An Investigation into the System Production Balance within Three Mechanised Harvesting Case Studies

A dissertation submitted in partial fulfilment of the requirements for the degree of Bachelor of Forestry Science with Honours by:

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1.0 Abstract

Safety issues and high costs of traditional harvesting methods have been driving mechanisation increases in New Zealand. However, productivity increases from mechanisation alters system productivity balance. This can result in underutilised machinery and cause an increase in harvesting costs in real terms.

A time study was carried out to understand the system productivity balance between felling, extraction and processing and the factors affecting system component productivity rates, for three case studies. The three case studies observed were (1) a semi-mechanised cable yarder extraction operation, (2) a fully-mechanised swing yarder operation and (3) a fully-mechanised ground based operation.

There were large production imbalances between felling, extraction and processing in all three case studies. Felling was the most productive system component, being 98%, 37% and 88% (case studies 1 to 3 respectively) more productive than the bottleneck. System bottleneck for case studies 1 and 3 was extraction, and processing for case study 2.

The number of stems bunched, number of stems shovelled, wind throw interference and machine position shift affected felling cycle time. For every stem bunched, average productivity decreased by 35% (24m^3/PMH) and 21% (20.9m^3/PMH) for case studies 2 and 3 respectively. Every additional stem shovelled reduced felling productivity by 7.4m^3/PMH for case study 2. Haul distance, the number of stems extracted and site factor affected extraction productivity. Haul distance and the number of stems extracted had significant impact on hourly productivity for all case studies. Site factor affected hourly productivity by 6.9m^3 and 56.7m^3 for case studies 1 and 3 respectively, largely attributed to the cable system employed and ground conditions. Processing was affected by the number of logs cut per stem and if delimbing occurred. Delimbing and each additional log processed, decreased productivity by 16% and 14% respectively.

These three case studies showed that mechanised systems are often not well balanced and result in system components being underutilised. Companies can consider task strategies, or machine sharing between systems to minimise the effect on cost.

Key Words: Mechanised Harvesting, Production Balance, Operational Efficiency, Productivity, Utilisation, Forestry.

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3.0 Introduction

3.1 Background

New Zealand forest harvesting on steep terrain has numerous safety issues with traditional methods used. Traditional methods are motor-manual felling followed by cable extraction with choker-setters (colloquially called breaker-outs in New Zealand) and motor-manual processing at the landing (Visser, Raymond & Harill, 2014a). 2008 to 2013 witnessed thirty-two forestry fatalities making it New Zealand's most dangerous industry (Adams, Armstrong & Cosman, 2014), with the highest reported incident rates within harvesting operations (Bentley, Parker, & Ashby, 2004). 5 forestry fatalities have occurred to date in 2016 (September), 4 of which from traditional methods (2 manual felling, 2 breaking-out). The dangerous working environment has resulted in a poor safety record for traditional harvesting methods. There are doubts that such hazards can be permanently removed from the workplace (Adams et al., 2014; Amishev, 2012).

Traditional methods are also associated with harvesting high costs due to a combination of low production operations and operating costs. Highly productive, fully-mechanised ground based operations, are at least 50% cheaper than cable extraction operations employing traditional methods (Raymond, 2012). The low profit margin associated with steep terrain harvesting requires more cost effective harvesting methods for the New Zealand forest industry to remain internationally competitive and continue future growth (Raymond, 2012).

With the area of steep terrain harvesting to increase to 77% by 2030 (Raymond, 2012), the issue of safety and high harvesting costs on steep terrain is increasing in importance. A long term solution to ensure a safer working environment, at lower unit cost is exchanging traditional methods with machinery (called mechanisation). On flat terrain the transition has been straight forward through introductions of felling machines, skidders and forwarders, and mechanised processors (Amishev, 2012). Difficulty arises on slopes greater than 27 degrees with ground based felling and extraction methods deemed unsuitable (Amishev, 2012). In recent years a strong industry drive has seen a focus towards more mechanised operations, to achieve greater safety and cost-effectiveness on steep terrain (Visser, Raymond & Harrill, 2014b). Most recent developments include a range of cable assist felling systems and innovative motorized grapple carriages.

3.2 Problem Statement

Nelson Forest Limited (NFL) have worked alongside industry objectives to increase safety and reduce harvesting costs on steeper terrain through mechanisation. Numerous cable contractors have introduced tethered falling machines, complementing mechanised extraction and processing components. Capability of ground based operations have been pushed onto steeper terrain to reduce harvesting costs. Certain ground based operations include self-levelling felling machines with tether ability extending felling and shovelling capability.

Through increased levels of mechanisation, the consideration of wood flow within an operation is vital. In any harvest system, individual operational phases aim for balanced production with the preceding and/or following phase. Uneven balances of productivity causes utilisation levels to drop, resulting in increased harvesting costs in real terms (Competenz, 2005).

Additionally increasing mechanisation results in greater operational costs. With the already tight profit margin of harvesting on steep terrain, increased machinery costs and likely to fall NZ dollar (driving up already inflated machine costs), profitability on steep terrain becomes progressively more sensitive with increasing mechanisation (Raymond, 2012). The effect of uneven production balance within mechanised harvesting systems has been identified by NFL as an area of improvement to reduce harvesting costs on steeper terrain.

The major objectives of this study are to:

- Understand the system productivity balance between felling, extraction and processing system components for three case studies.
- Determine the major factors affecting productivity of each system component (e.g. haul distance, piece size) and how understanding these factors can be used to achieve more balanced systems.

4.0 Literature Review

4.1 Study Method

Studies of forestry operations are often difficult and challenging due to the range of variability associated with activities. Productivity studies require a time consumption to be associated with some sort of product output (Acuna et al., 2011). In harvesting operations log/tree production is measured by the amount of time input to calculate productivity.

The most common methods for collecting productivity data are detailed time and motion studies and shift-level studies (Olsen, Hassain, & Miller, 1998). Aim of time studies are to analyse time inputs in order to relate them to operational variables or work conditions, with a typical purpose to analyse operational efficiency (Musat et al., 2015). Time and Motion studies are suited to short term applications, providing a snapshot of the observed operation and consequently have limited value in estimating long-term trends (Olsen et al., 1998). Shift level studies occur over a longer study period, capturing a range of conditions, with limited operational detail.

Time and Motion studies have the benefit of high precision (down to 1 second) through splitting studies into cycles and associated work elements. This allows work processes to be described in greater detail and provide greater understanding of system dynamics (Acuna et al., 2011). Greater description of the system dynamics can benefit through identifying specific machine element times, delineating productive time from delay time and separating elements that react differently to work factors (Acuna et al., 2011).

Studies have become increasingly difficult with the increase of mechanised operations. When conducting time studies on mechanised operations, the duration of work elements can be short with difficulty separating element changes (Musat el al., 2015). The diversity of felling machines also increases study difficulty with greater variability and uncertainty of activities completed (Acuna et al. 2011).

4.2 System Production Balance in Harvesting Operations

In all harvesting operations, system balance is aimed to be achieved for all system components in order to achieve operational efficiency (Competenz, 2005). Operational efficiency is defined as the ratio of productive time to scheduled time. Control of downtime and system component productivity within an operation is required to achieve operational efficiency (Smidt, Tufts, & Gallagher, 2009).

The aim of balanced systems is to achieve even wood flow through all system components, with the reduction of major bottlenecks to the greatest degree possible. The bottleneck (limiting productive phase) restricts operation production and causes disruptions between system components through interference (Competenz, 2005). More productive machinery become underutilised, reducing the ratio of productive time to scheduled time (i.e. reduced utilisation). Utilisation of forestry machinery significantly impacts harvesting costs and is one of the most important factors influencing machine rate calculations (Holzleitner, Stampfer, & Visser, 2011).

The complexity of harvesting operations influences machine productivity rates within an operation, affecting system production balance and operational efficiency. The issue is that many of the factors influencing productivity and efficiency are out of the contractor's control (Smidt et al., 2009). Contractors and forest managers look to alleviate effects of influential factors through alterations of harvesting systems and techniques employed (Smidt et al., 2009). Understanding of such factors can support strategic and operational planning within an operation (Holzleitner, Stampfer, & Visser, 2011), which can balance system productivity and positively influence machine utilisation.

4.3 Mechanisation Cost and System Production Balance

Logging machines are extremely expensive (Riddle, 1995). Increasing mechanisation within an operation significantly increases overall system costs, which are aimed to be offset through production benefits. As an example, the ClimbMax steep slope felling machine is estimated to cost $1750 per day (based on 8 PMH) (Amishev & Evanson, 2013) in comparison to a manual faller rate that mainly comprises of labour costs. Approximately half of the machine rate in operations can be attributed with owning costs (driven by capital costs, resale and machine life) (Raymond, 2012). The ClimbMax felling machine has an estimated capital value (base machine and modifications) of $1,030,000 (Amishev & Evanson, 2013) in comparison to a new Stihl 660 magnum chainsaw valued at $3295 (Stihl Shop, 2016). Machine owning costs occur whether the machine is working or not. When machinery are underutilised, machine owning costs continue to be incurred, increasing logging costs in real terms (Competenz, 2005). An example of an imbalanced mechanised system stated balancing of the system could reduce production cost by 59 percent (Pan et al, 2008) (this study however did not take into account all operational costs). Increasing efficiency is therefore needed to compensate for the steadily rising cost of equipment (Pfeiffer, 1967).

4.4 Mechanisation in New Zealand and System Production Balance

Purpose built, self-levelling felling machines began the shift towards mechanised felling on steeper terrain 20 years ago (Raymond, 2012). Recent innovation has come from cable-assist felling machines, revolutionising steep terrain felling in New Zealand. Cable assist systems were introduced to increase the range ground based machinery, either for felling and bunching in a cable logging operations, or felling and shovelling in ground based operations (Visser, Raymond & Harill, 2014). New Zealand's first example of cable assist technology occurred in 2007 with a Nelson contractor, attaching a cable-winch to an excavator to bunch and shovel stems, aiding yarder extraction (Evanson & Amishev, 2010). Numerous tethered felling systems have transpired from the introductory cable assist machine, such as the Falcon Winch Assist system and ClimbMax steep slope falling machine.

Traditional methods of manual breaking-out remain the most common cable extraction method employed, with limited mechanisation shifts in cable yarding over the past 35 years (Raymond, 2012). The major piece of innovation with cable yarding was the introduction and development of swing yarders in 1987 (Raymond, 2012). Recent innovation has occurred through mechanised grapple carriages for tower yarders such as the Falcon Forestry Claw and Alpine Logging Grapple, aimed at reducing accumulation time of the cycle. Mechanised grapple carriages, although becoming more widespread were used by less than 25% of a recent survey during a five year period (Harrill and Visser, 2011).

