The productivity and stem breakage impact of fixed felling harvest heads in New Zealand.

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Executive Summary

Felling heads are a piece of machinery used to mechanically fell trees. A range of felling head variations are used around the world. In New Zealand dangle felling heads, where the head dangles from the end of the boom on a freely rotating link, are the most widely operated type of felling head. Fixed felling heads use a hydraulic ram between the boom and the felling head to control the felling. Fixed felling heads are considered to reduce stem breakage. Although fixed felling heads are becoming more common in New Zealand, they are still not widely used by industry with only a handful of crews opting to use them.

A time study was carried out across three operations with varying stand characteristics aiming to determine the productivity of the machine. Additionally, the extraction data from the processing machine at each operation was obtained, and the small end diameter of each stem was recorded to indicate whether stem breakage occurred. Lastly, operators and owners of the crews were surveyed for their opinions on fixed felling heads, the suitability for the site, and their advantages and disadvantages.

In total six days were spent in the field, spending two days at each site, with over 1000 cycles recorded. Site one was in Te Pōhue, Hawkes Bay, and was a road lining operation on rolling country, with Radiata Pine stocked at 369 stems/ha, and an average piece size of 1.75m^3. This site returned an average cycle time of 40.2 seconds and a utilisation of 82%, resulting a productivity of 73 stems/productive machine hour, or 128 m^3/PMH. Site two was in Kohatu, Nelson, and was a fully mechanised, cable yarding operation with an average slope of 45%. The crop was Douglas Fir stocked at 573 stems/ha, and with an average piece size of 1.12m^3. Site two returned an average cycle time of 35.2 seconds and a utilisation of 79%, resulting in a productivity of 81 stems/productive machine hour, or 91 m^3/PMH. Site three was also in Kohatu, Nelson, and was a winch assisted cable yarding operation with an average slope from 57-70%. The crop was Radiata Pine stocked at 260 stems/ha, with an average piece size of 2m^3. Site 3 returned an average cycle time of 52.2 seconds and a utilisation of 71%, resulting in a productivity of 49 stems/productive machine hour, or 98 m^3/PMH.

Stem breakage was analysed using data obtained from the processor operating on the landing. However, this data included both felling breakage and extraction breakage. Determining which sub-process caused the breakage was, therefore, difficult. However, a visual assessment carried out during the time studies indicated that stem breakage was less at all sites. This was partially confirmed in the site two processing data which suggested a significant reduction in stem breakage through use of the fixed felling head.

Overall, this data showed that fixed felling heads were capable at a range of different sites with varying stand characteristics in New Zealand. Analysis of the cycle times reflected that fixed felling heads can effectively fell and position stems at a consistent rate with little variation. The walking to and clearing around the tree was heavily affected by stocking. Denser undergrowth was the main cause of slower cycle times. Fixed felling heads present a range of advantages, its controlled and directional felling capability is noticeably beneficial, the ability to prepare bunches for extraction, and its reduction in stem breakage was reinforced by the operators' opinions. When compared to similar time studies using dangle felling heads with similar piece sizes, it returned competitive productivity rates.

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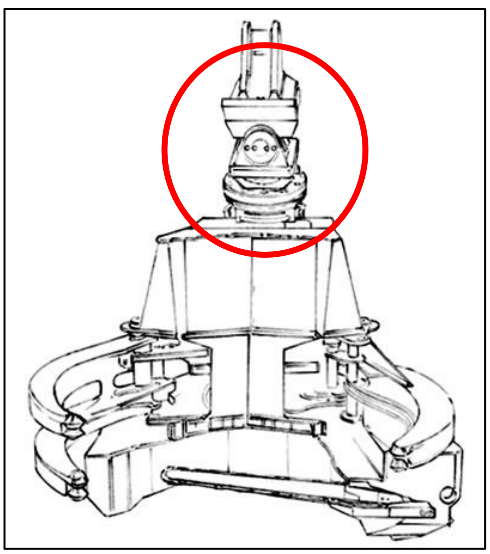
Introduction

In harvesting, felling is one of the first steps (Lambert M. , 1996). The task of tree felling is known to be a high-risk activity, meaning there has been multiple initiatives to take chainsaws out of the hands of forest workers and put them in machines instead. The mechanisation of felling has also seen a significant increase in productivity. A range of harvesting machinery and attachments have been developed, all offering different advantages and disadvantages for different activities.

Mechanised harvesting is defined as a forest operation that involves the use of machines to complete the felling, delimbing and/or processing of plantation trees (SafeTree, 2005). For the last 50 years, there has been an increase in mechanisation of harvest operations. There is an extensive range of benefits that are almost common knowledge to the industry, including high production, felling and delimbing quality, environmental benefits and better working conditions (SafeTree, 2005).

In mechanised felling, felling heads are the piece of equipment mounted to a machine to carry out the severing of the stem and bringing it to the ground. The three main categories of felling heads are bunching heads, processing heads, and felling heads. The most popular felling head is a processing head, which can both fell and process stems. This type of head 'dangles', meaning it has limited directional control on the felling, as the felling head is attached to the boom with a freely rotating link, and the tree will fall over under its own weight after being sawn. A fixed felling head has control over the tree when it is falling, by support of a hydraulic ram on the boom. This means the operator can guide and place the stem down slower once felled, with the assumption being that the trees are less likely to break. Figures 1 and 2 show a diagram of a dangle felling head, with the freely rotating link circled, and a fixed felling head on a machine, with the hydraulic ram on the boom circled, giving it its controlled felling capability.



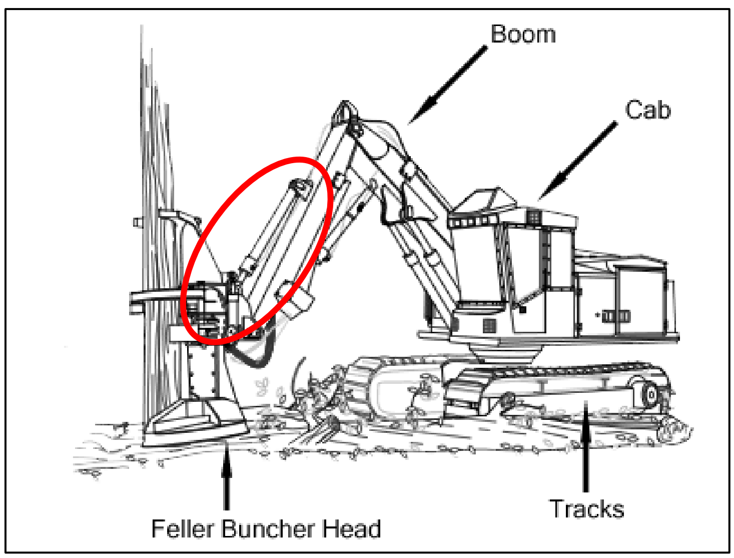


Figure 1 and 2: dangle felling head diagram (left). Fixed felling head diagram on machine (right). Retrieved from U.S Forest Service.

The introduction of fixed felling harvest heads into New Zealand dates back to the 1980s, with its initial use being production thinning and clear fell of minor species (Gleason, 1986). However, in more recent times fixed felling heads have become more widely used throughout New Zealand with the ability to be used in forests with larger trees. With this introduction, it had been identified that there were varying views on the applicability of fixed felling heads in all harvesting operations (Prebble, 2021). Contractors and operators often believed that although the fixed felling heads had bunching ability and reduced stem breakage, they were limited by their inability to shovel (meaning the moving of logs to a new location via successive swinging of the machine), high cost and lack of control over larger trees.

Despite the increase in fixed felling head applications across New Zealand, there is still little accessible data regarding the productivity of fixed felling heads, and little information on their impact on stem breakage. This project will also complete a time study to measure felling head productivity, an analysis of stem breakage from extraction data, and a survey of the contractors and operators involved in this study.

A thorough literature review will outline and discuss existing literature on fixed felling heads, felling productivity and stem breakage to gain a greater understanding of the topic.

Literature Review

A range of characteristics are taken into account when selecting the type of felling heads and/or equipment a harvesting crew implements. One characteristic that often determines this is whether the trees need to be laid in a way to optimise extraction. Felling machinery can be characterised by machine size, machine function and type of felling head. Machine size and function has little variation in New Zealand, with most of the felling machinery being excavator based. Felling heads however are the main distinguishing factor between different felling machines.

Felling heads can be split into three classes, feller directors, feller bunchers and feller processors (MacDonald, 1999). In New Zealand, the more common name for feller processor is a harvesting head, and feller directors are just called fellers. Feller Bunchers can fell trees and can also pick up multiple stems at a time to place them into bunches. This makes them suitable for cable yarding operations, as it helps present bunches to the yarder. Feller bunchers are often fixed felling heads, equipped with the hydraulic ram on the boom allowing them to control the descent of a felled tree. Feller processors combine the falling and log-manufacturing functions into one machine (MacDonald, 1999). Feller processors can delimb stems and cut them into the desired log lengths. Feller processors are popular overseas for cut-to-length operations. In New Zealand, a popular manufacturer of these types of felling heads is Waratah, and they are universally used across the country. Feller processors are predominantly dangle felling heads. Lastly, feller directors can fell only, and they can fell the tree to a desired direction (MacDonald, 1999). Although they can direct the tree, they cannot control the falling of the tree, like a fixed felling head. They are mainly dangle felling heads.

With the increased introduction of fixed felling heads in New Zealand, it was identified that there was a range of views on the machine’s applicability (Prebble, 2021). A total of 28 individuals which included owners, operators and or managers of fixed felling head machines were surveyed to gain a greater understanding and compilation of these views. This project was identified in Prebble’s initial study on the fixed felling head's impact on stem breakage. It was found that the introduction had mixed responses across the industry with 50% saying it was well suited to their operation, and 34% believing the fixed felling head was unsuitable (Prebble R. , 2021). In terms of the machine’s capability, the study demonstrated several advantages which included reduced breakage, better environmental outcomes and improved value recovery. However, in the opinion of some operators fixed felling heads had shovelling and reach limitations, had higher costs and lacked sufficient control over larger trees. An interesting finding from the survey was that it highlighted that much of the success of fixed felling heads in crews was due to operator recruitment, training and skill and that experience in 'dangle' felling heads did not seem to make an ideal fixed felling head operator.

Stem Breakage

The action of tree felling aims to aid subsequent extraction by felling a tree in such a way that the following operations are helped as much as possible (Raymond, 2012). This aim can often be satisfied when applying mechanised felling as the machine has more control on where the tree will end up rather than manual felling. Raymond (2012) also discusses Radiata Pine's susceptibility to breakage during felling, with the only practical way to consistently gain a reduction in breakage is to use cross-slope mechanised felling.

