td>
<td>292</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>578</strong></td>
<td><strong>920</strong></td>
<td><strong>1.6</strong></td>
</tr>
</tbody>
</table>

### 5.3 Processing productivity

Processing productivity translates processing time for a given piece size into the equivalent production volume per productive machine hour (PMH). Processing productivity was shown to be strongly influenced by piece size and productivity tended to be more variable as piece size increased. The productivity by piece size data also suggest the trend in productivity peaks at a piece size of around 3.0 cubic metres.

Base diameter appeared to influence processing time and productivity. This is expected as base diameter gives a strong indication of piece size. The length of each sample did not show any strong trends with processing time or productivity. This is likely due to the variable nature of stocking and tree volume within the plantation, where taller trees did not necessarily always have large diameters and a larger piece size.

The number of saw cuts made by the processors on each sample appears to have influenced processing time, which is expected as it takes longer for the processor to make a higher number of cuts. There was no clear trend between the number of cuts and processing productivity. However, samples with the highest productivity were observed when the processor made between three and six cuts. Beyond this level, it is likely more cuts had to be made to remove defects which effectively reduced productivity.

Figure 11 illustrates all of the sample data points for processing time and productivity against the key operational variables of piece size, base diameter, length and the number of saw cuts made by the processor for each sample.
Processing time vs. piece size

Processing productivity vs. piece size

Processing time vs. base diameter

Processing productivity vs. base diameter

Processing time vs. piece length

Processing productivity vs. piece length

Processing time vs. no. of saw cuts per piece

Processing productivity vs. no. of saw cuts per piece

Figure 11: Processing time and productivity by key operational variables for all study data
Analysis was undertaken to understand the relationship between productivity, piece size and the number of log sorts. The impact of piece size, which is a significant driver of productivity, must be controlled to make conclusions about the impact of the cutting scenarios on productivity as piece size naturally differed by cutting scenario. Figure 12 plots each of the raw data points for productivity and piece size by cutting scenario. The variability of the data points is expected from such operational data and is similar to other harvesting production studies. The scatterplot indicates some differentiation in productivity between cutting scenarios.

Figure 12: Data points for productivity and piece size by cutting scenario
5.4 Productivity relationships

Analysis of covariance (ANCOVA) was applied to evaluate whether productivity is equal across different cutting scenarios using piece size as a covariate. A series of iterations was undertaken using R statistical software to determine if both piece size (continuous variable) and cutting scenario (categorical predictor) significantly influenced processing productivity (continuous response). Regressions were fitted to each of the four cutting scenarios and then tested for statistically significant differences. Figure 13 shows smoothed line ‘best fit’ productivity trends by cutting scenario, which shows a similar relationship with piece size in each scenario.

![Figure 13: Smooth line productivity trends by cutting scenario](image_url)

Linear regression suggests some differences between cutting scenarios, particularly between the five sort scenario and the others. A linear significance test, using piece size as a covariate, shows piece size being a highly significant predictor of productivity ($\alpha < 0.01$) and cutting scenarios being a significant predictor at a significance level of $\alpha < 0.1$ (p-value of 0.08). This linear model explained 65% of variation (adjusted R-squared of 0.65). There was no significant interaction between piece size and the number of sorts.
The ‘smooth best fit’ trend lines suggested a tendency for productivity relationships to follow non-linear trends in each cutting scenario. This suggests non-linear relationships could provide a more appropriate representation of productivity trends. Quadratic functions have been considered an appropriate regression for mechanised productivity relationships, while power function regressions can be considered too aggressive and mono-directional (Visser & Spinelli 2011).

To test the representativeness of a non-linear relationship, second-degree polynomial regressions (quadratic regressions) were fit to the data. These regressions explained more variation than linear functions, as shown by a higher adjusted R-squared value of 0.69. Cutting scenarios were shown to have a significant effect on productivity with a p-value of 0.003. The F-statistic also showed a significant model. Therefore, it is likely that null hypothesis 1 should be rejected.

Figure 14 shows the productivity curves for each cutting scenario. Optimal productivity occurred around a piece size of 3.5 cubic metres and productivity from the five sort scenario was estimated to be around 10% higher than the fifteen sort scenario at a piece size of 2 cubic metres. Coefficients for the productivity curves are listed in Table 9.