Despite less than half of operations utilising mechanised processing, log processing has seen the greatest degree of innovation over the past 25 years (Raymond, 2012). The major shift within New Zealand harvesting operations has been the introduction of Waratah's single-grip, processing head. The Waratah processing head has been designed and manufactured specifically to process New Zealand's radiata pine (Saathof, 2014).

Increased mechanisation aimed at increasing production has affected the system productivity balance within harvesting operations. Intuitively contractors attempt to reduce unit costs as much as possible by utilising machinery to their full capacity (Riddle, 1995). Higher production of mechanised systems have frequent production imbalances between system components felling, extraction and processing (Evanson & Amishev, 2010). Unbalanced systems require varying work hours per system component to balance production, with more productive machinery typically underutilised. Motor manual systems have the luxury of shifting workers between activities to balance system productivity, however this is much more difficult and problematic with machinery (Riddle, 1995).

4.5 Previous Studies

Limited studies have occurred observing the production balance between felling, harvesting and processing of mechanised systems (including tethered felling machines) on steeper terrain. Typical studies observe a single system component with fewer studies observing how system components production rates compare within an operation. 2 New Zealand studies of fully mechanised, swing yarder operation have been observed to analyse the production balance within the system. Bunched yarder extraction was the most productive (74.1m^3/PMH) in the first study, following by felling (64.7m^3/PMH), processing (57.7m^3/PMH) and unbunched extraction as the operational bottleneck at 48.8m^3/PMH (Evanson & Amishev, 2010).

An alternate study identified processing as the most productive operational at 86.0m^3/PMH. Extraction was the operational bottleneck at 62.6m^3/PMH, with felling average hourly productivity at 80.5m^3/PMH (Eavnson & Amishev, 2009).

Many studies have been conducted over the years to evaluate factors that affect production of harvesting operations. Principle factors influencing operation and equipment productivity are well known from studies conducted over the years (Gardner, 1980). Depending on site and operation structure, factors affecting machine productivity will vary. Examples of factors that are commonly found to have effect on productivity include yarding distance, terrain and slope, number of logs extracted and piece size (Gardner, 1980).

5.0 Method

5.1 Study Location

The study observed three harvesting operations within the NFL estate throughout Nelson and Marlborough. Six sites were studied with each operation observed at 2 sites. Three sites were studied during summer and three sites during winter. Sites were chosen based on the location of the harvesting operation at time of data collection. Stand and Slope maps for each study sites including haul corridors are included in the Appendix for additional site information. Stand characteristics for each block are summarised below:

Table 1: Stand Characteristics of the 6 study sites

Block	Crop	Stocking (SPH)	Merchantable Piece size (m^3)	Average Slope (^{0})	Max Slope (^{0})
Western Boundary, Golden Downs	PRAD 1990	469	1.23	28.7	40.7
Long Gully, Golden Downs	PRAD 1990	218	1.6	26.2	34.3
Brightwater Block	PRAD 1987	218	2.5	25.1	34.2
Olivers, Golden Downs	PRAD 1989	331	1.47	22.1	28.8
Pascoes, Golden Downs	PRAD 1988	284	2.3	12.8	24.8
Fairacres, Wairau South	PRAD 1988	256	1.64	26.6	34.9

5.2 Case Study Description

5.2.1 Case Study 1: Semi-Mechanised Tall Tower Operation

Table 2: System Component, Machine Description and Site for Case Study 1

System Component	**Machine Description**	**Site**
1. Felling	Tigercat 655, tethered Self-levelling felling machine.	Western Boundary, Golden Downs.
2. Extraction	Washington 127 – Manual B/O, Shotgun system.	Western Boundary, Golden Downs.
2. Extraction	Washington 127 – Manual B/O, Running skyline system.	Long Gully, Golden Downs.
3. Processing	Tigercat excavator & Waratah Processing head.	Western Boundary, Golden Downs.

During the study operation, the felling machine was secured to a winch assist excavator operating mid-upper slope of a long face. The winch assist machine, situated at the top of the slope provided power to aid movement of the felling machine. The operating method was to fell trees into the stand or parallel to the stand edge. Bunching occurred by rotating stems into bunches above the cutover. Multiple stems were often felled followed by bunching perpendicular to direction of the slope.

The yarder used for extraction was a Washington 127 with manual choker-setters. Live skyline with shotgun carriage and scab (grabinski) systems were used at the Western Boundary (site 1) and Long Gully (site 2) respectively. At Western Boundary a large patch of ‘dead ground’ (previously extracted cutover) of around 150 metres was yarded across. Stems were unhooked by a pole man at the landing and cleared by the Tigercat processing machine. Trees were delimbed and processed during chute clearance away from the yarder, above the stand.

5.2.2 Case Study 2: Fully-Mechanised Swing Yarder Operation

Table 3: System Component, Machine Description and Site for Case Study 2

System Component	**Machine Description**	**Site**
1. Felling	Sumitomo tethered felling machine, Satco felling head.	Brightwater Block, Golden Downs
2. Extraction	Madill 122 swing yarder, grapple extraction.	Brightwater Block, Golden Downs
2. Extraction	Madill 122 swing yarder, grapple extraction.	Olivers rd, Golden Downs
3. Processing	Sumitomo Excavator, Waratah processing head.	Brightwater Block, Golden Downs

Felling was completed by a Sumitomo excavator with a fell and bunch head. The tethered felling machine was secured by a cable assist excavator at the top of the slope. Felling of stems occurred while working up and down the felling face. The operating method was to fell multiple stems downhill followed by shovelling.

Extraction was completed by a Swing Yarder with mechanical grapple on a running skyline system. An excavator with raised T-bar was used for the functions of a tail hold. Stems were either grappled from the deck (bunches) or fed into the grapple by an excavator (also used to shovel and bunch stems to haul corridors). Logs were extracted to a small landing and cleared by either the processor (Olivers block) or excavator for two staging by grapple skidder (Brightwater block).

Processing was completed by a Sumitomo excavator attached with a Waratah processing head. The processor works in a circular motion, choosing stems from a surge pile created from the two-stage operation. Stems were completely delimbed at the edge of the skid prior to log processing.

5.2.3 Case Study 3: Fully-Mechanised Ground Based Operation

Table 4: System Component, Machine Description and Site for Case Study 3

System Component	Machine Description	Site
1. Felling	Tigercat 655, tethered Self-levelling felling machine.	Pascoes Block, Golden Downs
2. Extraction	Cat 535 Grapple Skidder	Pascoes Block, Golden Downs
2. Extraction	Cat 535 Grapple Skidder	Fairacres Block, Wairau South
3. Processing	Cat Excavator & Waratah Processor	Pascoes Block, Golden Downs

During the study operation of Case Study 3, felling and delimbing was completed by a self-levelling John Deere felling machine. Felling occurred on rolling country with patches of wind throw scattered throughout the stand. The operating method of the felling machine was to fell trees into or parallel to the stand. The felled stem was then slewed away from the stand where delimbing occurred prior to being released in a butt first orientation.

The first stage of extraction is completed by a shovelling excavator. Stems are shovelled from the cutover into bunches at trails for skidder extraction. The operating method for the skidder extraction was to drive uphill along the skidder trail to stems and extract drags downhill to the landing, prior to dropping stems in a surge pile. Processing is completed by a CAT excavator attached with a Waratah processing head. Stems are picked up by the processing head at the butt end and processed into logs. Stems rarely requiring delimbing (roughly 10% of the time) due to field delimbing by the felling machine.

5.2.3 Data Collection

A detailed time and motion study was used to capture data for each of the system components studied. The 'time study' application created by NuVizz was used to capture data of work cycles and corresponding cycle elements. The total study time for each system component ranged between 5.5 and 12 hours. Longer studies were spent with extraction operations to gather a sufficient number of cycles for analysis. Factors corresponding with cycle elements were captured, such as haul distance and stem extraction. Binary factors measured throughout data collection were listed as 1 or 0 depending on occurrence throughout cycle (1 = factor occurred during observed cycle, 0 =

factor did not occur). System component cycle elements and corresponding definitions (including elements specific to single Case Studies) are listed below:

Felling Cycle Elements

- **Shift** - Machine shifts position and attaches to next standing tree.
- **Fell** - Felling head (attached to tree) cuts tree to the deck.
- **Bunch** - Felled stem are slewed and repositioned into bunches away from the stand.
- **Shovel** - Stem is shovelled away from the felled location.
- **Delimb** – felling head delimbs stem from butt to head with 1 pass of the stem.

Extraction Cycle Elements

- **Outhaul** - Machine/carriage begins to move from landing to stand and stops/slows significantly above drag.
- **Hookup** - Grapple/carriage accumulates payload (which includes lowering and raising grapple/carriage) to the point that it begins towards the landing.
- **Inhaul** - Drag begin moves until it stops at the landing.
- **Unhook** - Stems are shovelled away from the felled location.

Processing Cycle Elements

- **Slew** – Machine slews and grabs next stem after previous log has been cut.
- **Delimb** – The stem is pushed through processing head from butt end to head and back, removing limbs.
- **Processing** - Stems are processed into logs following delimbing.

Whenever the machine was not productive (performing a common element) this was classed as a delay. Common delays for all system components were classified as the following:

Delay Elements

- **Mechanical** - Delay caused by mechanical issues/breakdown occurred to the machine.

- **Operational** - Delay that is required for operations to occur, however is not part of the typical work cycle.
- **Other** - Any other delay that could occur.

A laser range finder was used to determine distance of the carriage or grapple along the haul corridor. As it was unsafe to be situated near the yarder and tail hold of the cable operations, trigonometry equations were used to calculate accurate haul distance. Ground based haul distance was calculated using a mixture of scale forest maps and laser range finder measurements.

Throughout the time study of each system component, a number of additional factors were measured that were associated with the operation, for example, shovel fed hook up, extraction distance and logs cut per stem. Additional factors were measured through direct observation of the system component. Factors that were unable to be effectively quantitatively measured were noted as a binary variable (i.e. factor occurred or did not during the productive cycle). Examples of binary variables used were wind throw and shifting position between standing trees for the felling operation.

5.2.5 Data Analysis

5.2.5.1 Multiple Linear Regression

To calculate the underlying productivity balance within each of the case studies, individual system component productivity rates were required. Delay free productivity rates for each system component were calculated and compared with other system components (within individual operations) to identify the system productivity balance. Insufficient samples of delays were observed throughout the study and resultantly not included in analyses.

For each system component, summary statistics were gathered for average cycle elements, cycle times and productivity rates. Element and cycle information provided information necessary for machine productivity calculations. Cycle element statistics provide information and identification of variability within particular elements, allowing areas of identification for further study and aid understanding factors affecting productivity.