That is not to say that mechanised felling is immune to tree breakage, and the reduction in tree breakage when comparing manual and mechanised felling varies. An extensive study was carried out in 1997 reporting on the tree breakage of a total of one thousand manually felled trees aged 25 to 30 across 20 different sites around New Zealand. A stem was considered to have broken if the diameter at the first break was greater than 10cm. With the percentage breakage ranging from 10%-98%, it was identified that the most significant variable affecting probability of breakage was tree height, followed by site. However, the most common cause of breakage was topography and crossed stems (Fraser, et al, 1997). This is reflected in Figure 3 below showing the distribution of the breakage causes.

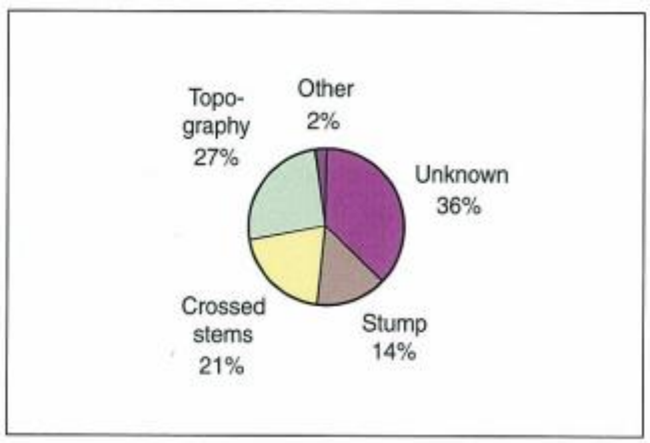


Figure 3 – Distribution of cause of breakage (CBK) (Fraser, Palmer, McConchie, & Evanson, 1997).

As seen in this figure, the main causes were topography and crossed stems, which accounted for the most breakage. However, these two causes are still smaller than the unidentified reasons for tree breakage, where the tree broke for unknown reasons. Of the 1000 stems studied, 314 were unbroken, meaning 68.6% of trees broke. The summarized data showed that smaller trees broke less. The mean tree height and DBH was notably smaller in the unbroken trees. This information is reflected in Figure 4 below.

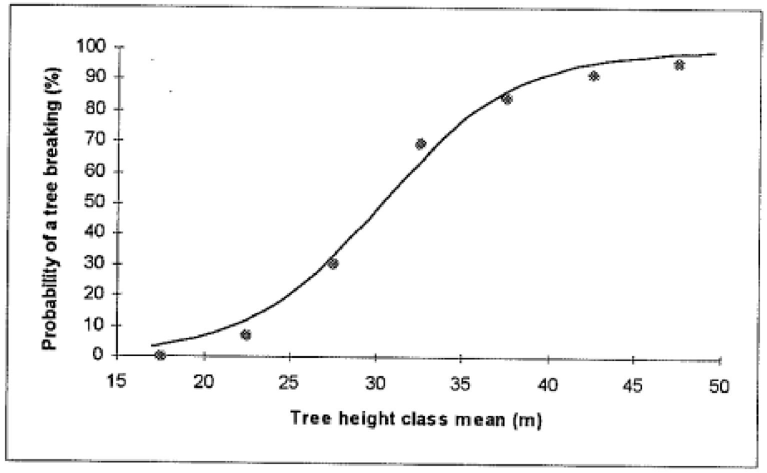


Figure 4: Effect of tree height on tree breaking probability (Fraser, et al, 1997).

In addition, two characteristics that may reduce tree breakage is branching and felling angle. Sites that had low breakages had combinations of heavy branching or low felling angles.

Felling angle is a notable characteristic that has been well researched. The most practical way to fell a tree manually on steep country is to fell in the direction of the slope, as the tree will be leaning that way already, in an attempt to reduce tree damage, increase utilization and value and to align the trees for easier extraction (Murphy & Gaskin, 1982).

Murphy & Gaskin (1982) tested the hypothesis of directional felling reducing the damage on trees on a 41-year-old Radiata Pine stand in Rotorua's Whakarewarewa State Forest. Four different felling arrangements were trialled which included downhill crossed, downhill parallel, across slope and uphill 45%. It was noted that only 78 of the 200 trees to be felled uphill were felled due to no reduction in breakage being recorded, and the operation was considered too dangerous and time consuming at the time to continue. However, its findings are still relevant as they were able to gather data on cause of breakage.The main cause of breakage was tree crossing, amounting to 54-72% of the breakage depending on felling angle. In terms of percentage of trees breaking, when felling downhill crossed, 99% of trees broke. Across slope and uphill 45% had a small reduction in breakage probability of 92%.

The shift from manual felling to mechanised felling was more importantly due to improved worker safety when operating. The above literature highlights the fact that manual felling has a very high breakage rate which mechanised should reduce as the operator has more control over the trees placement.

A study done by Andrews (2015) compared motor-manual felling and mechanised felling impact on stem breakage. 183 stems were assessed by measuring breakage frequency, first break and volume retention of 3 felling arrangements, motor manual, mechanised felling out of the stand and mechanised felling into the stand. Interestingly, at 73% motor-manual felling had the smallest number of stem breakages, which was followed closely by mechanised felling out of the stand at 76%, and lastly mechanised felling into the stand at 94% (Andrews, 2015). Volume across the board was similar, however. For the stems that didn't break, the DBH means were almost Identical at 41cm versus 41.8cm. A notable point from the study is the significantly high break percentage for mechanised felling into the stand. This was likely due to the trees striking standing trees upon falling.

Even though the above study received relatively similar results in stem break percentage for mechanised felling and motor manual, this may have been a relatively low value for mechanised felling. In Kinleith forest, a range of stands were assessed for stem breakage using dangle felling heads. This study resulted in a percentage breakage ranging from 84 to 100% (Lambert, 1996). This range was mainly due to the variation in machines and machine operators, with the Timco One machine having the least stem breakage at 84%. The study's findings also are consistent with the Andrews (2015) study even though the largest reason for breakage was unknown, the largest known causes of breakage across all machines were from hitting felled logs or hitting stems, where overall, 23% were from hitting felled logs and 13% were from hitting stumps.

From these studies, it was evident that neither motor-manual nor dangle head mechanised felling have significant advantages over each other with regards to a reduction in stem breakage. This subsequently leads to the question of whether fixed felling heads reduce stem breakage. A fixed felling head has control over the tree when it is falling, meaning they can place the stem down slower once felled. When dangle and fixed felling heads were compared, it was clearly seen through the harvester's wood flow management software (STICKS) data that the small end diameter of the stems felled using a fixed felling head where consistently smaller, demonstrating that break height much further up the stem (Figure 5), and that there was less breakage (Prebble & Scott, 2019).

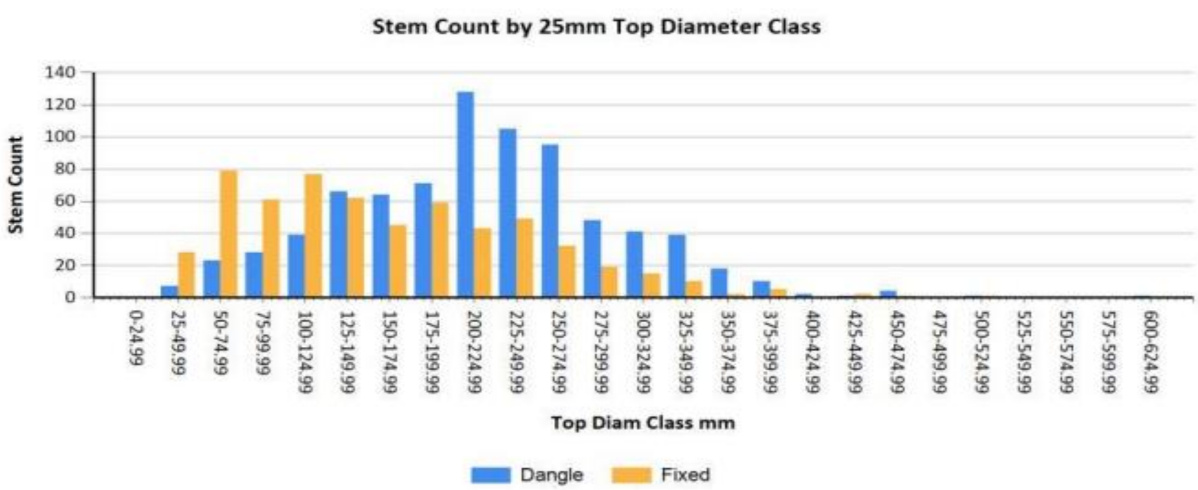


Figure 5: Fixed and dangle STICKS analysis data of small end diameter class comparison (Prebble, 2019).

This data becomes more impressive when knowing that the fixed felling heads trees felled had a larger piece size, the average SED (small end diameter) was still 27% lower than the dangle heads. Average merchantable stem lengths for the dangle head were 16.05m compared to the fixed felling heads 22.5m.

Productivity

As new technologies enter the industry, it's important to optimize their productivity by understanding the parameters that affect them. Harvesting machinery is influenced by stand and terrain variables. Within those, certain variables have a greater affect than others. A notable parameter identified by multiple studies is the effect piece size has on productivity.

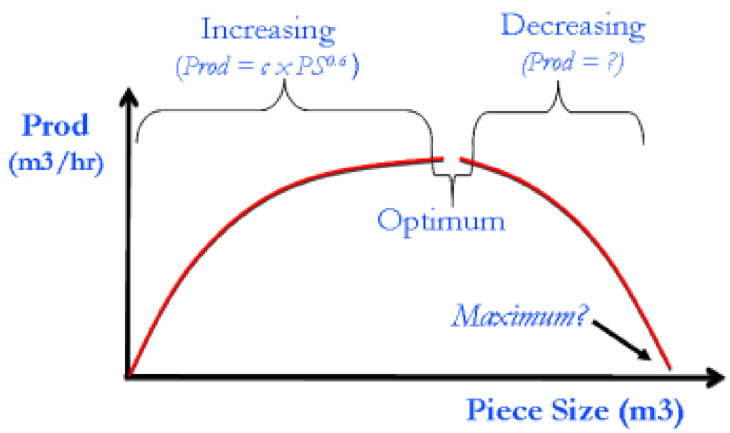


Figure 6: Basic relationship between piece size and productivity (Visser, 2009).

Four mechanised felling and/or processing operations were evaluated via a time study to greater understand the effect of piece size on productivity. The machines studied including their sites were:

- Waratah 622 harvester in Bottlelake Forest – flat terrain with sandy soils (1)
- Waratah 624 harvester in Lowmount Forest – rolling terrain with silty sandy soils (2)
- Satco 630 feller-director in Ashley Forest – rolling to steep terrain (3)
- Woodsman harvester in Tarawera Forest – rolling terrain with volcanic ash soils (4)

A range of results were identified across the board with the four machines, with some not having an obvious optimum piece size and not showing a clear decline in productivity, and others did succeed to illustrate the relationship pictures in Figure 7.