![Figure 14: Quadratic regressions by cutting scenario](image)

Different slopes were considered for the linear and quadratic coefficients in each of the four quadratic regression trends fitted to the cutting scenarios. ANCOVA was used for
this analysis, which compared the slope of the cutting scenario with five sorts with the different slopes of the other cutting scenarios. This test also determined if there was any significant interaction between piece size and cutting scenarios. ANCOVA results showed there was no significant interaction and no significant evidence to justify different slopes, with p-values all exceeding 0.4. Therefore, applying the same slope for each of the four regression models represented a more parsimonious approach. The quadratic function is described below:

\[ Y = \beta_0 + \beta_1 x_1 + \beta_2 x_1^2 \]

Where \( \beta_0 \) is the y intercept, \( \beta_1 \) is the linear slope, \( \beta_2 \) is the quadratic slope and \( x_1 \) is piece size.

Quadratic regression functions sharing the same slope were tested for statistical differences between cutting scenarios. The scenario with five log sorts was used as a baseline group for comparison. Modelling showed the nine sort cutting scenario was not significantly different, while the twelve and fifteen sort scenarios were significantly different with p-values of < 0.05 and < 0.01, respectively (Table 9). This showed a significant difference in productivity between the cutting scenario producing five sorts and the cutting scenarios producing twelve and fifteen sorts.

<table>
<thead>
<tr>
<th>Cutting scenario (No. of log sorts)</th>
<th>y-intercept (( \beta_0 ))</th>
<th>Linear slope (( \beta_1 ))</th>
<th>Quadratic slope (( \beta_2 ))</th>
<th>Standard error</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 (Base)</td>
<td>14.94</td>
<td></td>
<td></td>
<td>2.55</td>
<td>(Base)</td>
</tr>
<tr>
<td>9</td>
<td>13.02</td>
<td>50.91</td>
<td>-6.28</td>
<td>2.41</td>
<td>0.43</td>
</tr>
<tr>
<td>12</td>
<td>9.70</td>
<td></td>
<td></td>
<td>2.29</td>
<td>0.02</td>
</tr>
<tr>
<td>15</td>
<td>6.88</td>
<td></td>
<td></td>
<td>2.32</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

As this analysis used the five log sort cutting scenario as a base, further analysis was conducted using the nine sort scenario as a base. This test was conducted to identify if there were any significant differences between the nine sort cutting scenario and the twelve and fifteen sort cutting scenarios. ANCOVA tests using quadratic regressions showed no significant the difference between nine and twelve log sort cutting scenarios (p-value 0.14) and a significant difference between the nine and fifteen log sort cutting scenarios (p-value < 0.01).
5.4.1 Transformation of response variable

As the variance around productivity curves showed some signs of a non-normal, heterogeneous distribution, the data was transformed using the Box-Cox technique in R. Box-Cox suggested a Lambda value of 0.5, which recommends a transformation of the response variable by taking its square root. Figure 15 shows the variance of productivity residuals against the fitted values. Transformation reduced signs of heteroscedasticity in the variance of the residuals, with no strong evidence of a trend of increasing variance as fitted values rise.

![Original data vs Transformed data](image)

Figure 15: Distribution of productivity residual values against fitted values

As a result of the transformation, the distribution of productivity data showed signs of a more normal distribution. Productivity values were somewhat skewed to the left prior to transformation which reflects the higher occurrence of smaller piece sizes relative to the lower occurrence of larger piece sizes. Figure 16 shows the distribution of productivity data before and after the data transformation.
5.4.2 Productivity functions based on normalised data

Quadratic functions with different y-intercepts and the same slope were applied to the normalised data. ANCOVA tests, using the five sort scenario as a base, showed an adjusted R-squared of 0.73 and p-values showed the twelve and fifteen sort cutting scenarios still being significantly different from the five sort scenario (0.03 and <0.01, respectively). An F-statistic of 319 showed that the overall model was highly significant. There was still not enough evidence to suggest any difference in productivity when processing five and nine sorts (p-value of 0.73). The new equation includes a step to back transform the response variable by squaring the result of the transformed equation:

\[
Y = (\beta_0 + \beta_1x_1 + \beta_2x_1^2)^2
\]

Where \(\beta_0\) is the y intercept, \(\beta_1\) is the linear slope, \(\beta_2\) is the quadratic slope and \(x_1\) is piece size.