5.2.5.2 Multiple Linear Regression

To identify factors that significantly affect cycle time and productivity for each of the system components, multiple linear regression was used. Multiple linear regression was used as a substitute of stepwise linear regression due to the limited number of factors observed. Comparison of influential factors was completed in Microsoft Excel under the Data Analysis toolbar, providing regression coefficients, standard errors, t value, p value and standardised estimates (shown in Appendix tables). The statistical significance of measured variables was based on an alpha (significance level) of 0.05. A significance level of 0.05 was applied to the regression analysis due to the conventional use of this value in statistical studies (Perneger, 1998). The typical significance level applied in forest operations is 0.1 due to the variability observed in operations, however this alpha will detect a wider range of difference that may occur. Numerous regressions were run to analyse the effect of observed factors for each system component within each case study. Similarity of processing operations on the landing allowed for a single regression to be for this system component across case studies. Regression outputs of individual system components were included in the Appendix.

5.2.5.3 One-Way ANOVA

Throughout the analysis, certain variables will likely be not significant in predicting cycle time or productivity, however field observations and logic would suggest a significant impact. To test the effect of certain factors on individual elements or productivity further analysis was conducted to test significance through a one-way ANOVA. The one-way ANOVA test allowed comparison the means to analyse if they were significantly different from one another.

One-Way ANOVA test was completed using the Data Analysis toolbar in Microsoft Excel. A significance value of 0.05 was used to determine if the mean values were significantly different. The One-Way ANOVA is appropriate for this additional analysis as only two groups of means were compared. Greater quantities of means require an ‘omnibus’ test to evaluate which specific groups were significantly different from one another.

6.0 Results

6.1 Operational Phase Statistics

6.1.1 Felling Operational Phase Statistics

Table 5: Felling cycle and productivity statistics for the three case studies observed.

Felling Elements	Case Study 1		Case Study 2		Case Study 3	
	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
Felling	18.8	9.6	15.2	8.5	17.3	7.3
Shift	40.6	37.6	28	34	30	24.6
Bunching	16.6	78.3	30	36.4		
Shovelling			10	25.8		
Slash Clearance	7.3	20.4				
Delimb					18.6	14
Windthrow					10	42.2
Average Cycle (Sec)	**82.8**	45.3	**83.2**	48.5	**76**	44.3
Trees Felled/PMH	43.5		43.3		47.4	
Piece Size (m^3)	1.6		2.3		2.5	
Productivity (m^3/PMH)	**69.6**		**99.5**		**109.0**	

During observations of case study 1, 204 felling cycles were completed at an average cycle time of 82.8 seconds or 1.38 minutes. Throughout the study work elements were often completed in a random order (cycle defined by tree felled) due to operator preference and site conditions. Elements, bunching and slash clearance only occurred within 69 and 49 respectively of the observed cycles. With an average stand piece size of 1.6 tonne, delay free productivity (per PMH) was calculated at 69.6m^3/PMH from 43.5 trees felled/PMH.

A total of 220 cycles were observed during the observation of case study 2. The average delay free cycle time was very similar to case study 1 at 83.2 seconds or 1.39 minutes. Delay free hourly productivity was however greater than the felling machine of case study 1 due to the larger piece size (2.3m^3). This translated to an average delay-free hourly productivity of 43.3 trees or 99.5m^3.

During the observation of case study 3 a total of 252 felling cycles occurred. Throughout the stand patches of wind throw occurred with wind throw observed 74 times throughout the 252 cycles. The average cycle time for the felling machine was 76 seconds or 1.27

minutes, resulting in a delay free productivity rate of 47.4 trees felled/PMH or 109m^3/PMH. Average cycle time was slightly less than case study's 1 and 2 with resultant productivity rate largely influenced by average piece size (2.5m^3).

6.1.2 Extraction Operational Phase Statistics

Table 6: Extraction cycle and productivity statistics for the three case studies observed.

Extraction Elements	**Case Study 1** Average	Std. Dev	**Case Study 2** Average	Std. Dev	**Case Study 3** Average	Std. Dev
Outhaul	37.6	9.5	24	10.84	164.7	32.9
Hook-up	167.2	62.4	18.9	10.38	29.5	26.5
Inhaul	99.6	35.4	53.3	28.59	124.4	53.2
Unhook	48	18.2	18.9	5.83	21.1	13.5
Average Cycle (Sec)	**352.2**	91.1	**83.2**	34.86	**310.2**	100
Stems/PMH	23.8		43.3		32.8	
Heads/PMH	7.7		10.6		9.2	
Piece Size (m^3)	1.6/1.5		2.3/1.5		1.65/2.3	
Productivity (m^3/PMH)	**35.1**		**79.1**		**57.8**	

During the study of case study 1, 119 cycles were measured with an average cycle time of 352.2 seconds or 5.87 minutes. For all cycles, stem and head volumes (m^3) were assumed 0.85 and 0.15 of the average piece size respectively (assumption used across all case studies). This resulted in a delay free productivity of 35.1m^3/PMH from an average of 32.8 stems and 7.7 heads extracted. Hook-up element accounted for the largest contribution to cycle time at 47% with largest variability (standard deviation of 62.4).

Yarder extraction for case study 2 was observed over three days with 205 cycles recorded. Average delay-free cycle time was significantly quicker than extraction of case study 1, at 83.2 seconds or 1.38 minutes. This translated to an average delay-free productivity of 79.1m^3/PMH. In contrast to case study 1, the Inhaul element exhibited the greatest addition to average cycle time (64% of total) and widest variation (standard deviation of 28.6) compared with other elements.

102 extraction cycles were observed during the observation of case study 3. Average cycle time for the study was 310.2 seconds, or 5.17 minutes, very similar to case study 1. During the study, an average of 32.8 stems/PMH and 9.2 heads/PMH were extracted, resulting in an average hourly productivity rate of 57.8m^3/PMH. The greatest addition to total cycle

time occurred through inhaul and outhaul elements, which contributed to 86% of total cycle time conjointly. Outhaul element was however the longest on average, likely due to the uphill outhaul phase required to reach stems in the stand.

6.1.3 Processing Operational Phase Statistics

Table 7: Processing cycle and productivity statistics for three case studies

Processing Elements	**Case Study 1**		**Case Study 2**		**Case Study 3**	
	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
Slew/Grab	17.9	7.27	17.7	10	14.4	7.4
Processing	45.2	19.73	39.5	20.5	40.1	20.8
Delimbing	17.4	8.24	12.9	4.5	10.2	28
Average Cycle (Sec)	**80.4**	26.1	**70.1**	22.6	**55.7**	24.3
Pieces processed/PMH	44.8		46.2		59.7	
Head/Stem Ratio	0.3		0.2		0.3	
Piece Size (m^3)	1.6		2.3		2.3	
Productivity (m^3/PMH)	**50.5**		**72.4**		**85.9**	

During the study of the processing operation a total of 208 log processing cycles were measured at an average of 80.4 seconds, or 1.34 minutes, resulting in an average delay free productivity of 50.5m^3/PMH. The assumption of 0.33 heads per 1 stem processed was based on the ratio of stems and heads extracted in the yarder study (technique used for all case studies).

Processor productivity occurred for a total of 382 cycles for case study 2. Average delay-free cycle time for this operational phase was slightly faster than case study 1 at 70.1 seconds or 1.16 minutes. This resulted in a delay-free productivity of 46.2 pieces processed/PMH or 72.4m^3/PMH, based on average piece size of 2.3m^3.

A total of 320 cycles were observed for case study 3 with significantly shorter average cycle time of 55.7 seconds, or 0.93 minutes. This was mainly comprised of the processing element which accounted for 75% of the cycle time on average. The average number of pieces processed was 59.7/PMH, translating to an average productivity of 85.9m^3/PMH. Throughout the study delimbing occurred within only 9.3% of the observed cycles, due to delimbing completed during the felling component.

Across all case studies the processing element accounted for the largest proportion of total cycle time with the greatest variation indicating the influence on hourly productivity. Other observed elements exhibited much lower average times and standard deviations in comparison.

6.2 System Production Balance

Table 8: Matrix of productivity rates for felling, extraction and processing system components for individual case studies.

	Case Study 1	Case Study 2	Case Study 3
Felling (m^3/PMH)	69.6	99.5	109.0
Extraction (m^3/PMH)	35.1	79.1	57.8
Processing (m^3/PMH)	50.5	72.4	85.9

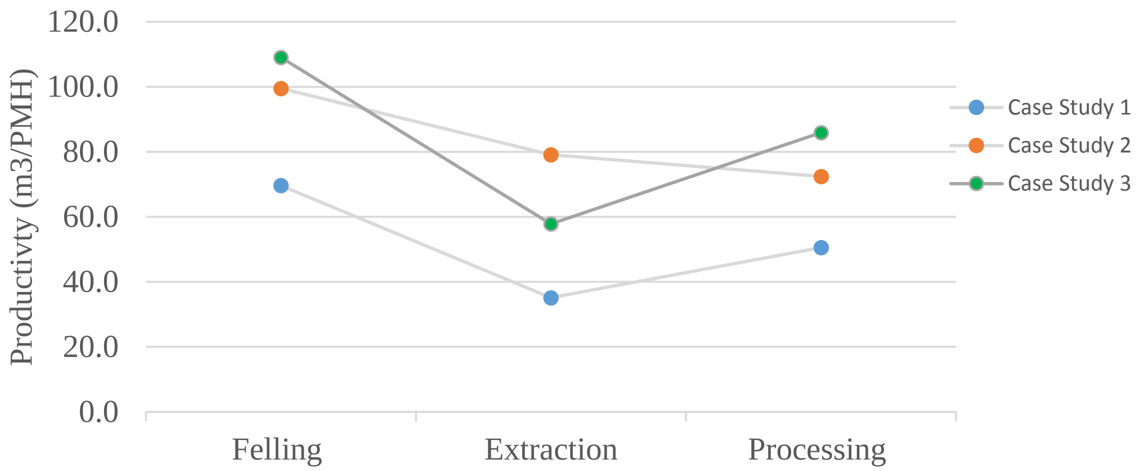

Figure 1: System production balance between felling, extraction and processing.

Felling was the most productive operational phase in case study 1 exhibiting an average productivity rate 19.1m^3/PMH and 34.5m^3/PMH greater than processing and extraction system components respectively. Subsequently extraction is the limiting operational phase of the operation, with a productivity rate 15.4m^3 less than processing. Under observed conditions, with the felling operation working 6.0 PMH per day at 69.6m3, processing and extraction phases would be required to work an additional 2.26 PMH and 5.89 PMH respectively to balance daily productivity.