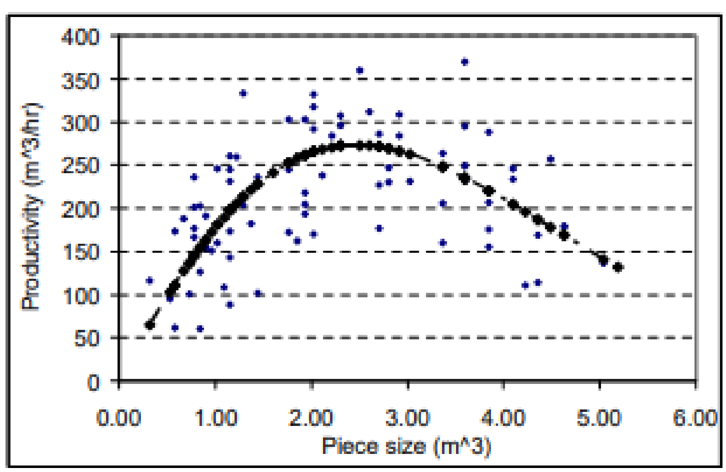


Figure 7: Waratah 624 productivity data with varying piece size.

As seen in the above figure, The Waratah's piece size 'sweet spot' was $2.2m^3$. As mentioned before, some of the machines were deemed to be not obvious enough to identify and fit an equation to the data to identify the optimum piece size (Visser, 2009). To determine these optimum piece sizes, a common power function was used in the form of

$$\text{Productivity } (m^3/hr) = a\ PS^b$$

Where PS is the piece size, and both a and b are coefficients determined by the regression function. However, for example in the Waratah analysis, a quadratic function was used instead due to the shape of the data, and that it would be unreasonable to fit a mono-directional function on the data, as enough was gathered to illustrate the clear decline in productivity. For the waratah data the following equation was determined

$$\text{Prod} = 200 \times PS + 35.9 \times PS^2$$

This study was further expanded with two more machines being evaluated in Italy and their results compared. Two JD 758 dedicated felling machines were studied in *Picea abies* (European Spruce) stands where one had similar stand characteristics, and the other smaller. The number of observations were approximately five times as much as the New Zealand machinery tested.

Table 1 shows a summary of the function calculation parameters determined from the Waratah 622 and 624 in New Zealand (test 1 and 2) and the machines tested in Italy (test 3 and 4).

Table 1: Main parameters calculated for the alternative equation types (Spinelli, 2011).

Test	1	2	3	4
Quadratic function (Eq. 1)				
a	235.2	199	54.1	54.3
b	−54.8	−35.5	−15.6	−15.8
r^2	0.46	0.33	0.75	0.81
Optimum size (m^3)	2.1	2.8	1.6	1.6
Max. productivity ($m^3\ h^{-1}$)	252	280	47	46
Exponential function (Eq. 3)				
a	240	203	155	70
b	−0.20	−0.14	−1.40	−0.55
c	1.65	1.65	0.90	1.46
r^2	0.49	0.58	0.81	0.86
Optimum size (m^3)	1.9	2.5	0.7	1.3
Max. productivity ($m^3\ h^{-1}$)	256	269	39	41

Maximum productivity is achieved at optimum size

It can be seen through the r^2 value that the data found from the machinery studied in Italy illustrated a much stronger relationship of the given quadratic and exponential functions. However, it must be noted that their productivity is significantly less by approximately 6.5 times. Empirically based productivity functions are a common way to describe machine performance depending on varying stand and terrain variables (Visser & Spinelli, 2011). It provides valuable data to be able to optimize its use and compare against similar machinery configurations and equipment.

Mechanised cut to length harvesting systems is another form of harvesting where stems are cut in the forest rather than on the landing. These types of systems are predominantly in European countries, where they have become widely used in industrialised countries such as Sweden, Ireland, and Finland. Meaning, a range of productivity studies have emerged from Europe for this type of harvesting. Three different classes of harvesting machines were studied to determine harvest productivity and cost in Irish forest conditions. the three classes of machines were based on engine size, ranging from small (less than 80kw output power) to large (higher than 210kw output power).

The study found harvest productivity ranged from 13.5 to 60m^3 with average tree volume found to be a main factor affecting productivity (Jirousek, Klvac, & Skoupy, 2007). From the resulting data a power function equation based on the data across all the harvester was determined:

$$Prod = 60.7 \times PS^{0.6545}$$

Although this seems similar to the productivity equations mentioned above, it is significantly smaller. This is due to average tree volume being much smaller, ranging from 0.2 to 1m^3, where the above studies had piece sizes up to 3m^3. This suggests CTL logging lends itself to smaller forests with smaller diameter trees.

Fixed felling heads are not uncommon internationally. The Pacific Northwest and Europe often use feller-bunchers, which are type fixed felling head, for their tree felling. A study done in in Turkey aimed to determine the productivity of mechanised harvesting machines and collected a range of cycle time data for different feller bunchers on a 35% slope (Abdullah, Arkay, & Sessions, 2004). Below in table 2 shows a summary of those.

Table 2: Cycle times for specific feller bunchers (Average slope = 35%) (Abdullah, Arkay, & Sessions, 2004).

Machine make	Volume (m^3 log^{-1})	Number of trees per h	Cycle time (min $tree^{-1}$)
PRENTICE 720	0.68	65	1.10
PRENTICE 730	0.68	75	0.80
TJ 2618	0.68	50	1.20
TJ 2628	0.68	60	1.00
TIMBCO T225-B	0.68	60	1.00
TIMBCO T445-B	0.68	70	0.86

They had a productivity ranging from 60 - 75 stems felled per hour, with a piece size of 0.68, and a productivity of 40.8 - 51 m^3 per hour. Another study completed in Tasmania measured the productivity of a self-levelling feller-buncher using lidar and found that an average productivity of 73 m^3 per productive machine hour (PMH) was achieved with at a piece size of 0.53 m^3 and slope that ranged from 32 – 50% (Alam, Acuna, & Brown, 2013).

Although both these studies reflect capable productivity values on moderate to steep slope harvesting operations, the piece size is too small to compare to New Zealand plantation forestry. This highlights the importance of this study, which aims to gather productivity data on fixed felling heads that is relevant to New Zealand's industry.

Objective of the Study

The aim of this study is to investigate three different harvest settings to determine the harvester's productivity, and the impact it has on felling induced stem breakage. This Information will be used to compare against existing felling head alternatives to better understand the fixed felling heads capability in mechanized harvesting operations. This will benefit the industry in providing beneficial data that can be compared to existing productivity studies, and the productivity of existing crews' systems.

Additionally, a survey will be carried out to gain greater insight into contractors and operator's overall impressions on fixed felling heads and whether they consider it to be a capable piece of logging equipment.

Methodology

Productivity Analysis

To find the productivity of the fixed felling machines, a time study will be carried out, using a stopwatch to track cycle times. The machines work cycles will be timed, which includes walking to the tree, felling it, and placing it in its chosen position. The work cycle has been split into more specific actions as stated below to help understand the distribution of time spent across each action:

Walking to/between trees
Where the machine walks and positions itself correctly to prepare itself to fell the tree.

Felling and placing
The action of the machine actively felling the tree, and the time for it to be placed in its final position for extraction.

Bunching
This action is for when the operator specifically takes time away from felling trees to correctly realign and present stems in bunches for extraction, which is separate from when the positioning done when initially placing.

For this data to be collected, three different harvesting operations were studied that had a fixed felling head in use to gather a range of data at multiple sites. This ensured the data was not biased towards optimal operations that overly suited the fixed felling head, unfairly representing its capability. Upon the arrival at each study site, its site characteristics were recorded including slope, stocking, weather conditions, piece size and soil type. As well as this, stand characteristics were recorded such as age, mean top height, pruning regime if applicable and basal area to aid in drawing relationships in the results.

Throughout this work cycle, there was a chance that delays would be incurred while operating. When they occured, the work cycle time was paused, and the delay was measured and noted so they did not skew the work cycle time. From there, the total delay times were calculated.

Once the data from a site had been retrieved, the following calculations were made:

Average time to complete each action in the work cycle
Calculated by averaging the recorded time taken for each action stated above.

Average cycle time
Calculated by averaging the total cycle time recorded of each cycle.

Productivity
Calculated by averaging the number of stems felled per hour.

Productive machine hours
Determined by calculating the number of hours the machine is carrying out its primary task using the equation below:

$$PMH = SMH - Delays$$

SMH = Scheduled machine hours in which the machine was being studied.

Delays = time taken for the delays recorded in the time study.

Productivity per productive machine hour
Calculated by dividing the productivity by the productive machine hours.

Stem Breakage Analysis

For determining the impact on stem breakage that a fixed felling head had, an analysis of the crew's extraction data was carried out. This was in the form of programs like STICKS, .pri, and StanforD.

Once the same trees recorded in the productivity analysis (time study) were extracted, the respective log by log extraction data was obtained from the crew. The key parameters analysed were the small end diameter of the stems, where it was determined whether the stem had broken or not. From this gathered information, the aim was to determine height and frequency of breakage. Then, a relationship was calculated of the height of breakage in relation to the MTH of the stand. These were compared across the three sites.

It was noted that the extraction data was limited by the inclusion of breakage during extraction. This is addressed and discussed further in the analysis.

Impression Survey Parameters

For retrieving the impressions of the operators and crews involved on the fixed felling head, a survey was created and conducted in person with the following sections and questions:

- Machine, operation and site description
- Operator experience
- Site conditions
- Machine performance and suitability at this site
- The advantages and disadvantages experienced
- Would they recommend the purchase of a fixed felling head for other crews.

Site and Machine descriptions

A total of three sites were studied. Below is a description of each site studied and the machine on each site.

Site 1 - Napier

Study 1 was conducted in Te Pōhue, 45 mins Northwest from Napier, along State Highway 5 on the way to Taupo. The forest is owned and managed by Rayonier Matariki Forests. The crew studied was Lew Prince Logging, who have both a ground based and hauler crew. The forest was a 24-year-old Pinus radiata stand with an average stocking of 370 stems/ha, mean top height of 38m and an average piece size of 1.75m^3. Throughout the course of the time study at site 1, the weather stayed clear and sunny with no wind, temperature averaging 15 degrees Celsius. The soil itself was comprised of orthic pumice soil and was relatively dry.

The operation studied was a road line felling in preparation for roading upgrade and skid installation. The slope was mainly rolling country and predominantly flat, with the slope not going above 9 degrees (~16%). Upon initial inspection, this operation setting meant that a notable number of stems in this study were large with heavy branching, which was a characteristic to keep in mind when recording and later analysing the data. Figure 8 shows the crews felling machine in operation.

Figure 8: Felling machine operating in action at study site 1.