The effect of the transformation resulted in lower values for model parameters. This is due to the scaling involved using the square root transformation. Coefficients for productivity functions based on normalised data are listed in Table 10.
Table 10: Coefficients for productivity functions based on normalised data

<table>
<thead>
<tr>
<th>Cutting scenario (No. of log sorts)</th>
<th>y-intercept ($\beta_0$)</th>
<th>Linear slope ($\beta_1$)</th>
<th>Quadratic slope ($\beta_2$)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4.29</td>
<td></td>
<td></td>
<td>(Base)</td>
</tr>
<tr>
<td>9</td>
<td>4.24</td>
<td>3.65</td>
<td>-0.51</td>
<td>0.73</td>
</tr>
<tr>
<td>12</td>
<td>4.00</td>
<td></td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>15</td>
<td>3.81</td>
<td></td>
<td></td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

5.4.3 Summary

Regression analysis showed that it is highly likely null hypothesis should be rejected. Normalised quadratic regressions were used to predict processing productivity from each cutting scenario. Different y-intercepts were used, as the cutting scenarios with twelve and fifteen log sorts were shown to be significantly different, as shown by the p-values of less than 0.05, from the base cutting scenario with five log sorts. However, there was no statistically significant difference in productivity between the cutting scenarios producing five log sorts and nine log sorts. There was not enough evidence to suggest different slopes were required and there were no significant interactions between piece size and cutting scenario. In addition, the difference between the nine and twelve sort scenario was insignificant, while there was a significant difference between the nine and fifteen sort scenario (p-value <0.01).

Table 11 shows a summary of the quadratic regressions which were considered to evaluate the effect of cutting scenarios on productivity. The normalised quadratic regressions had an adjusted r-squared value of 0.73 and the cutting scenarios with twelve and fifteen log sorts showed p-values of 0.03 and less than 0.01, respectively. This suggests that increasing the number of log sorts to twelve or above affected mechanised log processing productivity.

Table 11: Statistical significance of quadratic regressions

<table>
<thead>
<tr>
<th>Regression type</th>
<th>Adjusted $R^2$</th>
<th>Cutting scenario p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>(Base)</td>
</tr>
<tr>
<td>Quadratic</td>
<td>0.73</td>
<td>(Base)</td>
</tr>
<tr>
<td>(different intercepts, same slope)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 17 shows the productivity curves derived from the normalised quadratic regressions. Each curve peaks at a piece size of around 3.5 m³, which reflects an estimate of the optimum piece size for maximising processing productivity. Beyond these peaks, productivity is expected to fall at larger piece sizes as the processing heads reach their operating limits for tree size. There was limited data above a piece size of around 4 m³ and the relationship was not extrapolated beyond this point.

Figure 17: Productivity curves for the normalised quadratic model by cutting scenario

Table 12 shows predicted processing productivity across different piece size classes using the quadratic regression model. At a piece size of 2.0 cubic metres, the model suggests processing productivity was 11% higher when producing five sorts compared to producing fifteen sorts and 9% higher when producing nine sorts. As piece size increases, the difference in productivity marginally diminishes.
<table>
<thead>
<tr>
<th>Piece size class (m³)</th>
<th>Productivity by cutting scenario (no. of log sorts; m³/PMH)</th>
<th>% difference between 5 and 15 log sorts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 sorts</td>
<td>9 sorts</td>
</tr>
<tr>
<td>1.0</td>
<td>55</td>
<td>54</td>
</tr>
<tr>
<td>1.5</td>
<td>74</td>
<td>73</td>
</tr>
<tr>
<td>2.0</td>
<td>91</td>
<td>90</td>
</tr>
<tr>
<td>2.5</td>
<td>104</td>
<td>103</td>
</tr>
<tr>
<td>3.0</td>
<td>113</td>
<td>112</td>
</tr>
</tbody>
</table>
5.5 Value recovery

Value recovery was derived by applying log prices to the log grade outturn of the processed volume for each stem. Stem files downloaded from processor on-board computers contained information on the grade and volume of every processed log. This allowed value recovery to be assessed on a stem by stem basis. This study focussed on comparing actual value recovery and did not attempt to estimate the potential optimum value recovery for each sample or cutting scenario.