Consistent with case study 1, felling was more productive than extraction and processing phases. Felling was 20.4m^3/PMH and 27.1m^3/PMH more productive than extraction and processing. Processing was the production bottleneck which was slightly less productive than extraction by 6.7m^3 per PMH. System balance under these conditions at 6.0 PMH for the felling machine (597m3 per day) requires an additional 1.57 and 2.25 PMH by extraction and processing respectively per day.

Felling was the most productive phase for case study 3, followed by processing, with the operational bottleneck extraction. Case study 3 exhibited the greatest discrepancy in hourly productivity between felling, extraction and processing. Felling was significantly greater than both processing and extraction by 23.1m^3/PMH and 53.1m^3/PMH respectively. Assuming the felling operation works 6 PMH's per day at 654m3, system balance under these conditions would require an additional 1.16 and 5.34 PMH's from processing and extraction phases separately.

6.3 Cycle Time Analysis

6.3.1 Felling Cycle Time Analysis

Felling machines of the three case studies although of similar arrangement performed a range of different work elements, therefore separate regressions were conducted to analyse the effect of measured factors on cycle time for individual case studies.

Case Study 1 *(sec)* = 33.1 + 33.5SB + 27.4PS

Case Study 2 *(sec)* = 30.2 + 7.5SS + 21.8SB + 39.4PS

Case Study 3 *(sec)* = 55.8 + 68.0W

Where,

SS = number of Stems shovelled

SB = number of Stems bunched

W = wind throw (1/0): 1 = wind throw interference; 0 = No Wind throw interference

PS = position shift (1/0): 1 = machine shifts during cycle; 0 = machine remains stationary.

Within case studies 1 included 2 the number of stems bunched and position shift factors were found to be statistically significant at p value < 0.05. Cycle time increases by 27.4 seconds if the machine moves (p value < 0.001) and 33.5 seconds per additional stem bunched (p value < 0.001).

The felling machine for case study 2, is a similar system to case study 1 (tethered with fell/bunch head). Significant factors that affected cycle time were similar to case study 1, however the number of stems shovelled was significant, with each additional stem shovelled increasing cycle time by 7.5 seconds (p value < 0.005) (shovelling did not occur in case study 1). The number of stems bunched altered cycle time by 21.8 seconds (p value < 0.001), which was less significant than case study 1.

Case study 3 had one significant measured factor that affected cycle time being wind throw interference (p value < 0.001), with bunching and shovelling not occurring within this operation. Wind throw interference, involving moving and delimbing windblown trees and root balls increased cycle time by 68 seconds.

The relationship between the 2 significant factors and cycle time for case study 1 was reasonably strong indicated by an adjusted R^2 of 0.68. This indicates the equation can therefore be used as a reasonable estimator and gain good understating of felling cycle time. This relationship for case study 2 was considerably lower providing an R^2 of 0.25. This indicates only 25% of the variation of cycle time is explained by the measured factors, where the equation should be considered to solely gain some understating of cycle time. Similar to case study 2, case study 3 produced a low R^2 of 0.37 indicating the regression is only suitable to aid understanding of cycle time.

6.3.2 Extraction Cycle Time Analysis

When performing the analysis of the extraction phase, the expected difference between the case studies was obvious. This is illustrated through figure 2 displaying the difference in common work elements between the three case studies. The difference is due to the difference in extraction systems employed between case studies. Individual regressions were completed for individual case studies as a result of operational differences.

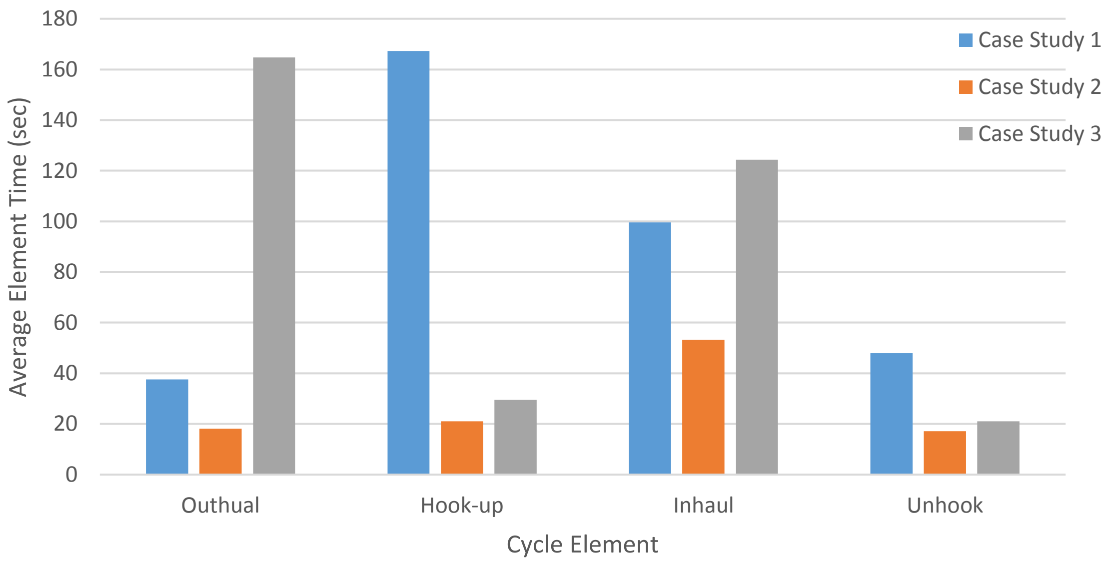

Figure 2: Comparison between average element times for the four common work element for three case studies sampled.

Comparing cycle times for each case study, case study 2 (swing yarder extraction) was significantly quicker than case studies 1 and 3. Average cycle times between case studies 1 and 3 were very similar with cycle time averages of 352 and 310 seconds respectively. Time performed per element was however variable, exhibited by figure 2 with hook-up and inhaul accounting for 80% of the cycle time for case study 1. Outhaul and inhaul accounted for majority of the cycle time (75% of cycle time) of case study 3, likely due to the slower inhaul and outhaul speed and greater haul distance compared to cable extraction.

Extraction Cycle Time: Case Study 1

Case Study 1 (sec) = $154.4 + 0.49HD + 22.1S + 99.8ST$

Where,

HD = haul distance (m)

S = number of stems extracted (per cycle)

ST = Site factor (1/0) (1 = site 1; 0 = site 2)

The relationship between extraction cycle time and significant variables produced an adjusted R^2 of 0.24. This value suggests there is a poor relationship between the predictor variables and extraction cycle time and should not be used a predictor of cycle time. The poor R^2 indicates there is a lot of variability not explained within the regression, which is likely due to no measured factors associated with the variable hook-up element (47% of total cycle time, standard deviation of 64.2).

Significant measured variables in the extraction cycle time analysis for case study 1 were haul distance, the number of stems extracted and site factor. Site factor was highly significant indicated by the significance value (p value < 0.001). The difference in cycle time between sites can be largely attributed to the extraction system employed. At the first site a shotgun cable yarding configuration was used, in comparison to a scab (grabinski) configuration at site 2. Resultantly cycle time is 96.1 seconds slower at site 2 on average in comparison to the first study site. Figure 3 exhibits the difference between site factors with inhaul time for site 1 visibly shorter.

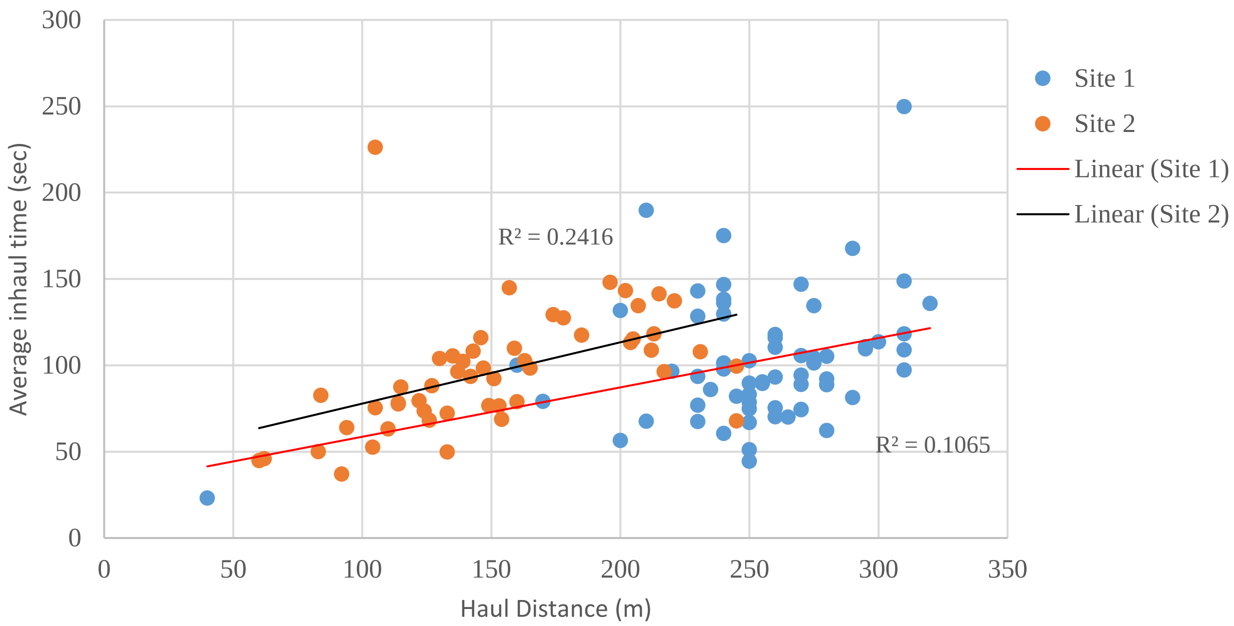

Figure 3: Effect of site factor on inhaul time for case study 1.

The number of heads extracted did not have significant impact on cycle time (p value < 0.4). The number of stems extracted did have significant impact on which can be attributed to the larger payload on inhaul time and the greater hook-up time from more stems requiring breaker out attention. Haul distance was highly significant as inherently thought (p value < 0.001).

Extraction Cycle Time: Case Study 2

Case Study 2 (sec) = 42.39 + 0.45*HD* + 5.37*S* + 4.43*H*

Where,

HD = haul distance (m)

S = number of stems extracted (per cycle)

H = number of heads extracted (per cycle)

The relationship between the three statistically significant variables and cycle time provided the greatest correlation coefficient of the three extraction systems observed (R^2 = 0.72). This R^2 within this range indicates that the equation is a reasonably strong predictor of cycle time.