Machine description

Lew Prince Logging's felling machine was an Eltec 316 base machine with a Quadco QB4400 fixed felling head attached (see figures 9 and 10). The Quadco felling head weighed 3.3 tonnes, with an open-close diameter of 170-1400 millimetres, a 60cc motor and 255 degrees of saw bar rotation. The Eltec 316 base machine weighs around 36 tonnes and has a boom reach length of 7 metres.

Figure 9 and 10: Lew Prince Logging's felling machine (left). Close up of the felling machines Quadco QB4400 felling head (right).

Site 2 - Nelson

Study 2 was conducted on the Spooners Range in Kohatu, 40 minutes south of Nelson. The forest is owned and managed by OneFortyOne. The crew studied was Hightrack Harvesting, a fully mechanised hauler crew. The forest was a 34-year-old Douglas Fir stand, with an average stocking of 573 stems/ha, a mean top height of 33.5m and average piece size of 1.1m^3. The weather was mainly clear with little wind, and an average temperature of 15 degrees Celsius. The soil properties were moderately well drained clay over loam to loam over clay.

The stems studied over two days were situated on a slope with an average grade of 24 degrees (45%). The face was located separately from the rest of the harvesting system as the rest of the crew was still hauling in another gully before they could move to the setting in question. Figure 11 shows the main angle at which the time study was conducted, and the fact that the feller was felling.

Figure 11: Felling machines main work area where most of its time felling was spent across the study.

What became apparent when discussing with the operator Andy, was that because the yarder would be placed at the top of the hill in the top right of the figure, it was important to ensure the butts of the stems were lying towards the location of the hauler, and that the stems were presented in bunches making extraction faster and more efficient.

Machine description

Hightrack Harvesting's felling machine was an Eltec 316 with a Woodsmanpro CFH1400 controlled felling head. The Woodsmanpro weighed 3.2 tonnes, had a 1400mm max cut diameter, 60cc motor, and 243 degrees of saw bar rotation.


Figure 12 and 13: Hightrack's Felling machine (left). Close up photo of the Woodsman CFH1400 Felling head (right).

Site 3 - Nelson 2

The third study was conducted on Spooners range again in Kohatu, 40 minutes south of Nelson. This forest is owned and managed by OneFortyOne. The crew studied was Endurance Logging/Barnes Grapple Yarding, a fully mechanised hauler crew. The Forest was a 26-year-old Radiata Pine stand, with an average stocking of 260 stems/ha, a mean top height of 40m and an average piece size of 2.0m^3. The weather while conducting the time study at this site varied, with a clear day with little wind on day 1, but rain all of day 2. The soil profile was the same as site 2's, with moderately well drained clay over loam to loam over clay.

The crew was situated on a steep slope block with slopes ranging from 30-35 degrees (57-70%). Due to the steepness of the slopes, the crew was opting to perform winch-assisted felling for this forest. Figure 14 shows a wide shot of the felling machine felling, while being tethered to the winch-assist machine, which was the position in which majority of the study was conducted.

Figure 14: Endurance logging's Felling machine in action at its main work for most of the study.

Same with site 2, the operator Brendan was keeping in mind the positioning of the trees, aiming to aim the butts of the stem bunches in the direction of where the hauler would be situated, on the other side of the gully.

Machine Description

Endurance Logging's felling machine was a Tigercat 855 base with a Quadco 4400QB fixed felling head attached (see figures 15 and 16). The operator of the felling machine Brendan is the owner/operator of the machine as he has part ownership in it. The Tigercat 855 base machine weighs around 30 tonnes and has a boom reach length of 4 metres.

Figure 15 and 16: Endurance Logging/Harmon Harvesting's felling machine (left). Close up photo of the felling machines Quadco 4400QB fixed felling head (right).

Results

Site 1 - Napier

At site one in Napier, an Eltec 316 machine with a Quadco 4400QB fixed felling head attached was studied. At this site, the average cycle time to fell one tree was 40.2 seconds, this in turn resulted in 89.5 stems felled per hour, with a machine utilisation of 82%. The determined productivity per productive machine hour was 73.3 stems. Table 3 shows the average time to complete each action, the average cycle time, productivity, and productivity per productive machine hour. The corresponding 5th, 95th and 80th percentile values are provided to help indicate the bounds around the majority of times.

Table 3: Summary table of the average action times, cycle times, and productivity, including percentiles.

	Average	5th percentile	95th percentile	80th percentile
Elements				
Action 1: Walk/Clearing (secs)	22.4	5.0	62.2	35.0
Action 2: Felling & Placing (secs)	17.8	6.6	39.9	22.8
Total Cycle time (secs)	40.2	16.0	94.5	56.8
Productivity (stems/hour)	89.5	225.0	38.1	63.4
Productivity per PMH	73.3	184.4	31.2	51.9

When breaking up the cycle times, two main actions were identified when recording. Action 1 represented the machine walking from one tree to another, with the relevant clearing and positioning needed to be able to grab and fell the tree. This is referred to as Walk/Clear. Action 2 represents the machine felling and placing of the tree down in its desired position. This is referred to as Fell/Place. As seen from the table, Walk/Clear on average took longer to complete than Fell/Place. This is likely because on this site, the stems often possessed heavy branching, due to a number of them being edges trees, and it was situated on an exposed ridge. This is further reflected in in Figure 17, which shows the average percentage each action took up from the total cycle time.

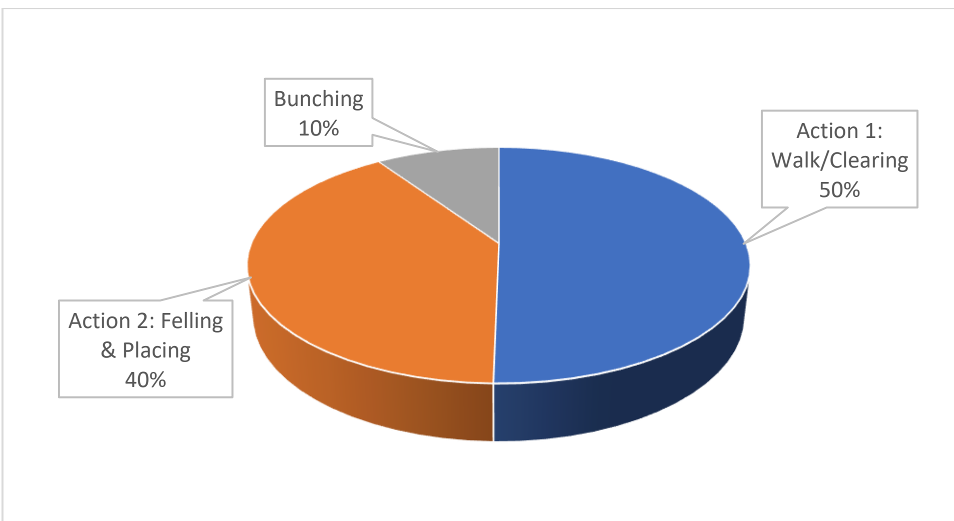


Figure 17: Pie Graph displaying the average time spent completing each action.

As can be seen, 10% of the average time spent was in the third action of bunching. This action was not included in the table above because bunching did not occur in every action, instead it was only done when needed, meaning often spans of 15-20 cycles were recorded before bunching needed to occur again. It is important however that the time spent bunching is represented in the above figure as it is done.

Splitting up the cycle times into their respective action times, a greater idea can be determined on what caused certain cycles to take longer than expected. Figure 18 shows the times taken for the Walk/Clear action to be completed in each cycle recorded.

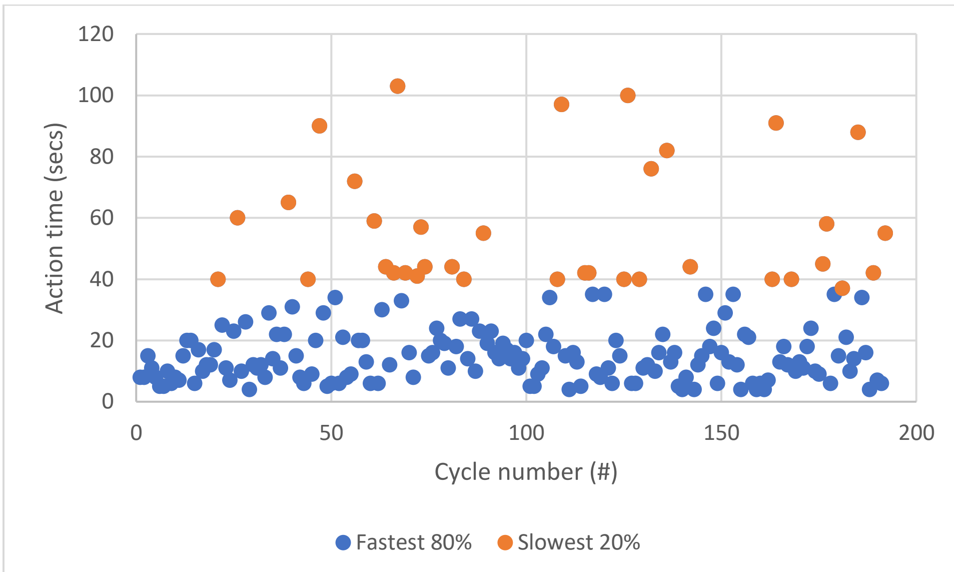


Figure 18: Individual action times for the Walk/Clear action.

As shown in the figure, the majority of the times stuck relatively close to or below the average of 22.4 seconds mentioned in Table 3. However, there are several cycle times that stretch significantly far away from the rest of the times. This is reflected by the standard deviation of this action determined to be 20.0, insinuating a notable amount of variance within the data. The points plotted in orange represent the slowest 20% of action times. These outliers have a notable effect on the average and hold valuable information on what causes this action to take longer. When recording the data, comments were made on the cycle itself and how it went. Figure 19 below shows a summary of what caused those action times to be in the slowest 20%.

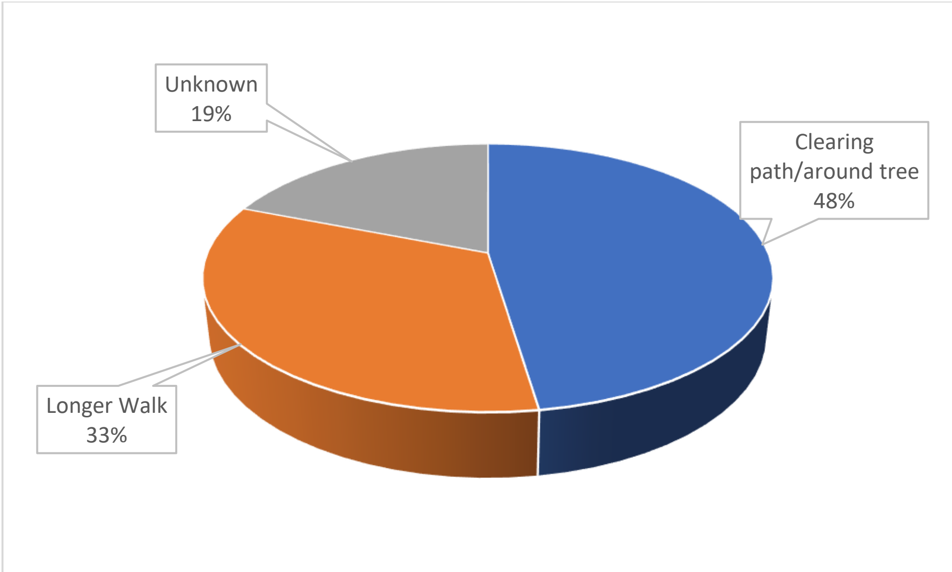


Figure 19: Causes for slowest 20% Walk/Clear times.