5.5.1 Log grade outturn and average gross value recovery

Cutting scenarios with a higher number of sorts showed lower proportions of pulp grades and higher KI compared to the five and nine sort scenarios. This was mostly due to the inclusion of the 3.15 metre KI sort in the scenarios with twelve and fifteen sorts. The outturn of pruned logs was highest in the fifteen sort scenario, largely due to the option of cutting a shorter 3.75 metre pruned log. The proportion of domestic S30 and export A grade was broadly similar across each scenario aside from the five sort scenario. The five sort scenario did not have S30 or A grade cutting options, which resulted in a large proportion of the expanded K grade. Figure 18 shows the log grade outturn by cutting scenario.

![Figure 18: Log grade outturn by cutting scenario](image)
Actual average gross value recovery was derived for each cutting scenario. The cutting scenario with five sorts showed an average gross value recovery of $108 per cubic metre. Even without any A or S30 grade cutting options, the average gross value recovery in the five sort scenario was only $3 less than the average recovery from the nine sort scenario.

The scenario with five log sorts reached 94% of the value recovered from producing fifteen log sorts. The difference in gross value recovery between scenarios with five and fifteen sorts was $7 per cubic metre (Table 13). Despite significant differences in the number of log sorts, the range in actual gross value per cubic metre by cutting scenario was marginal. This reflects market trends where prices for domestic S30 and export A, K and KI, which accounted for approximately 68% to 72% of production, were all trading in a narrow range of around $90 to $115 per cubic metre.

<table>
<thead>
<tr>
<th>Cutting scenario (no. of sorts)</th>
<th>Avg. gross value ($/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>$108</td>
</tr>
<tr>
<td>9</td>
<td>$111</td>
</tr>
<tr>
<td>12</td>
<td>$113</td>
</tr>
<tr>
<td>15</td>
<td>$115</td>
</tr>
</tbody>
</table>

As with the productivity data, the impact of piece size, which is also a significant driver of value recovery, must be controlled to make conclusions about the differences in gross value recovery by cutting scenario. Therefore, ANCOVA was undertaken to evaluate gross value recovery relationships and to compare each cutting scenario using piece size as a covariate.

5.5.2 Gross value recovery relationships

The assessment of gross value recovery relationships tests null hypotheses 2 to investigate if gross value recovery were affected by the number of log sorts. To do so, gross value recovery was analysed on a stem by stem basis. Figure 19 plots gross value recovery data, which shows a strong increasing trend with increasing piece size. Some differentiation of gross value recovery by cutting scenario was evident. The range in gross value recovery by stem extends from $4.42, which relates to a very small piece of pulp log with a volume of
0.1 m³, to $572.50, which relates to a large stem of 4.8 m³ that was cut into one pruned log, four A grade logs and one K grade log.

![Graph showing gross value recovery and piece size by cutting scenario](image)

**Figure 19: Data points for gross value recovery and piece size by cutting scenario**

Figure 20 shows the ‘smoothed best fit’ trend lines for gross value recovery for each cutting scenario. These smoothed trend lines suggest strong linear, straight-line, relationships between gross value recovery and piece size in each cutting scenario. Data variability also appeared to be similar in each cutting scenario.
Figure 20: Smooth line gross value recovery trends by cutting scenario

Linear regressions, using different y-intercepts and slopes, for each cutting scenario (categorical predictor variable) showed strong trends between piece size (continuous predictor variable) and gross value recovery (continuous response variable). These trend lines are illustrated in Figure 21. ANCOVA analysis shows piece size and cutting scenario as both having a significant effect on gross value recovery (p-values < 0.01). The model, which used the five sort cutting scenario as the base category, also suggested each cutting scenario trend had a significantly different slope (p-values < 0.05). This is expected as the cutting scenario has a direct impact on the value that can be recovered from a stem.
The overall adjusted R-squared value for the linear gross value recovery model was 0.97. Although the differences appear to be minor, the model suggested it was likely that null hypothesis 2 should be rejected and that gross value recovery is not affected by the number of log sorts. ANCOVA tests analysed the differences in linear trends by cutting scenario, which gave mixed results. Gross value recovery in the nine sort scenario was considered to be significantly different from the five sort scenario (p-value < 0.05) when using the five sort scenario as the base category. Using the nine sort cutting scenario as the base category showed the five and twelve sort scenarios to be significantly different (p-values < 0.05).