The three statistically significant factors in the regression were haul distance, the number of stems and the number of heads extracted. Haul distance predictably has the greatest effect on extraction cycle exhibiting the greatest significance value (p value < 0.0e-18). The number of stems and heads extracted has similar levels of significance, (p value < 0.05 and p value < 0.05) respectively indicating their relative uniform significance towards cycle time.

Intriguingly there was there was shown to be no significant difference between cycles that had included shovel machine fed hook-up versus ground hook-up (bunches). A likely reason for this is the small proportion (23%) of time the element associated overall cycle time. Although not significant, machine feeding of the grapple is stated to reduce cycle time by 4.9 seconds on average.

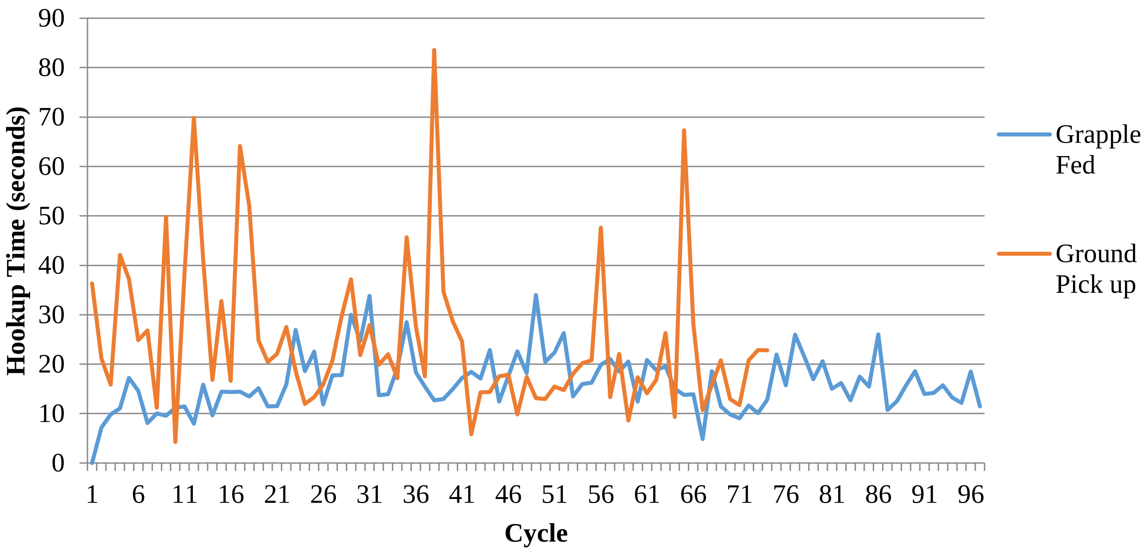

Figure 4: Hook-up element time comparison between cycles with or without machine fed hook-up.

Further analysis was conducted to evaluate the true effect of feeding the grapple on the hook-up time and payload. A comparison of the two techniques identifies a difference in variability, with machine fed displaying a lower standard deviation of 6.8 compared to 9.9 of ground pick up. Figure 4 illustrates the variability difference between the two techniques, shown by difference is spikiness in hook-up element time.

Table 9: Comparison of stems and heads yarded per cycle for shovelled or ground fed grappling.

Hook Type	**No. cycles**	**Mean no stems per cycle**	**Mean number of heads per cycle**
Machine fed	160	1.73 *	0.45
Ground hook up	45	1.06 *	0.7
* indicate difference at p > 0.05			

To compare the difference in payload between the two techniques, a one-way ANOVA was conducted on stems and heads extracted per cycle. At a significance level of 0.05, the difference in number of stems extracted was greatly significant (p value < 0.001), whereas the number of heads was not significant (p value > 0.5). Productivity is therefore increased by 0.63 stems, or 1.57m^3 on average for every cycle if machine grapple feeding occurs.

Extraction Cycle Time: Case Study 3

Case Study 3 = 243.9 + 0.61*HD* - 210.5*ST*

Where,

HD = Haul Distance (m)

ST = Site factor (1/0) (1 = site 1; 0 = site 2)

The relationship between skidder cycle time and the significant factors produced an R^2 value of 0.38. This indicates the regression can be used as a useful guide for understanding the factors affecting cycle time but not an accurate predictor.

The significant factors measured that affect cycle time were haul distance and site factor. The likely reason for the difference in cycle time from site factor can be attributed to differing ground conditions and piece size between site. Site 1 is stated to be have an average cycle time 210 seconds quicker than site 2. Although this value appears abnormally large, the factor provided a p value < 0.001. The apparent difference is shown in figure 5, comparing inhaul time for each site against inhaul element time.

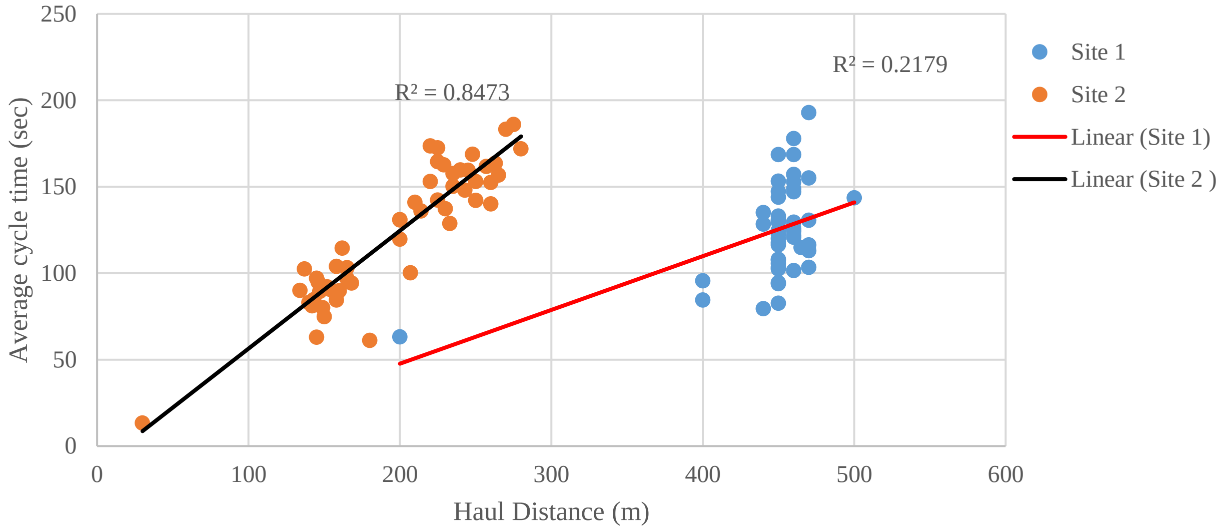

Figure 5: Effect of site factor on inhaul time for case study 3.

Haul distance was intuitively significant with a p-value < 0.001. The number of stems and heads extracted is not significant (p-value > 0.05). This is likely due to the payload not affecting the downhill extraction speed and consistent drag size during the study observations.

6.3.3 Processing Cycle Time Analysis

When evaluating the processing system component for each case study, a high similarity between the case studies became apparent. Running the regression model found the cycle time difference between the case studies not to be significant (p value < 0.05), which is probably due to the similarity of processing operations between case studies. Consequently a single regression was completed, combining data from the 3 case studies.

Total Cycle Time (sec) = 21.6 + 11.3*D* + 10.30*L*

Where,

D = Delimbing (1/0)

L = # logs cut

The relationship between total cycle time and the two factors produced an R^2 of 0.59. The R^2 value in this range suggests the regression model can be used to provide understanding of what affects the cycle time, however not used as predictor of cycle time, with 41% of the variation not explained within the regression model.

The major significant factor was the number of logs cut per stem. For every additional log cut (ranging from 1 to 7) the average processing cycle time would increase by 10.03 seconds. The effect was shown to be very significant under the regression producing a p value < 7.5E-110. This effect of this factor was very consistent between the three case studies illustrated by the linear trend between processing element time and number of logs cut per cycle in figure 6. This factor was plotted against the processing element to understand the variability within this major element, with slew/grab and delimbing elements accounting for a small percentage of total cycle time.

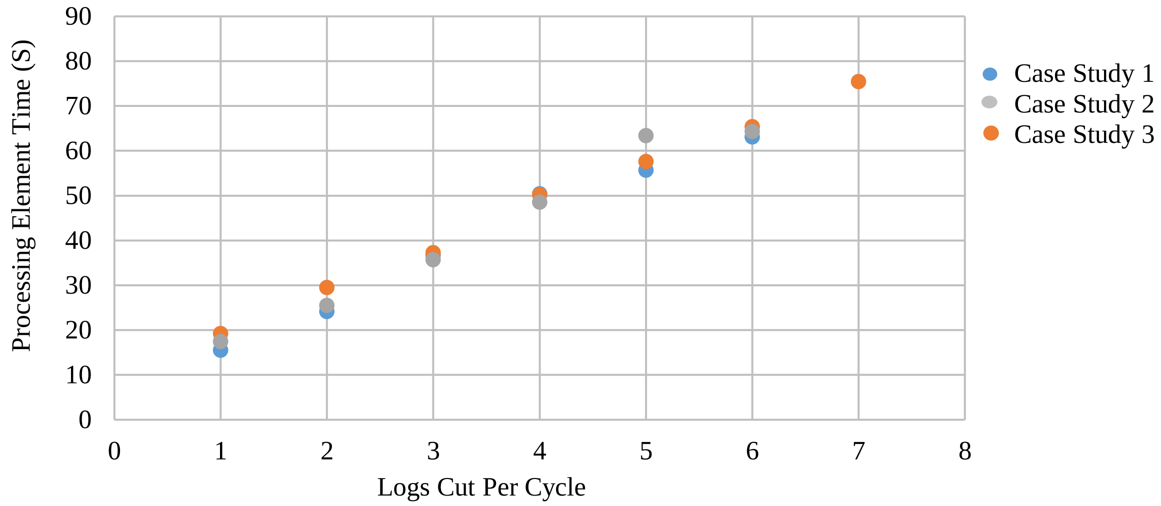

Figure 6: The positive influence of logs cut per stem processing element time.

The regression analysis indicates that for each cycle, the average cycle time is increased by 11.3 seconds if delimbing occurs, which makes sense due to the time required to cover the stems for 1 or 2 lengths. As the effect of delimbing was only able to be measured within case study 3, an ANOVA analysis was conducted to asses' validity.

Table 10: Effect of delimbing on cycle time for case study 3

Element	No cycles	Average cycle time
Delimbing	262	58.5*
No Delimbing	24	71.5*
* indicate difference at p > 0.05		

Table 10 indicates a significant difference in cycle time if delimbing occurs or does not occur. Average time difference between is 12 seconds indicating the validity of the delimbing factor in understanding processing cycle time.