Two main causes for Walk/Clear taking longer than expected were observed. 48% of the slower action times were caused by notable clearing needed around the tree so the operator could get in a clear and safe position to be able to fell the tree successfully. 33% of the action times were due to a longer walk to the next tree to be felled.

Figure 20 below this time shows the times taken for the Fell/Place action.

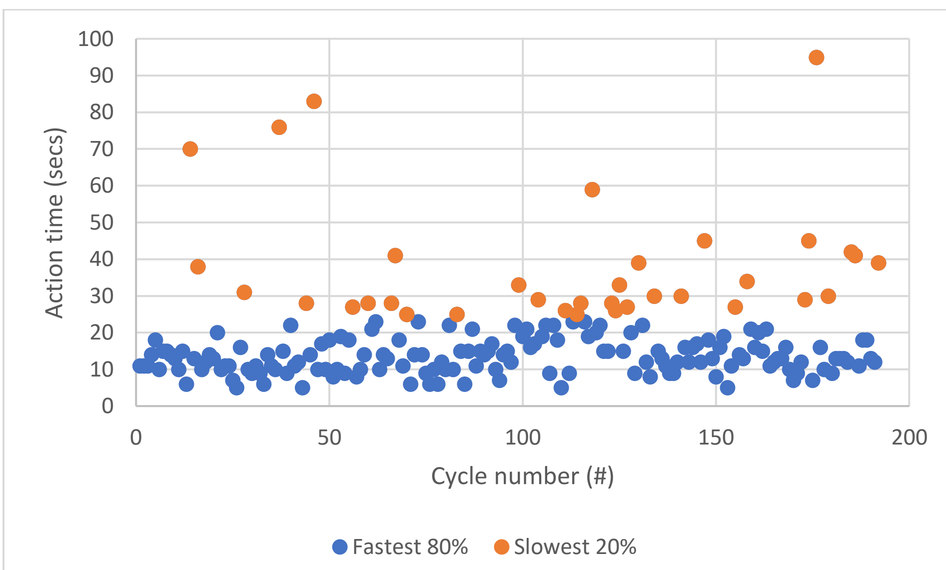


Figure 20: Individual action times for the Fell/Place action.

The Fell/Place action is shown to have its times more consistent in staying around its average of 17.8 seconds. The standard deviation determined for Fell/Place was 12.8, significantly lower than Walk/Clear, inferring a more consistent action time. However as like Walk/Clear, the slowest 20% of action times are significant outliers. Figure 21 shows the different causes of those action times being in the slowest 20%.

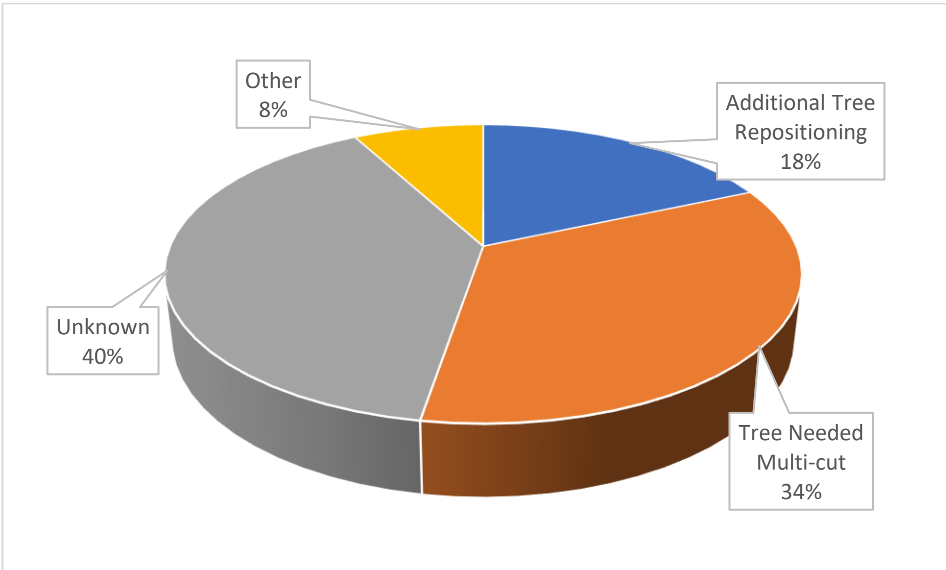


Figure 21: Causes for slowest 20% of Fell/place times.

The largest known cause for Fell/Place times taking longer on this site was that the trees needed a multi cut to be felled. This involved the operator swinging the saw outside the felling heads clamp, doing an initial cut on the far side of the tree, then clamping the tree normally for its final cut. This is often a technique used when tree sizes and diameters are larger, meaning one cut cannot pass the full way through the tree. Another cause was that the tree needed additional repositioning once felled. Usually, the tree was placed in its final desired position for extraction with the fixed felling head on its first try, as the operator has control over where it falls. This is not always the case as sometimes it may not land in the right place, or it needs to be moved because it was not in a desirable extraction position. This action was not considered bunching as the operator was still only dealing with the tree that had just been felled.

Extraction Data Results

For site 1, STICKS extraction data was retrieved from the processor on the skid. This data included information on each log that was being cut, from which stem, its length and diameter measurements. The small end diameter of the last log cut from each stem indicates information on whether the stem may have broken or not during felling. It is important to note in this data, that breakage may occur in extraction as well, meaning a broken stem recorded doesn't directly mean that it broke during felling as there is still a possibility during extraction. However, the data can still be used as an indication. Figure 22 shows the distribution of the small end diameter measurements of the last log of each stem cut. This extraction data includes the stems recorded in the time study above.

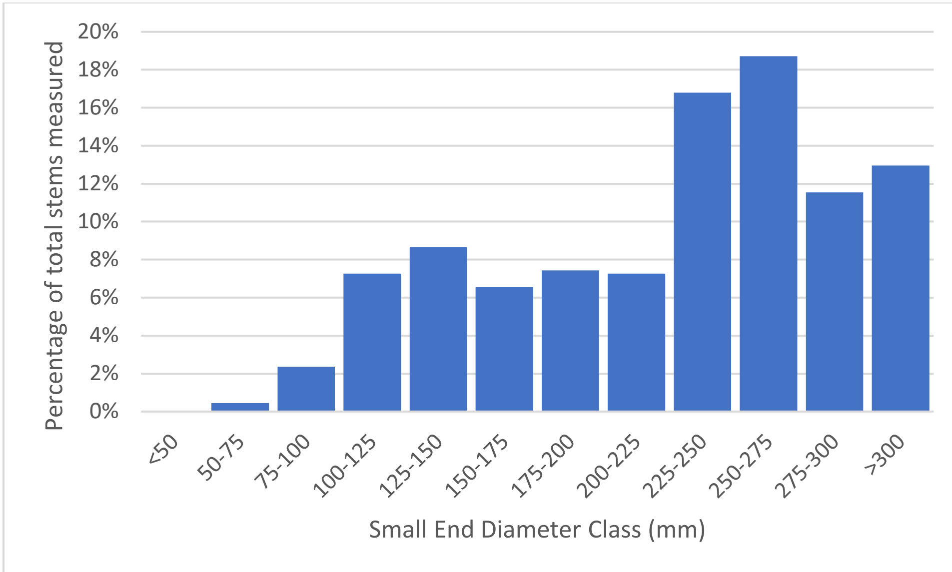


Figure 22: Site 1 distribution of SED from the top of the extracted stems.

As shown in the figure, at this site a large percentage of small end diameters were recorded to be over 225 mm. This is to be discussed as it was identified that unbroken stems had a diameter ranging from 50-150 mm.

Operator Comments

The operator of the felling machine at site 1 had extensive experience in the operation of fixed felling heads both in New Zealand and abroad for over 20 years, as well as rotary hot saw felling heads, and bar saw heads. He believed that the current operation was very suitable for the machine, commenting that it was "very flat easy terrain and the trees were a perfect size, being small and easy to reach and thus retrieve." The main advantages Identified by the operator was that the machine offered better directional felling control, quicker cycle times, and due to it being fixed, didn't get caught as easily on dense undergrowth and was able to push through it more easily. The disadvantages were that it worked the machine harder, had limited shovelling as "it wasn't built for it", branches often got caught on the additional hydraulics on the boom and that it was more expensive. The operator believed that he would suggest it to another crew, but it would depend on what the crew needed from the machine, as often the fixed felling head would fall faster than the crew can process and that needed creating a bottle neck in the operation.

Site 2 – Nelson

At site 2 in Nelson, an Eltec 316 base machine was also used, except the fixed felling head model for this machine was a Woodsman 1400. The average cycle time was determined to be 35.2 seconds, in turn resulting in a productivity of 102.4 stems/hour. Considering the delays that occurred throughout the data collection, a utilisation of 79% was determined, leading to adjusted productivity per PMH of 81 stems/PMH. Table 4 shows the average times for each action, the cycle, productivity and productivity per PMH as well as each of their respective 95th, 5th and 80th percentile times.

Table 4: Summary table of the average action times, cycle times, and productivity, including percentiles.

	Average	5th percentile	95th percentile	80th percentile
Elements				
Action 1: Walk/Clearing (secs)	16.1	7.0	30.5	20.8
Action 2: Felling/Placing (secs)	19.1	12.0	32.0	22.0
Total Cycle time (secs)	35.2	22.0	55.0	43.0
Productivity (stems/hour)	102.4	163.6	65.5	83.7
Productivity per PMH	81.0	129.5	51.8	66.3

Different from site 1, Fell/Place took longer than Walk/Clear (Table 4). Again, this is further reflected in in Figure 23, which shows the average percentage of time spent completing each action.