Table 14 lists the coefficients for the linear relationships between each cutting scenario and piece size using the five sort cutting scenario as the base category. The Linear function is described below:

\[ Y = \beta_0 + \beta_1 x_1 \]

Where \( \beta_0 \) is the y intercept, \( \beta_1 \) is the linear slope and \( x_1 \) is piece size.
Table 14: Coefficients for gross value recovery functions

<table>
<thead>
<tr>
<th>Cutting scenario (No. of log sorts)</th>
<th>y-intercept ($\beta_0$)</th>
<th>y-intercept p-value</th>
<th>Linear slope ($\beta_1$)</th>
<th>Linear slope p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-1.97</td>
<td>(Base)</td>
<td>108.25</td>
<td>(Base)</td>
</tr>
<tr>
<td>9</td>
<td>-10.95</td>
<td>0.04</td>
<td>117.19</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>12</td>
<td>-3.03</td>
<td>0.79</td>
<td>114.47</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>15</td>
<td>-8.47</td>
<td>0.14</td>
<td>118.81</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

5.5.3 Optimal cutting scenario

The results of statistical analysis were used to compare productivity and gross value recovery at the same piece size. Table 15 shows estimates of productivity and gross value recovery for each cutting scenario using the regression functions at a piece size of 2 m³, which was close to the mean piece size recorded in the field study. Estimates from the regression trends show an ordered decline in productivity and increase in gross value recovery as the number of log sorts increased.

Table 15: Estimated productivity and gross value recovery using regression functions at a piece size of 2 m³

<table>
<thead>
<tr>
<th>Cutting scenario (no. of log sorts)</th>
<th>Productivity (m³/PMH)</th>
<th>Gross value recovery (NZ$)</th>
<th>Value per PMH (NZ$/PMH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>91</td>
<td>215</td>
<td>9,783</td>
</tr>
<tr>
<td>9</td>
<td>90</td>
<td>223</td>
<td>10,035</td>
</tr>
<tr>
<td>12</td>
<td>86</td>
<td>226</td>
<td>9,718</td>
</tr>
<tr>
<td>15</td>
<td>82</td>
<td>229</td>
<td>9,389</td>
</tr>
</tbody>
</table>

The value per PMH (which is simply a multiplication of productivity and gross value recovery) indicated that the most optimal cutting scenario was the cutting scenario producing nine log sorts, which reached the highest value per PMH at $10,035. Value per PMH declined to $9,718 and $9,389 when processing twelve and fifteen sorts, respectively. This suggests predicted falls in processor productivity offset gains in gross value recovery when producing twelve and fifteen sorts and that a cutting instruction including around nine sorts would achieve optimal value from processing (Figure 22).
5.5.4 Market sensitivity analysis

Analysis was undertaken to evaluate the sensitivity of value recovery to changes in log prices, which tend to be volatile over time due to changes in supply and demand in domestic and global markets. Two market scenarios were considered against the base case for sensitivity analysis by applying the following log prices:

1. June 2013 prices (base case): indicative log prices at the time of the field study;
2. Strengthening export market scenario: export prices increase by 20% and domestic prices increase by 10% from June 2013 prices; and
3. Softer export market scenario: average prices from the 2008 calendar year which had larger differentials between domestic S30 and export log prices.

Table 16 outlines estimates of gross value recovery for each market sensitivity scenario. Market scenario 2 shows similar relativities in gross value recovery between cutting scenarios to market scenario 1. Market scenario 3 applied the average 2008 log prices, which were much lower than current prices with larger price differentials between log grades. Market scenario 3 shows a marked difference between producing five log sorts and producing nine, twelve or fifteen log sorts. This is due to no S30 volume in the five sort cutting scenario, while all of the other cutting scenarios have similar proportions of S30 and A grade.
Table 16: Estimated gross value recovery by market sensitivity scenario at a piece size of 2 m³

<table>
<thead>
<tr>
<th>Cutting scenario (no. of log sorts)</th>
<th>Gross value recovery (NZS) by market scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 (Base)</td>
</tr>
<tr>
<td>5</td>
<td>215</td>
</tr>
<tr>
<td>9</td>
<td>223</td>
</tr>
<tr>
<td>12</td>
<td>226</td>
</tr>
<tr>
<td>15</td>
<td>229</td>
</tr>
</tbody>
</table>

The estimates of gross value recovery for each market sensitivity scenario were combined with productivity estimates to give an indication of the optimal number of log sorts. Figure 23 shows all of the market sensitivity scenarios reached an optimal value per PMH from producing nine sorts at an average piece size of 2 m³.