6.4 Productivity Analysis

A further regression study was conducted to estimate productivity of extraction operation to evaluate the effects of observed factors on hourly extraction productivity. Productivity regressions were run solely for extraction and not felling and processing components as a single piece (average piece size) was processed or felled per cycle. Therefore it would be assumed regressions would be equivalent to cycle time analyses. Productivity regression equations for each of the case studies are as follows:

Case Study 1 (*t/PMH)* $= 13.8 - 0.04HD + 13.5S + 3.06H - 6.9ST$

Case Study 2 *(t/PMH)* $= 53.7 - 0.24HD + 46.9S + 1.5H$

Case Study 3 *(t/PMH)* $= 56.7ST - 0.09HD + 22.01S + 5.1H$

Where,

HD = haul distance (m)
S = number of stems extracted (per cycle)
H = number of heads extracted (per cycle)
ST = Site factor (1/0) (1 = site 1; 0 = site 2)

For all case studies the relationship between productivity and measured factors was much stronger relationship than cycle time. Case study 1 saw the greatest shift in R^2 value from 0.74 against 0.24 (cycle time relationship). Case study 3 also saw a great shift in R^2 value from the cycle time analysis, due to the same reasoning as case study 1. For case study 1 the R^2 provided in the regression was 0.80 (cycle time analysis, $R^2 = 0.37$, case study 1).

The greater R^2 values imply that a larger proportion of the variation has been explained in the regression, with equations for all case studies regressions providing a good understanding and prediction of system productivity. These equations are therefore better predictors than cycle time equations and more directly correlated to the effect of factors on machine productivity rates.

The number of stems and heads extracted were not significant in the cycle time analysis, however highly significant in the regression against hourly productivity. The number of stems extracted was the most significant factor in the regression producing p values below 0.001 for all case studies. Understandably the number of stems and heads extracted per drag became a significant when predicting productivity, due to the direct correlation with cycle payload and hence hourly productivity. Heads were less significant for all case studies presumably due to the smaller effect on payload.

An intriguing result was the effect of site factor on productivity for case study 3, which is stated to decrease by a momentous 56.7t/PMH. Changes in productivity occurred for case study 1 between sites, however the difference was only 6.9 t/PMH.

Haul Distance intuitively had a significant impact on hourly productivity. Haul distance had the greatest impact on case study 2 where productivity decreased by 0.24t/PMH for every additional metre (p value < 0.001).

7.0 Discussion

7.1 System Production Balance

The study of the three operations found large imbalances between felling, extraction and processing which is typical of higher production mechanised operations (Evanson and Amishev, 2012). The operational bottleneck for each case study was significantly lower than the most productive operational phase. For each case study, felling was the most productive phase with extraction the bottleneck for case studies 1 and 3, and processing for case study 2. This differed to 2 fully mechanised swing yarder studies that found bunched extraction and processing to be the most productive system components (Evanson and Amsihev, 2009; Evanson and Amishev 2010). The production difference between bottleneck and most productive component was however similar when comparing swing yarder operations, with production differences of 37%, 28% and 37% for case study 2 and the two alternate studies respectively (Evanson and Amsihev, 2009; Evanson and Amishev 2010). Extraction was the bottleneck in two of the three case studies which was similar to the results of the two alternate studies. Unbunched extraction was the bottleneck at for these studies, exhibiting productivity of 48.8m^3/PMH (Evanson and Amsihev, 2009). Increased productivity of the bottleneck and reduced felling productivity would be required for each case study to balance system productivity and result in greater machine utilisation rates. Processing would require a minor shift in productivity (excluding case study 2) due to hourly production rates between bottleneck and felling system components.

7.2 Factors affecting Felling

Productivity of the felling machine was near double bottleneck productivity for case studies 1 and 3. Productivity of the felling machine is understandably greater than other system components due to the simplicity of the felling cycle. Shifting position between stems significantly affected cycle time, however it would be impractical to shift machine position between trees if deemed unnecessary, in order to provide a more balanced system. The major factors that could be influenced to alter production would be increased bunching and shovelling. Bunching was found to reduce productivity by 24.1m^3/PMH and 20.9m^3/PMH for each additional stem bunched for case studies 1 and 2. An alternate study of a tethered felling machine found bunching (total stems bunched) to decrease productivity by 29.6m3/PMH or 26% for the total cycle time (Evanson & Amishev, 2013). The effect of bunching on productivity appears uncharacteristically high for case studies 1 and 3 (possibly due to the small sample size and single stem bunched per felling cycle) however indicate the significance of the number of stems bunched on productivity. Increased bunching would also aid extraction through reduced hook up time in mechanised extraction operation. An earlier study evaluating the effects of bunched extraction versus unbunched extraction saw an increase in productivity by 33% (Evanson & Amishev, 2009). With case studies 2 and 3 already employing shovelling/bunching excavators to aid extraction, such machines could be utilised elsewhere with the felling machine performing the duties of this machine.

Felling productivity for case studies 2 and 3 was near double the productivity of the bottleneck (88% and 98% difference respectively). Influencing factors to balance productivity is perhaps infeasible due to the large disparity between felling and bottleneck. A potential solution to maintain high utilisation rates is to use felling machines across multiple operations. This would however raise issues with transport costs and work availability at alternate operations.

7.3 Factors affecting Extraction

The number of stems significantly affected productivity within operations, due to the direct impact on payload. This factor appeared to have a stronger significance on productivity of the cable yarding case studies compared to the ground based case study. Alternate literature has also documented stems and payload significance on cable extraction productivity compared with ground based extraction (Sunderburg & Silverside, 1996). In harvesting systems the direct influence of the number of stems on productivity is well recognised with workers attempting to maximise payload in order to capitalize on productivity gains.

Inherently haul distance had the greatest impact on productivity for all case studies. Haul distance is renowned as one of the major factors affecting the productivity of all harvesting operations (Gardner, 1980). Haul distance was found to have the greatest affect in case study 2 with a reduction in productivity of 0.25m^3/PMH for every additional metre of haul distance. Average haul distance would therefore need to be reduced in order to increase extraction productivity. Increased roading density or two staging (where feasible) could potentially reduce haul distance if the benefits of reduced haul distance outweigh the costs of additional roading.

Haul distance however had lesser influence on extraction productivity for case study 1. This is due to the relative short inhaul and outhaul phases in comparison to the hook-up stage of the operation, accounting for half (47%) of average cycle time. Extensive hook-up time was due to the time required for manual breaker-outs to attach stems and retreat to a safe distance, before extracting the drag. To reduce hook up time, mechanisation could be employed in a way of a mechanised grapple carriage. A study of the Falcon forestry claw indicated the average hook-up time for the Falcon forestry claw on average (35.31 seconds) (Fairhall, 2014) was much quicker than hook-up with manual breaker outs observed at case study 1. This however would only be appropriate at sites where there is enough slope for gravity outhaul of the carriage (20%+)(Harill, 2014) due to the 2 drum cable system in case study 1 with no available haul back line. The Mega Claw line grapple carriage has the ability to operate on a running skyline system, although no studies have been completed to test its effectiveness (Evanson & Parker, 2011).

Site factor was also a major factor affecting the extraction productivity for case study 3. Average cycle time appeared relatively similar between sites however average haul distance was much greater at site 1. The major variables differing between sites were piece size, average slope (table 1) and ground conditions. Average piece size would affect productivity to some extent, with a similar number of stems extracted per average cycle between sites. Slope would have minimal effect as stems were shovelled from the steeper terrain to skidder trails at both sites. The major factor can therefore be attributed with differing ground conditions with observations occurring during summer and winter for sites 1 and 2 respectively. During observations of site 2, the skidder was struggling to gain traction on extraction trails, indicating the large inhaul and outhaul phases significantly impacting cycle time and hence productivity. This provides implications for case study 3, which would be more suited to work in stands with shorter haul distance during winter months and larger stands during summer, to reduce the effect of site conditions on productivity.

7.4 Factors affecting Processing

Processing cycle time was relatively similar between the three case studies, due to high similarity of processing operations. Independent of average piece size, average cycle times for each case study ranged between 0.93 and 1.34 minutes with case study 3 marginally quicker due to the absence of delimbing. This cycle time was also consistent to another study conducted by Evanson & Mcconchie (1996) with an average cycle time of 1.27 minutes.

The major factor affecting log processing was the number of logs cut per stem, with each additional log cut reducing hourly productivity by 16%. This factor was very consistent between all three studies with a linear increase in cycle time per log cut. The increase in cycle time is simply due to the extra time required to pass over the stem and drop log in appropriate pile. The number of logs cut is however dependent on meeting market requirements and therefore cannot be changed to balance productivity. As two of the three case studies lie between the bottleneck and the most productive system component, altering productivity of the processing operation to balance productivity is of limited importance.

Delimbing was also seen as a significant factor affecting average cycle time due to the additional time required to pass the processing head over the stem. The effect of delimbing had a much smaller effect on cycle time than reported by Evanson & Mcconchie (1996), who found delimbing to increase cycle time by 34 seconds in comparison to 11.3 seconds observed at case study 3. Removal of delimbing at the landing is only achievable for case study 3 as delimbing occurs within the field by the felling machine. Delimbing during felling cycles within semi-mechanised cable yarding case systems would also be less applicable due to reduced safety of breaker-outs from slippery and moving stems.

7.5 Further Analysis

The three case studies have shown that mechanised systems are often not well balanced and result in system components being underutilised. An approach to increase utilisation rates from more balanced systems is through task strategies and machine sharing between systems. Altering task strategies and system setup to gain more balanced systems, could prove uneconomic. Additional studies should occur analysing the true effects on costs from altering harvesting and task strategies in order to gain balanced systems. This will provide justification of management and planning decisions to achieve more balanced systems and the true costs of such activities.

An implication for NFL is that limited studies have been carried out on the capability of systems following the introduction of felling machines. The information provided from this study can be used as a base case for further study, categorising system performance on a variety of terrain classes. Further studies can be completed on a variety of terrain classes for these case studies and compared against base case data to understand machine and system capability. Greater system understanding can be used by management to situate operations in appropriate locations, based on machine and operational capability.

7.5 Limitations

A limitation of data collection is that the detailed time and motion study only takes a snapshot of a limited number of operations. Forestry operations are very complex with a wide range factors (e.g. slope or piece size) affecting machine productivity rates. The sample collected during data collection therefore does not provide an accurate representation of each system, and other harvesting systems of similar makeup. During observations, machine operators were also aware that they were subjects of a study, which may have altered work behaviour (known as the Hawthorne effect) and resulted in non-representative data collected. This study should therefore only be used to assist with the understating of harvesting production balance on steeper terrain and associated factors affecting productivity.