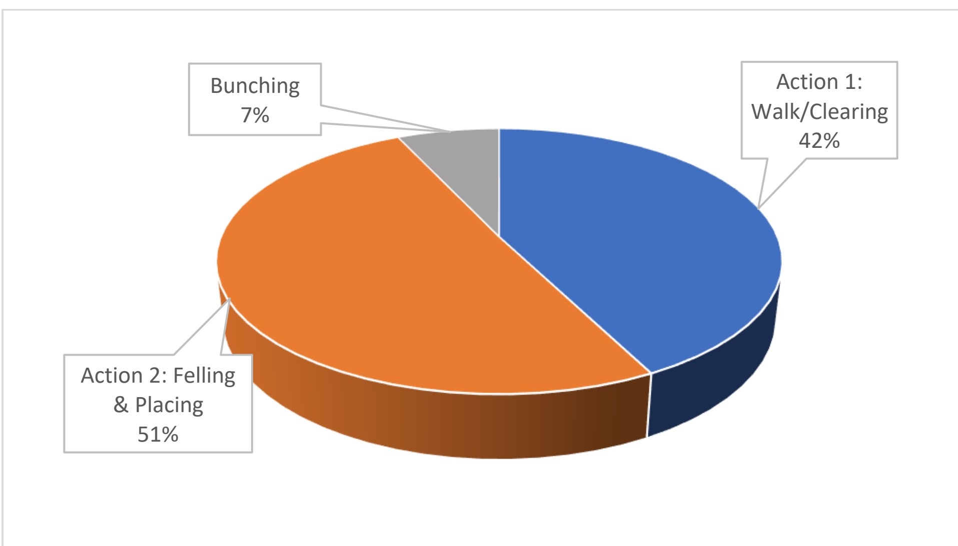


Figure 23: Site 2 average time spent completing each action.

Bunching is seen to take less of the average time spent than site 1 for completing each action in site 2. As before, the cycle times for this site have been split up into their respective action times and a greater understanding of the distribution and range of times can be seen with causes determined for outlying data. Figure 24 shows action times for the Walk/Clear action.

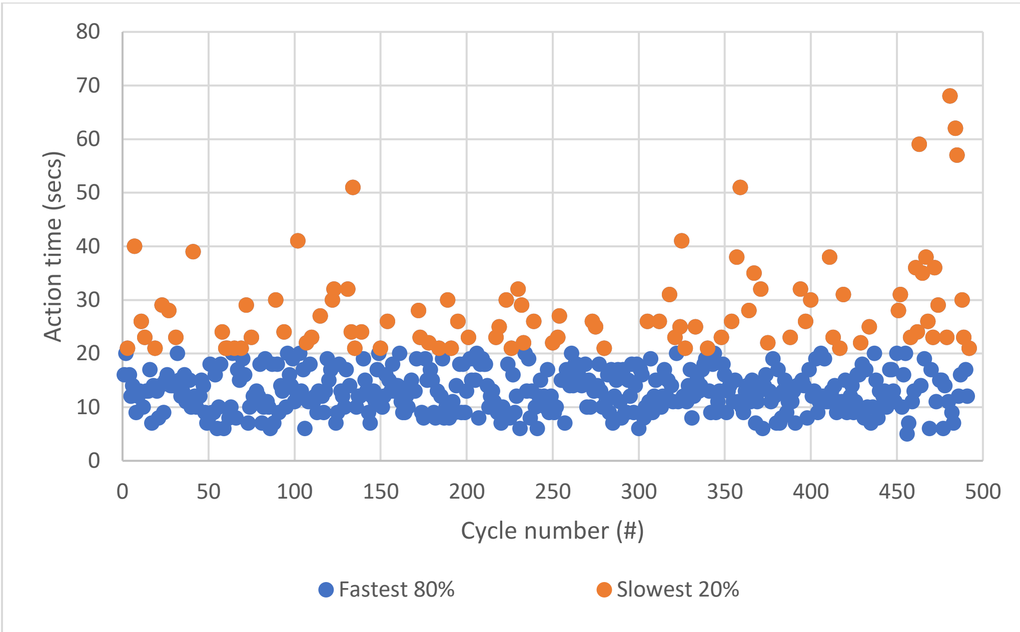


Figure 24: Individual action times for the Walk/Clear action.

As shown above, a tight band of action times is formed around the average action time of 16.1 seconds. The standard deviation for Walk/Clear of this Nelson site was 8.2, reflecting a much more consistent and less variant action time compared to Napier (site 1). Highlighted in orange represents the action times that were the part of the slowest 20%. Here it can clearly be seen that there are a number of significant outliers, as well as minor outliers. Figure 25 shows the causes for those being in the slowest 20% from what was identified while the data collection was occurring.

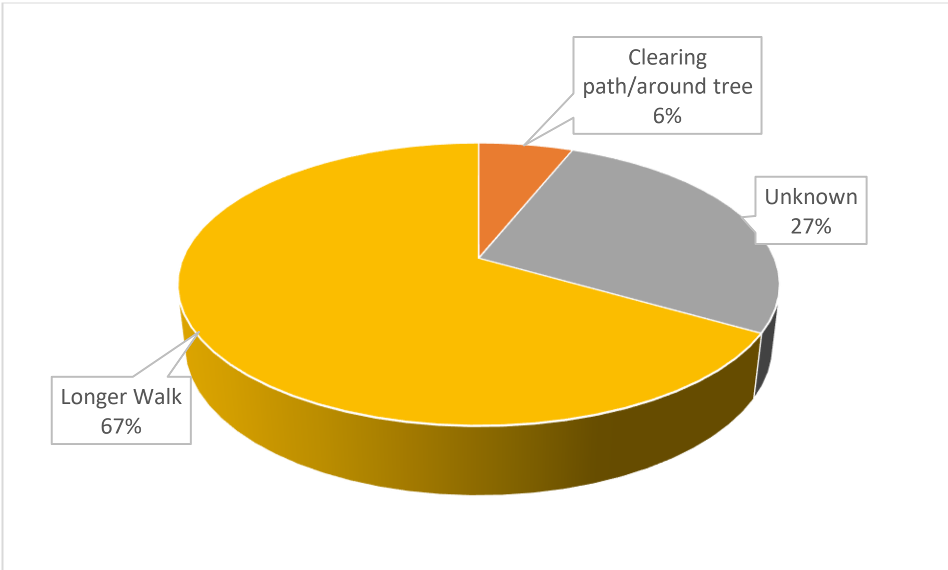


Figure 25: Causes for slowest 20% of Walk/Clear times.

67% of the causes recorded expressed that a longer walk occurred in this cycle, leading to an extended action time. Interestingly only 6% of the causes recorded were due to more extensive clearing to and around the tree unlike site 1's 48%.

Below shows the same analysis as above this time for the Fell/Place action.

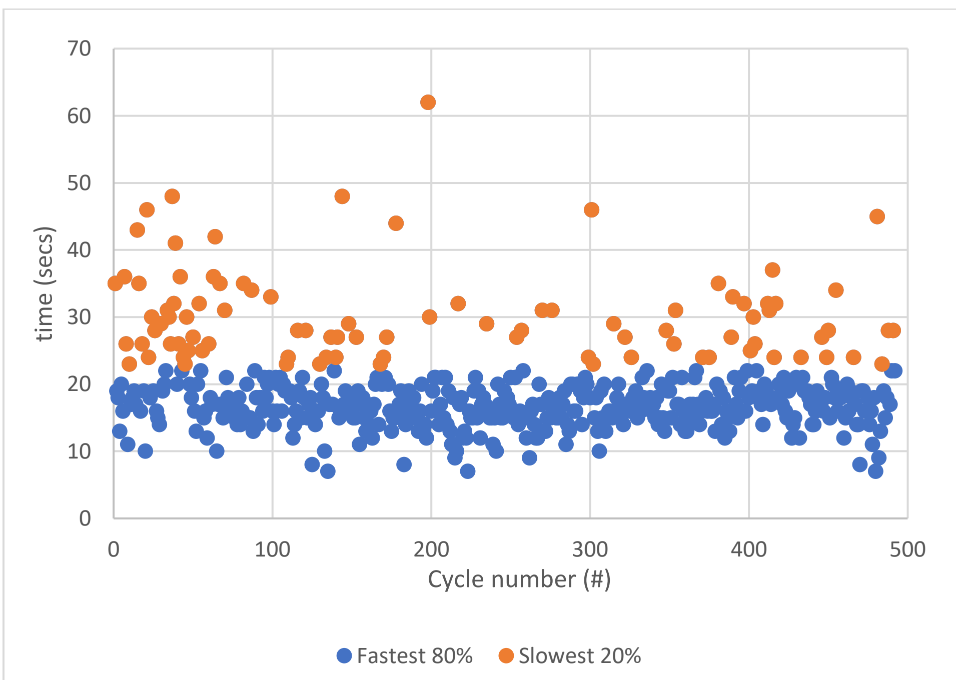


Figure 26: Individual action times for the Fell/Place action.

Figure 26 shows significant clustering around the average action timing of 19.1 seconds, similar to Walk/Clear. This is further reinforced by the lowest standard deviation of 6.7, reflecting notable consistency in the action times. However, there seemed to be more significant outlying recordings in the second action compared to Walk/Clear. These outliers again, are all highlighted in orange displaying the slowest 20% of action times. These times have notable influence over the average time of the action. Figure 27 shows the causes for those Fell/Place times being in the slowest 20%.

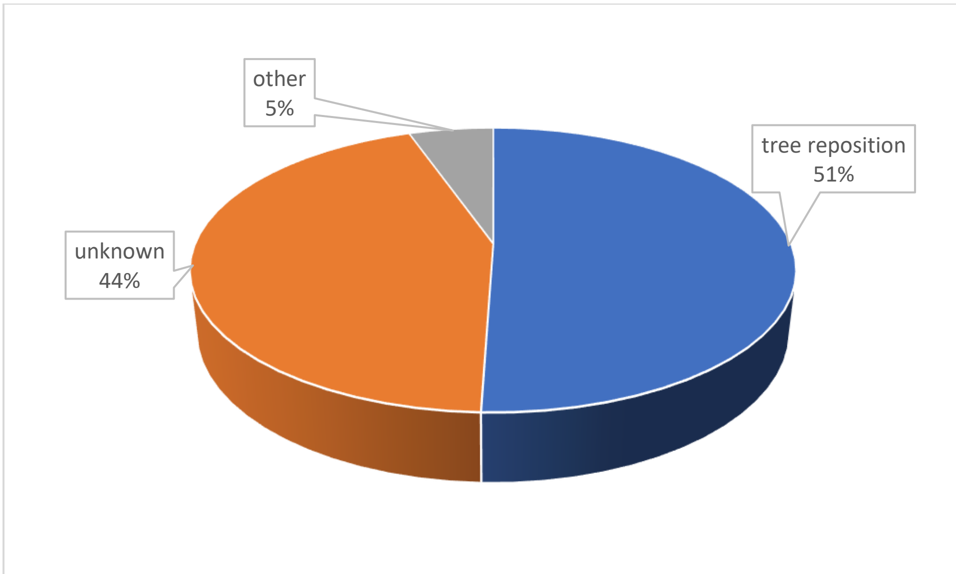


Figure 27: Causes for slowest 20% of Fell/Place times.