![Figure 23: Optimal market sensitivity scenario analysis (piece size of 2 m³)](image)

Market scenario 2 shows a similar value per PMH when producing five and nine log sorts. In market scenario 2, export A grade prices were 7% higher than domestic S30, which improves value per PMH in the five sort scenario as there was no domestic S30 volume. Market scenario 3 showed the lowest value per PMH producing five log sorts. This was the only scenario where production of twelve or fifteen sorts resulted in higher value per PMH than producing five sorts. Over 2008, the S30 price was 21% higher than export A grade and the price of A grade was 10% higher than K grade. These larger price differentials caused value recovery to be more responsive to changes in the number of log sorts.
The sensitivity analysis indicates log market dynamics impact on the number of log sorts required to optimise value outturn from log processing. Larger differentials between log prices can be a key driver for increasing the number of sorts to improve value outturn. In addition, smaller differentials between log prices can lead to the gains in gross value recovery being offset by losses in productivity.
6 Discussion

A key outcome of this study was determining if after a certain point, gross value recovery gains from increasing the number of log sorts would be offset by losses in mechanised log processing productivity. The optimal number of log sorts was estimated at around nine, where processing productivity was around 9% higher than productivity from producing fifteen log sorts. Murphy and Marshall (2003) conceptualised that every harvesting operation has an optimal number of log sorts for balancing value recovery and costs. Beyond this optimum, marginal gross value recovery gains are offset by increases in log-maker errors and in processing and landing costs.

Given that the number of log sorts can impact processor productivity, more research needs to be undertaken to quantify the effect on other parts of landing operations and subsequent parts of the supply chain. Visser (2010) showed that the number of log sorts can impact on the size of a landing, which has a significant bearing on engineering costs. The next logical step would be to quantify the effect of the number of log sorts on loader utilisation and quality control requirements.

In Finland, recent increases in the number of log sorts, albeit from a much lower base than in New Zealand, has led to concerns about increased production and logistics costs (Nurminen et al. 2009). Research is being undertaken to understand how time and machine requirements for handling more log sorts will affect harvesting and transport costs. Further research needs to be undertaken in New Zealand to understand the effect of the number of log sorts from a ‘whole supply chain’ point of view. This research could inform supply chain and marketing strategies and benefit the competitiveness of the industry.

The reduced production as the number of log sorts increased can be partly attributed to increasing complexity. It is understood that producing a high number of log sorts can contribute to more complex log-making which can impact on value recovery and productivity (Harris & Chaney, 1969; Parker et al. 1995). Predictive log-making tools for mechanised processing intend to maximise value and simplify operator input. However, the operator is still required to visually assess every stem for quality features and make the key decision about accepting the proposed cut from the computer programme. As concluded by Gellerstedt (2002), further machine automation is required to reduce the intensive workload for mechanised harvester and processor operators.
Processors working on cable yarder landings tend to have many other responsibilities as well as log processing, such as clearing the cable yarder chute, managing processing waste and pre-sorting logs for the loader. These other responsibilities can contribute to high machine utilisation rates despite the primary task of log processing often being constrained by the cable yarder extraction process. Machine utilisation results in this study showed processors spending 84% of time on productive tasks which included 49% of total time on the primary task of picking up and processing trees. This shows processors were heavily utilised despite some production constraints due to cable yarding extraction.

Production data from modern harvester and processor on-board computers provides a platform for collecting large datasets on machine and operator performance. The consistent StanForD format allows large amounts of data from multiple machines and locations to be consolidated. Machine software can also be configured to automatically collect time study and machine utilisation data. Collecting and centralising this data on a large scale has unprecedented potential for analysing harvesting operations in New Zealand. Such large scale studies have been conducted in Russia to assess drivers of harvester productivity in varying stand and site conditions (Gerasimov et al. 2012). Collecting large sample sizes in this manner could also mitigate the effect of individual operator performance and the Hawthorne effect on inferences from production studies.

The large extent of volume information collected by harvesters and processors is also useful to compare to pre-harvest inventory estimates. Pre-harvest estimates of piece size are generally used as part of harvest rate negotiations to determine the expected daily crew production. Actual piece size information from the processor could potentially be used to review and check the accuracy of these estimates of piece size. This could be particularly useful for cable yarding operations, where the degree of stem breakage during extraction can often be under or overestimated.