Throughout analyses, delay elements were not accounted for due to the small sample of observed delays. Specific operations observed that would likely influence cycle time and hence productivity include line shifts for tethered felling machines and tail hold shifts of the cable yarders. Although these delays are not part of the common working cycle, they are required to be productive and therefore should be included in the analysis to gain accurate system component production rates.

During studies of the extraction operation, multiple locations were observed to achieve a sufficient number of cycles for an analysis. This issue associated with multiple study sites is the variation of site factors that can significantly affect machine productivity. Varying factors observed between study sites were terrain, piece size, weather and operation setup. Extraction productivity rates provided will likely be under/overestimated, affecting the production balance results presented for each case study.

Cycle elements for felling operations were often short and performed in an unpredictable sequence. Delineation of cycle elements was difficult to achieve, resulting in the probability of slightly incorrect cycle element measurements. Felling machines were occasionally out of view while observing their activity, which could have also produced incorrect cycle element measurements.

Haul distance throughout the study was calculated with scale maps and range finders for case study 3. As it was unsafe to measure haul distance on foot, assumptions of distance were made to best possible judgement, based on the range finder and scale map measurements. Haul distances for case study 3 are consequently likely to be less accurate than distances for case studies 1 and 2.

8.0 Conclusion

The initial objective of this study was to understand the system production balance that occurred within three mechanised harvesting case studies. Across the three case studies it large production imbalances were apparent between felling, extraction and processing. Felling was by far the most productive phase, near doubling bottleneck production rates of case studies 1 and 3. Production of the felling operation was 98%, 37% and 88% more productive than the bottleneck for case studies 1, 2 and 3 respectively. System bottlenecks for case studies 1 and 3 was extraction, whereas case study 2 was processing. (Although very similar to extraction; 79.1m^3/PMH vs 72.4m^3/PMH). To balance system productivity across all case studies, felling operations are required to significantly reduce productivity with the system bottleneck significantly increase productivity.

The major aim of the study was to understand factors affecting system component productivity rates to aid planning in order to achieve more balanced systems. Measured factors affecting felling were the number of stems shovelled, the number of stems bunched, wind throw interference and machine position shift (case study 3). For every stem bunched, average productivity decreased by 35% (24m^3/PMH) and 21% (20.9m^3/PMH) for case studies 2 and 3 respectively. Every additional stem shovelled increased average cycle time by 7.5 seconds, resulting in a productivity shit of 7.4m^3/PMH for case study 2.

Factors affecting cycle time of extraction operations were haul distance, the number of stems extracted and site factor. Haul distance and the number of stems extracted had the greatest impact on hourly productivity for case study 2 (of the three case studies), due to shorter cycle time and greater hourly productivity. Site factor affected hourly productivity by 6.9m^3/PMH and 56.7m^3/PMH for case studies 1 and 3 respectively. The difference in productivity can be largely attributed to yarding systems (shotgun vs scab) for case study 1 and site conditions for case study 3.

Processing was affected by the number of logs cut per stem and if delimbing occurred. For every additional log processed per cycle, productivity decreased by 14%. Delimbing decreased productivity by an average of 16% with processing head requiring time to pass over the stem, increasing cycle time.

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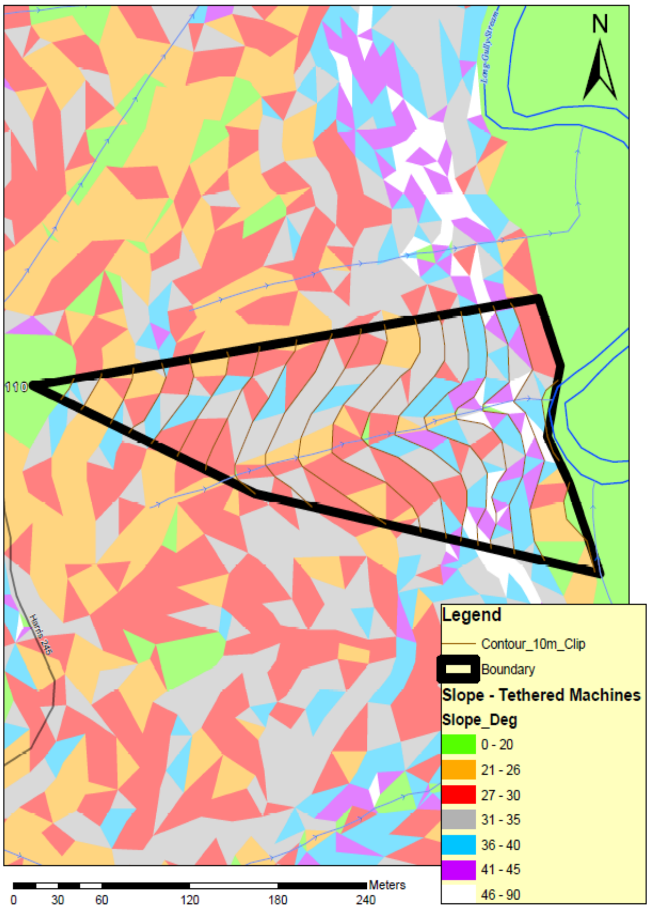
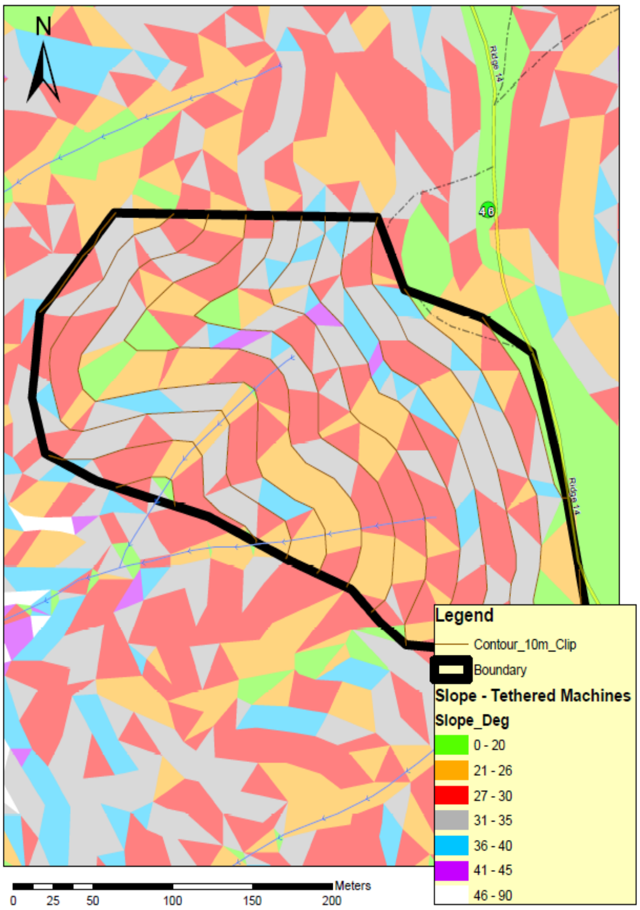
10.0 Appendix

10.1 Study Location Slope Maps

Case Study 1

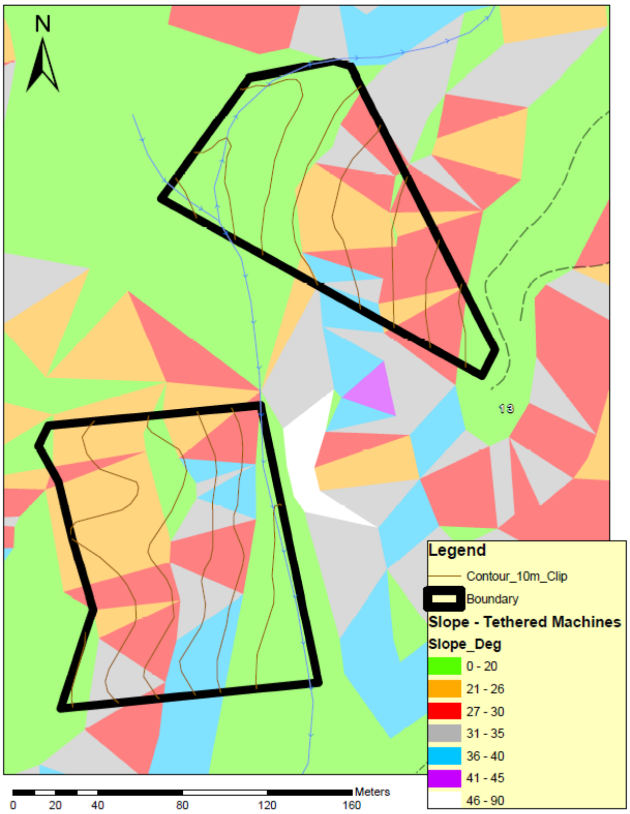


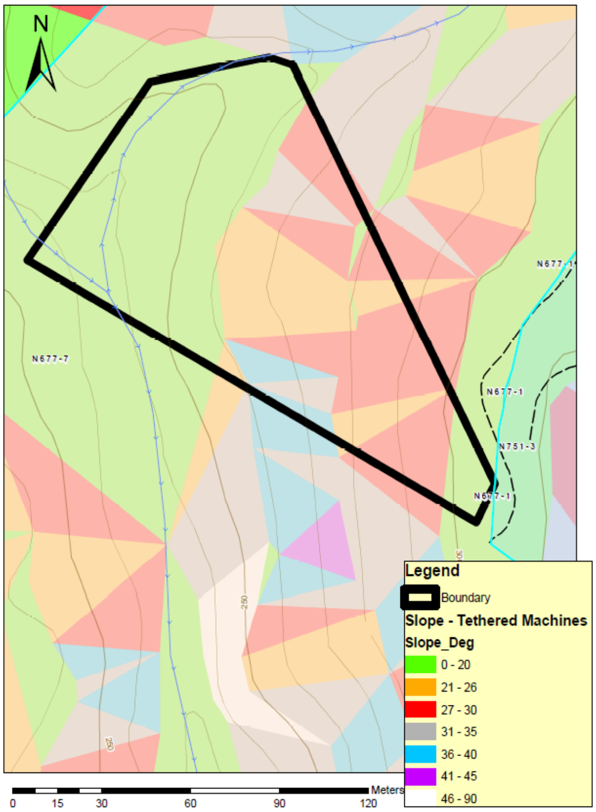
Appendix Figure 1: Slope map of study site for case study 1 at Western Boundary, Golden Downs forest.