From what can be seen in the figure above, the most prominent percentage was in additional repositioning of the tree into a more desirable position causing a longer action time. However, a significant percentage of times were deemed to have an unknown reason in the action time taking longer. Other reasons for the action time taking longer included abnormally large trees in the stand being felled, causing a slower felling and placing process, and sloven cuts being implemented.

Extraction Data

As the same in site 1, extraction data for the dates in which the trees recorded in the time study above were felled and was retrieved to help gain a greater understanding of the small end diameters of the stems once extracted, providing an indication on the condition of the stem and whether it breakage may have occurred during felling and/or extraction. Figure 28 shows the percentage distribution of the SED of extracted stems.

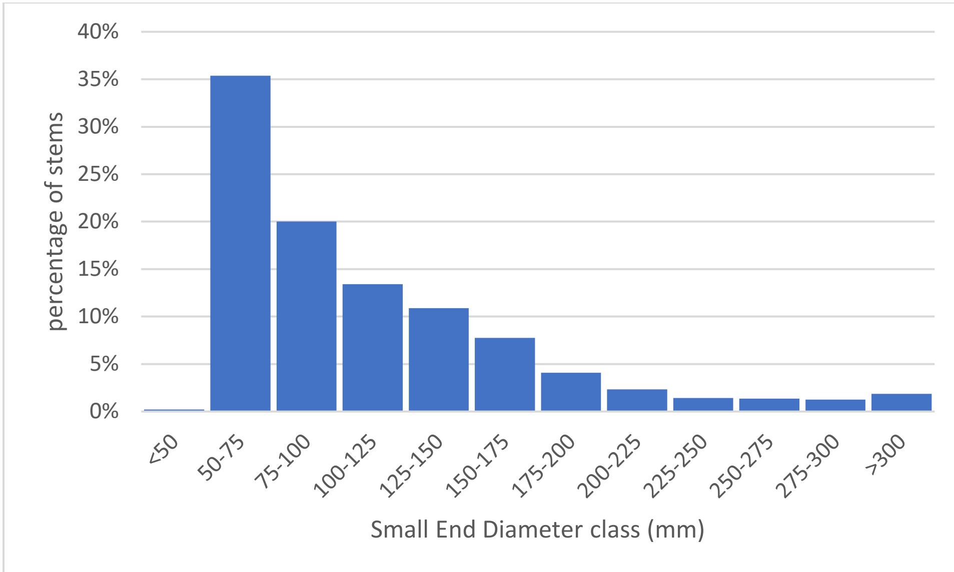


Figure 28: Site 2 distribution of SED from the top of extracted stems.

Over 50% of the stems measured have a SED under 100mm, and over 70% have under 150mm. This is very much different data retrieved from site 1.

Owner/Operator Comments

Due to external reasons, the usual operator was absent meaning one of the owners stepped in to operate the felling machine. This was beneficial as the survey answers came from operating the machine and being an owner of it. Besides not being the usual operator, the owner still had significant experience with fixed felling heads. He believed that the machine was very suitable for the operation, as it could handle steep terrain well and maintain good traction, and it was an easy piece size. The main advantages identified were cycle time improvements, bunching capability, and a significant reduction in breakage. The disadvantages were that the felling head was harder on the machine, assuming that would come with higher maintenance costs, it had notable shovelling limitations, and a higher upfront cost. The owner/operator would suggest other crews to get one, however again it would depend on if it was suitable for them.

Site 3 – Nelson 2

At site 3 in Nelson, a Tigercat 855 base machine was used unlike the Eltec base machines seen in the first two sites. This machine has a Quadco 4400QB fixed felling head attached, the same as site 1. The average cycle time calculated was 52.2 seconds, leading to a productivity of 69.0 stems/hour. With a calculated utilisation of 71% being determined considering the delays that occurred while studying, the productivity per PMH was found to be 48.9 stems/PMH. Below in Table 5 shows the average times for the two actions of the cycle, productivity and productivity per PMH as well as the respective 95th, 5th and 80th percentile times for each.

Table 5: Summary table of the average action times, cycle times, and productivity, including percentiles.

	Mean	95th percentile	5th percentile	80th percentile
Action 1: Walk/Clearing (secs)	33.6	93.1	6.0	45.0
Action 2: Felling/Placing tree (secs)	18.6	34.1	9.0	22.0
Total cycle time (secs)	52.2	112.2	21.0	67.0
Productivity (stems/hour)	69.0	32.1	171.4	53.7
Productivity per PMH	48.9	22.7	121.4	38.1

Table 5 helps show how Walk/Clear on average took significantly longer to complete than Fell/Place at this site. This difference in action times is further reflected in figure 29 where the average time spent completing each action is visualised.

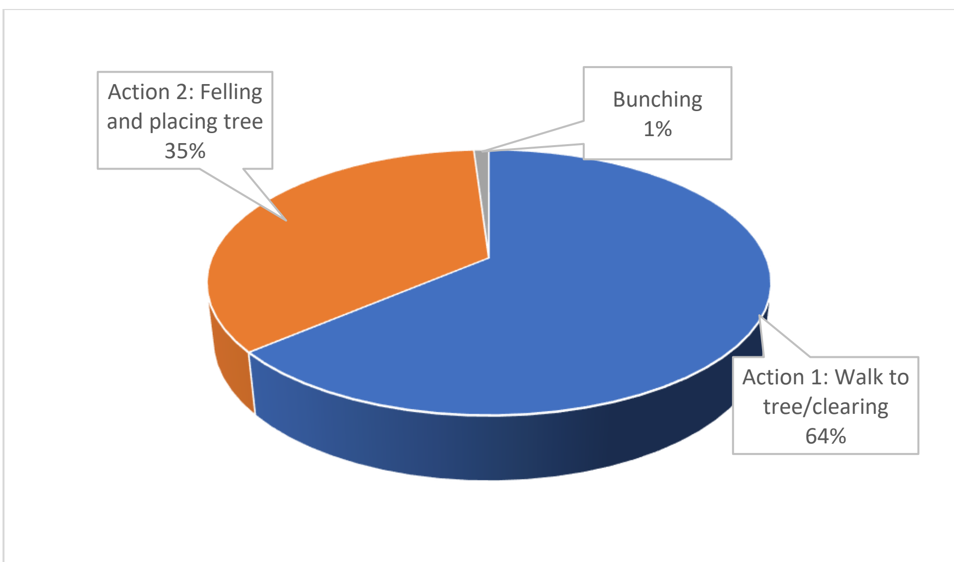


Figure 29: Site 3 average time spent completing each action.

This figure reinforces the difference in average time spent between Walk/Clear, versus Fell/Place, the action of felling and placing the tree in the desired extraction position. Bunching is also seen to again take up a very small percentage of the average time spent. Below shows the cycle times being split up into the two actions, where the range and spread of action times can be seen, as well as the ability to analyse the causes for outlying data. Figure 30 shows action times for the Walk/Clear action.

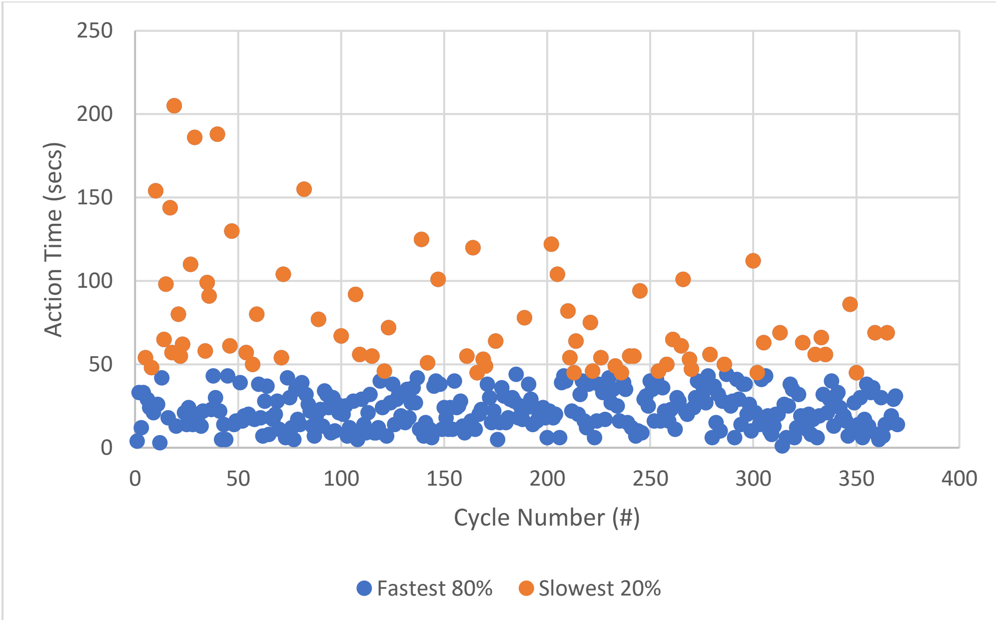


Figure 30: individual times for the Walk/Clear action.

As seen in figure 30, some of the data recorded resides relatively close to the average calculated for Walk/Clear of 33.6 seconds. However, there is a notable range in the action times. This is reflected in the determined standard deviation of 29.1, which is a significantly higher standard deviation time for Walk/Clear than both site 1 and 2. The figure above also shows there are many outliers within the data. In effort to make sense of these outliers, as in the previous sites figures, the points marked in orange on Figure 30 represents the slowest 20% action times. Information was stored within each cycle where comments were made on how the cycle went and what could be causing prolonged action times. Figure 31 shows the recorded causes for those actions falling being in the slowest 20%.

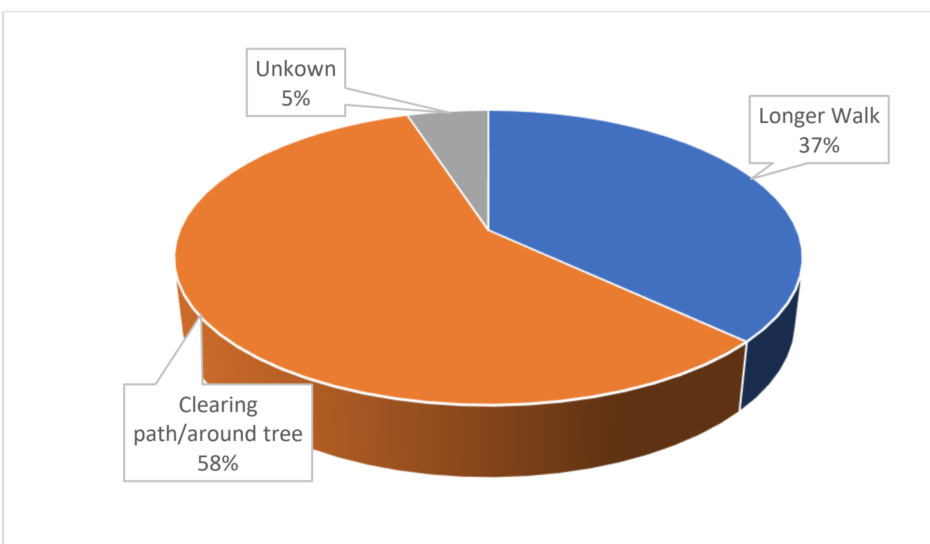


Figure 31: Causes for slowest 20% of Walk/Clear times.