Evaluating the performance of built-in predictive log-making functions was not part of this study. There is limited research on the performance or accuracy of these log-making functions in practice. A better understanding of how operators utilise these predictive functions for maximising value recovery could help continually improve mechanised log-making. Further research to determine log prediction accuracy and the frequency that operators accept or reject predictions would assist in a broader understanding of the utilisation of these log-making tools.
The shape of estimated productivity functions showed productivity reaching a peak at a piece size of around 3.5 m³. This was similar to quadratic productivity functions applied in other production studies in radiata pine plantations in New Zealand (Visser & Spinelli 2011). As there was limited data beyond around 4 m³, the downward trend in the productivity curves represents a conservative estimate at very large piece sizes. These functions follow a logical interpretation of productivity trends where each processing head has an optimum operating piece size. Beyond this optimal operating piece size, which is relative to the size and capability of the machine, productivity results tended to be mixed as machines took longer to delimb, pick up and process exceptionally large trees.

Harvesting production is affected by multiple variables which reinforces the requirement of large sample sizes in production studies. It is difficult to measure the effect of many individual variables, such as landing layout, landing size, time of day, day of the week, as many can interact to impact on productivity. The variation in productivity data was typical for harvesting production studies and the adjusted R-squared value of 0.73 for the overall productivity model was in the upper range in comparison to other studies (Evanson & McConchie 1996; Gerasimov et al. 2012; Nurminen et al. 2006; Visser & Spinelli 2011).

This study did not take potential optimum value recovery into account. The New Zealand forest industry has established methods of monitoring gross value recovery and estimating potential optimum gross value recovery from harvesting operations. Optimum value recovery assessments tend to be derived from intermittent, small sample trials, and operator performance could potentially improve during such trials due to increased supervision and personnel interaction (Karsten 2013). Recovering optimal value in normal operating conditions can be difficult for manual or mechanised log makers in practice due to limited operating space, impaired vision of parts of stems, fatigue, production pressures and changes in market requirements. However, despite such intricacies, optimum value recovery assessments are considered valuable training exercises for log makers.

This study has demonstrated some potential for cutting instruction decisions to have flow-on effects on the economics of landing-based harvesting operations. Productivity and value recovery need to be viewed as interdependent to maximise the net value of an operation. Sensitivity analysis showed the interaction between the number of log sorts and value per productive machine hour is largely dependent on log prices and market dynamics. Since the New Zealand forestry industry has been supplying a majority of log exports to
China, prices for export grades have risen and converged. This has reduced incremental gains in gross value recovery as the number of log sorts increases.

Strong demand for export grade logs from China has lifted prices for lower quality A and K grade logs to levels similar to prices for higher quality domestic structural sawlogs. Larger price differentials between log grades in 2008 meant producing a higher number of log sorts benefitted the economics of harvesting operations. This has historically been the case in the New Zealand forest industry. Current price trends are unprecedented and if they are expected to continue over the medium to long term, producing a high number of log sorts may only cause supply chain inefficiencies rather than net value gains. Should log prices converge further, producing as few log sorts as five may optimise the value outturn from log processing.

In response to recent price trends, forest managers and log exporters may look for opportunities to combine some log grades in order to reduce the number of log sorts while maintaining value recovery. An opportunity may arise to combine A and K grade, which only differ in SED range. Similarly, longer length log sorts with wider quality tolerances could be an option for export markets. However, changes to log grade specifications are only possible if there is an alignment with the requirements of customers.

Reducing the number of sorts could have efficiency benefits for the log supply chain. Wood availability is forecast to rapidly increase with the maturation of large areas of first rotation plantations established in the early to mid 1990s. Much of the potential new harvest volume is planted on marginal, steep land in smaller woodlots. Fewer log sorts reduces the required landing size and cost in steep terrain and simplifies the management and logistics of harvesting and transporting logs from multiple locations. There would also be efficiency benefits with fewer log sorts for log storage areas at ports and ship loading operations. Overall net gains from efficiency improvements due to fewer log sorts in each part of the supply chain could improve stumpage returns to forest growers and enhance industry competitiveness on an international scale.
6.1 Conclusions

Based on the results and analysis of the field study, the conclusions address the research questions outlined in Section 3.

I. Does the number of log sorts affect mechanised log processing productivity in landing-based cable yader harvesting operations?