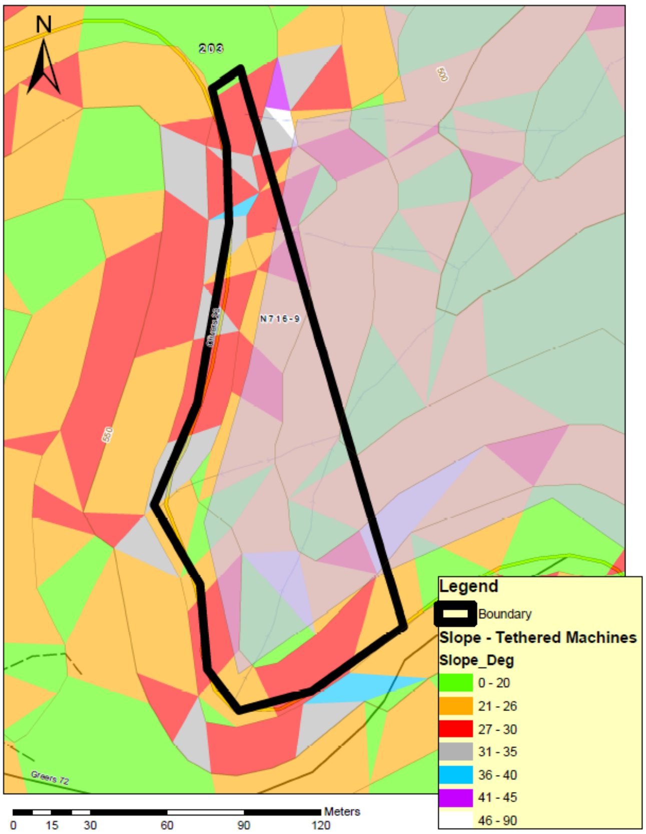
Appendix Figure 2: Slope map of second study site for case study 1 at Long Gully, Golden Downs forest.

Case Study 2



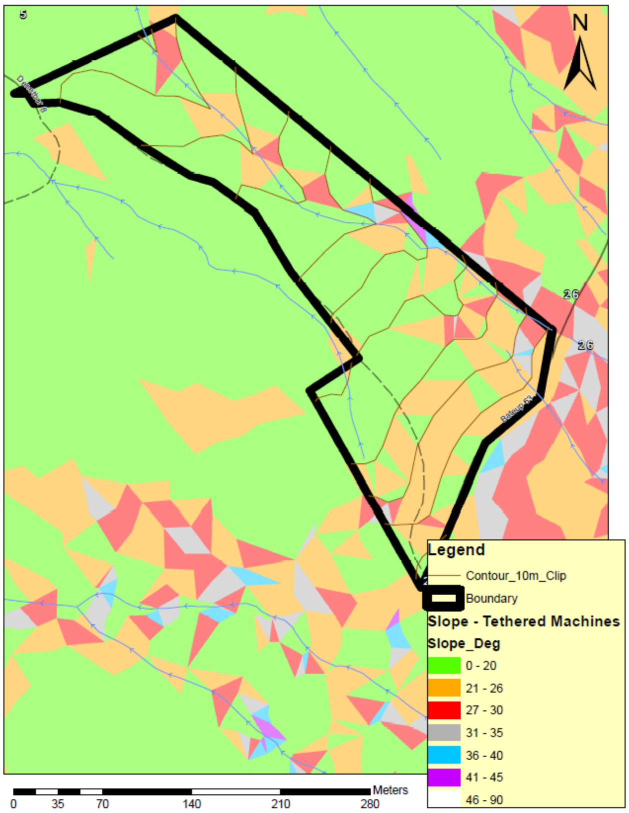


Appendix Figure 3 and 4: Slope maps for case study 2 study site, Brightwater block

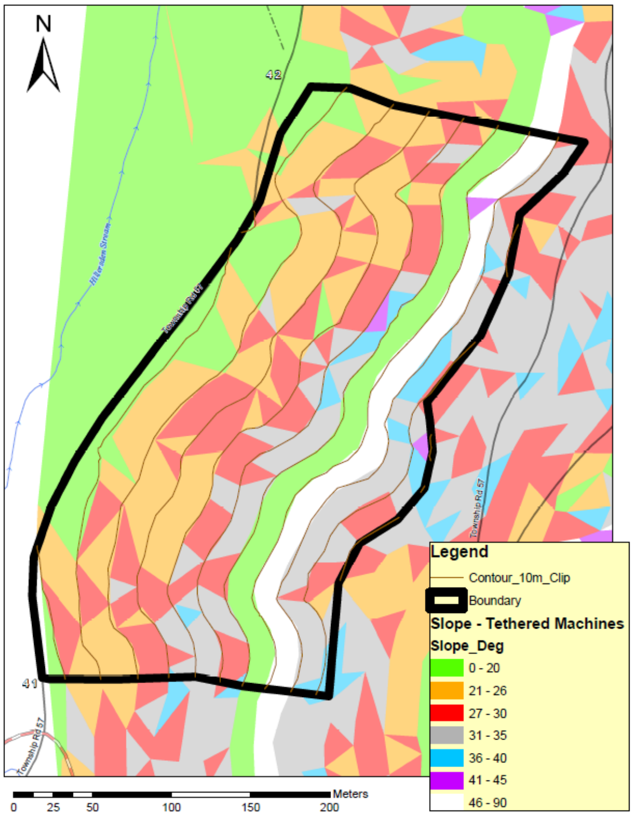


Appendix Figure 5: Slope maps for case study 2 second study site, Oliver's block, Golden Downs forest.

Case Study 3



Appendix Figure 6: Slope map of the first study site of case study 3, Pascoes block, Golden Downs



Appendix Figure 7: Slope map of the second study site for case study 3, Fairacres block, Wairau South

10.2 Regression Outputs

Felling Cycle Time

Appendix table 1: Regression output for felling cycle time of case study 1.

Regression Output				
Multiple R	0.83			
R Square	0.69			
Adjusted R Square	0.68			
Standard Error	40			
Observations	204			
	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	33	6.4	5.2	4.9E-07
Bunching (1/0)	-3.1	8.2	-0.4	0.70
Stems Bunched	34	2.1	16	7.8E-38
Position Shift (1/0)	27	6.8	4.0	8.8E-05

Appendix table 2: Regression output for felling cycle time of case study 2.

Regression Output				
Multiple R	0.50			
R Square	0.25			
Adjusted R Square	0.24			
Standard Error	38			
Observations	220			
	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	31	5.6	5.6	5.10E-08
Stems shovelled	11	3.9	2.7	0.0075
Stems Bunched	21	5.7	3.8	0.00022
Position Shift (1/0)	39	5.3	7.4	3.2E-12
Shovelling (1/0)	-11	10	-1.1	0.29

Appendix table 3: Regression output for felling cycle time of case study 3.

Regression Output				
Multiple R	0.61			
R Square	0.37			
Adjusted R Square	0.36			
Standard Error	37			
Observations	173			
	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	56	7.3	7.6	1.9E-12
Wind throw (1/0)	68	6.8	10.0	7.2E-19
Position Shift (1/0)	6.1	7.8	0.78	0.44

Extraction Cycle Time

Appendix table 4: Regression output for extraction cycle time of case study 1.

Regression Output				
Multiple R	0.50			
R Square	0.25			
Adjusted R Square	0.22			
Standard Error	67.9			
Observations	116			
	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	162	41	4.0	1.12E-04
Site (1/0)	107	20	5.3	7.0E-07
Heads	-10	8.3	-1.2	0.25
Stems	17	8.2	2.0	0.044
Haul Distance	0.5	0.1	3.6	0.00054
Pieces	0.0	0.0	65535	#NUM!

Appendix table 5: Regression output for extraction cycle time of case study 2.

Regression Output				
Multiple R	0.86			
R Square	0.74			
Adjusted R Square	0.73			
Standard Error	18.1			
Observations	205			
	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	67	8.5	7.9	1.39E-13
Shovel fed (1/0)	-6.4	3.4	-1.9	0.06
Site (1/0)	-20	5.1	-3.9	0.00015
Haul Distance	0.33	0.032	10.1	1.18E-19
Stems	7.7	2.0	3.8	0.00
Heads	5.3	1.9	2.7	0.0066

Appendix table 6: Regression output for extraction cycle time of case study 3.

Regression Output				
Multiple R	0.61			
R Square	0.38			
Adjusted R Square	0.35			
Standard Error	53			
Observations	100			
	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	250	31	8.1	1.63E-12
Site (1/0)	-212	31	-6.9	6.2E-10
Haul Distance	0.63	0.1	5.4	5.8E-07
Heads	0.30	4.5	0.1	0.95
Stems	-2.8	7.1	-0.4	0.69
Pieces	0.0	0.0	65535	#NUM!

Extraction Productivity

Appendix table 7: Regression output for hourly extraction productivity of case study 1.

Regression Output				
Multiple R	0.86			
R Square	0.74			
Adjusted R Square	0.73			
Standard Error	7.3			
Observations	116			
	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	14	4.4	3.2	1.95E-03
Haul Distance	-0.037	0.016	-2.3	0.0210
Stems	14	0.88	15.4	2.3E-29
Heads	3.1	0.90	3.4	0.00087
Site (1/0)	-7.0	2.2	-3.2	0.0017
Pieces	0.0	0.0	65535	#NUM!

Appendix table 8: Regression output for hourly extraction productivity of case study 2.

Regression Output				
Multiple R	0.94			
R Square	0.88			
Adjusted R Square	0.88			
Standard Error	12.9			
Observations	205			
	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	56	6.1	9.2	6.37E-17
Shovel fed (1/0)	3.6	2.4	1.5	0.15
Site (1/0)	-21	3.7	-5.8	0.00000
Haul Distance	-0.24	0.023	-10.5	6.6E-21
Stems	45	1.4	32.0	0.00
Heads	4.7	1.4	3.4	0.00081

Appendix table 9: Regression output for hourly extraction productivity of case study 3.

Regression Output				
Multiple R	0.89			
R Square	0.81			
Adjusted R Square	0.79			
Standard Error	12.9			
Observations	100			
	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	-4	7.6	-0.48	6.35E-01
Site (1/0)	56	7.6	7.5	3.54E-11
Haul Distance	-0.094	0.029	-3.3	0.00154
Stems	22	1.75	12.6	5.46E-22
Heads	5.1	1.1	4.6	1.50E-05
Pieces	0.0	0.0	65535	#NUM!

Processing Cycle Time

Appendix table 10: Regression output for processing cycle time of all three case studies.

Regression Output				
Multiple R	0.70			
R Square	0.49			
Adjusted R Square	0.49			
Standard Error	18			
Observations	871			
	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	25	4.1	6.0	2.3E-09
Logs Cut	11	0.4	25.9	7.5E-110
Case study 3	-4	3.8	-1.0	0.33
Case Study 2	3	1.6	1.8	0.074306
Delimbing (1/0)	11	4	3.0	0.0032