The number of log sorts was found to impact on mechanised processing productivity in landing-based cable yarding operations. Results of ANCOVA tests showed piece size (covariate) and cutting scenario (categorical explanatory variable) to be significant variables for predicting log processing productivity (p-values < 0.01). Therefore, it was likely null hypothesis 1, that the number of log sorts does not affect mechanised log processing productivity, should be rejected. Cutting scenarios with twelve and fifteen log sorts were significantly different from the cutting scenario producing five log sorts (p-values < 0.05), while the cutting scenario with nine sorts was significantly different from the fifteen sort scenario (p-value < 0.01).

Quadratic regressions were fitted to the data to represent productivity curves for each of the four cutting scenarios. At an average piece size of 2 m³, productivity was estimated to be around 11% higher when processing five log sorts compared to processing fifteen log sorts. Productivity was also estimated to be around 10% higher when producing 9 log sorts compared to fifteen log sorts. This could be due to the increased complexity of log-making for the machine operator as the number of log sorts increased.

II. A) Does the number of log sorts affect gross value recovery in landing-based mechanised log processing operations?

Average gross value recovery increased as the number of log sorts increased. Gross value recovery averaged $108 per m³ producing five log sorts and increased to $115 per m³ producing fifteen log sorts (producing five log sorts recovered 94% of the value of producing fifteen log sorts). As the average piece size was slightly different by cutting scenario, ANCOVA tests were used to isolate the impact of piece size to compare gross value recovery by cutting scenario.

A linear regression model showed a strong relationship between gross value recovery, piece size and cutting scenario. A significant model suggested it is likely null hypothesis 2, that the number of log sorts does not affect gross value recovery, should be rejected. There
were only small differences in variance between cutting scenarios and only some of these differences were statistically significant. The cutting scenarios with five and twelve sorts were shown to be significantly different from the cutting scenario with nine log sorts.

At a piece size of 2 m$^3$, which was close to the mean piece size recorded in the field study, estimates from the regression model show an ordered increase in gross value recovery as the number of log sorts increased. As with the average gross value recovery by cutting scenario, regression estimates showed the five log sort cutting scenario recovering 94% of the value of the cutting scenario with fifteen log sorts. Incremental gains in value recovery as the number of log sorts increased were marginal, which is largely due to log prices for many major log grades trading in a close range in relation to historic price trends.

**B) How many log sorts should be produced to optimise processing value outturn in landing-based mechanised log processing operations?**

The value per PMH (which is simply a multiplication of productivity and gross value recovery) indicated that the most optimal cutting scenario was the cutting scenario producing nine log sorts, which reached the highest value per PMH at $10,035. Value per PMH declined to $9,718 and $9,389 when processing twelve and fifteen sorts, respectively. This suggests predicted falls in processor productivity offset gains in gross value recovery when producing twelve and fifteen sorts and that a cutting instruction including around nine sorts would achieve optimal value outturn from processing.

Market sensitivity analysis suggested that differentials in log prices impacted on the number of log sorts which optimises the value outturn from log processing. Average log prices from the 2008 calendar year showed higher value per PMH producing a higher number of log sorts, while the five log sort scenario had the lowest value per PMH. Conversely, if log prices were to converge further from current positions, processor value outturn could potentially be optimised by producing fewer log sorts than nine.

**6.2 Limitations**

There are many variables associated with forest harvesting operations and caution must be taken when comparing one operation with another. Although a reasonable amount of data was collected as part of this study, this data may only reflect the two operations included in the study and not others. This could potentially limit the wider application of results when considering the impact of the number of log sorts on other harvesting operations.
6.3 Areas for further research

The effect of the number of log sorts on supply chain productivity and costs could be cumulatively quantified by assessing each component along the chain. This study assessed the first step in the log supply chain and further research needs to be conducted on subsequent activities to evaluate the impact of the number of log sorts on supply chain economics. This would assist with making value decisions from a ‘whole supply chain’ point of view rather than solely from a gross value recovery point of view.

Areas for further research include considering the effect of the number of log sorts on:

- Loader sorting and fleeting operations on landings;
- Log transport logistics, truck configurations and loading and unloading efficiency;
- Port operations such as scaling, log storage and ship loading; and
- Overall supply chain strategy.

As the number of export grade log sorts is largely driven by customer demand and sales negotiations, another key area of research includes the ability of export markets to accept changes to log grade specifications. Further areas for research related to mechanised harvesting and processing include the utilisation and accuracy of predictive log-making functions and scoping the requirements and potential for centralising production data from multiple operations and locations.
7 References