37% of the action times recorded that were in the slowest 20% were said to have been caused by a longer walk time to the next tree, which is much lower than site 2. Most notably, 58% of the action times were longer due to clearing to the tree or around it, amounting to more than half of the causes.

Figure 32 shows the individual action times now for the Fell/Place action.

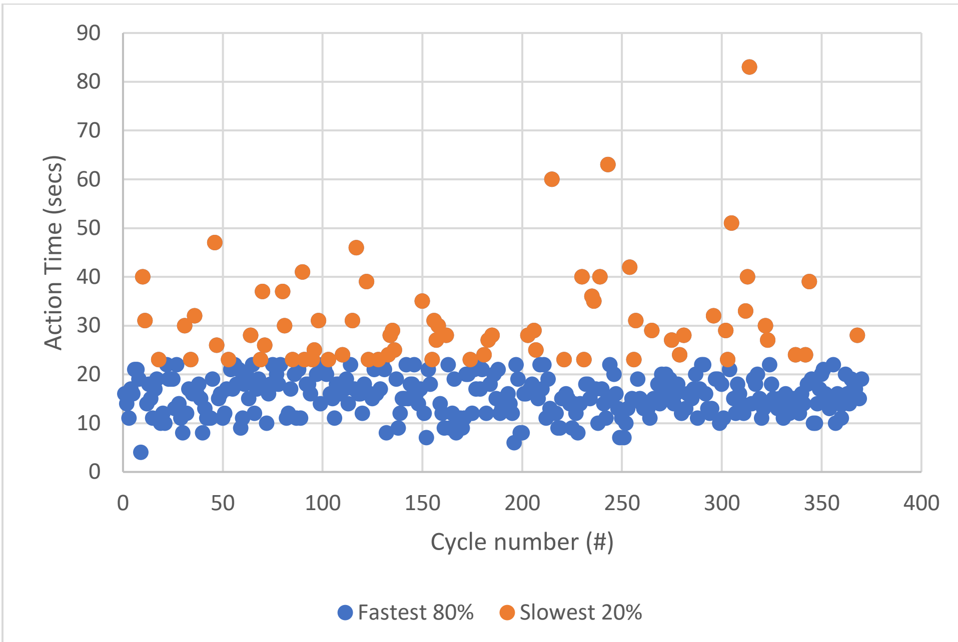


Figure 32: Individual action times for the Fell/Place action.

As from what can clearly be seen in the figure above, a very tight band of data was formed around the average action time of 18.6 seconds. This is further reflected in the standard deviation of the Fell/Place times, which was calculated to be 8.6 seconds, over a third smaller than Walk/Clear's standard deviation. Fell/Place also experienced times that took longer than expected, leading to a number of outliers which can be seen. Again, points marked in orange represent the slowest 20%. To help gain a greater understanding of the causes of this, Figure 33 has been created showing the reasons for those orange Fell/Place times being in the slowest 20%, and what lead to their times being prolonged.

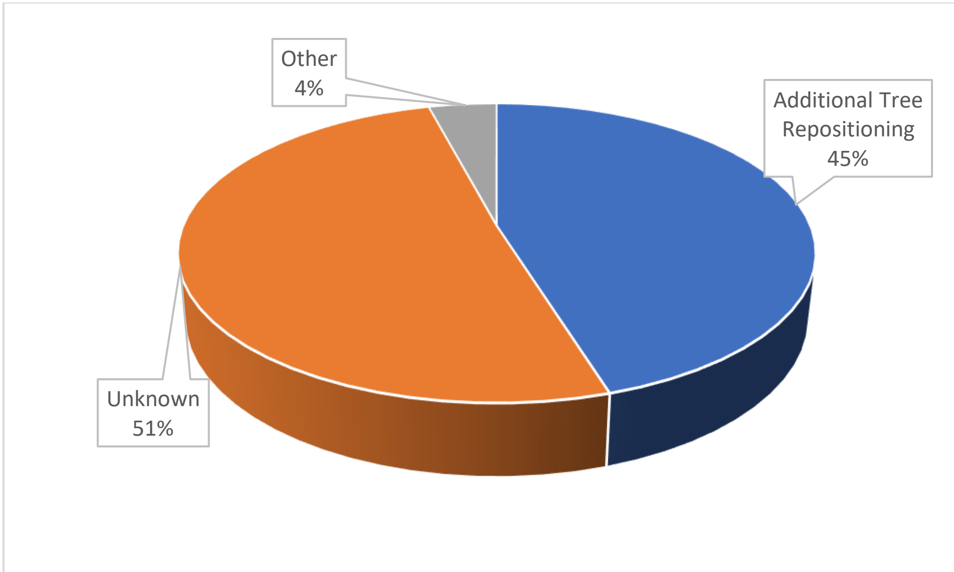


Figure 33: Causes for the slowest 20% of Fell/Place times.

51% of the slowest 20% action times lacked explanation on what caused the time to take longer, however, 45% of the times were caused by the tree needing to be repositioned into a more optimal extraction position. The 5% of other causes included reasons like the tree being notably larger, leading to a slower felling and positioning process, and limited room and access to the tree, causing an undesirable felling position.

Extraction Data

Once the trees recorded in the time study were extracted and processed, the related extraction data was retrieved from the processing machine in the crew. From this data, the small end diameter of the last log cut from each stem was recorded to help gain a better understanding of stem breakage, indicating whether the stem broke or not from the small end diameter measurement. As mentioned before, breakage can also occur during extraction, which needs to be considered. Figure 34 shows the percentage distribution of the SED of the last log cut of each extracted stem.

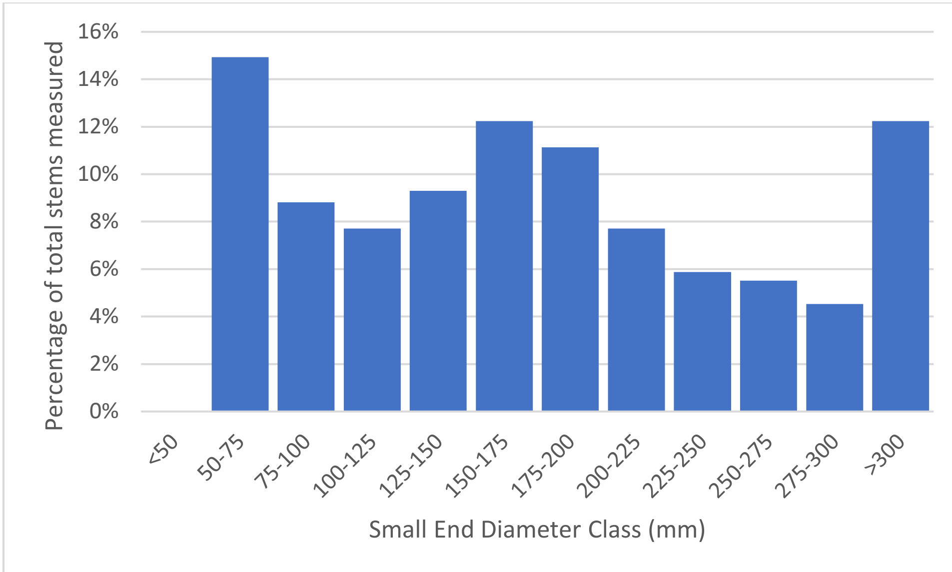


Figure 34: Site 3 distribution of SED from the top of extracted stems.

Figure 34 shows a fluctuating distribution of small end diameters across all bins. The largest percentage seen in the figure is small end diameters ranging from 50-75mm. An increased percentage gathered around the 125-200mm measurement was also seen.

Owner/Operator Comments

The operator on site 3 had recently moved to the operating of fixed felling heads three months prior by investing in part owning in one. They acknowledged that they were still getting the hang of it. Before that, he had had significant experience with dangle felling heads. The current operation was suitable, and the machine could handle the steep terrain and piece size. However, significant undergrowth caused a productivity problem but would have the same effect on dangle heads. They believed the advantages were its bunching ability, making it much easier to prepare stems fore extraction, and that there was notably less breakage. Its disadvantages included that the piece size was hard on the machine, it was higher cost upfront and the potential of higher maintenance cost. They also mentioned that the Tigercat machine suffered restricted reach due to its short boom length, which was smaller than the Eltec machines that the other two sites used. Again, they would suggest other crews to get one, but it would depend on its suitability.

Comparative analysis

After determining the results of each of the sites individually, two tables have been produced comparing the three sites making it possible to compare them and draw any relationships into the different variables impacts. Firstly, Table 6 shows a summary of all the relevant time study results as well as the machinery used at each site, and secondly Table 7 summarises the stand characteristics that may be deemed relevant for analysing the results.

Table 6: Productivity summary table comparing the three sites side by side.

	Site 1 – Napier	**Site 2 – Nelson 1**	**Site 3 – Nelson 2**
Machine	Eltec 316	Eltec 316	Tigercat 855
Felling Head	Quadco 4400QB	Woodsman 1400	Quadco 4400QB
Average Walk/Clear Times (secs)	22.4	16.1	33.6
Average Fell/Place Time (secs)	17.8	19.1	18.6
Average Cycle time	40.2	35.2	52.2
Productivity (stems/hour)	89.5	102.4	69.0
Productivity per PMH	73.3	81.0	48.9
Utilisation (%)	82%	79%	71%

Table 7: Summary table of each of the sites stand characteristics relevant to productivity.

	Site 1	Site 2	Site 3
Piece size	1.75	1.12	2
Slope (%)	rolling/flat	45%	57-70%
Stocking (stems/ha)	369	573	260
MTH (m)	38	33.5	40

The two fixed felling heads that were seen across the three sites were the Quadco 4400QB Felling Head and the Woodsmanpro 1400 Controlled Felling Head (Table 6). There is little difference identified in the felling heads, as they have very similar weights (3.3 and 3.2 tonnes), similar opening and closing diameters (170-1400mm and 170-1388mmm), the same motor size (60cc), similar saw rotation and cut capacity (Quadco Group, 2023) (Woodsmanpro, 2023). So, it has been determined that the felling head has little to no effect on the site productivity differences.

However, in terms of the base machine, Eltec 316 has a notably larger boom reach of 7m compared to the Tigercat 855, which only has a boom reach of 4m. As well as this, the machine was tethered to a winch-assist machine for majority of the time that it was studied. These could have potentially had an impact on the productivity difference experienced in site three, as it may have limited the operator's positioning options when felling, forcing him to get closer to the tree along with other implications.

The Walk/Clear action saw the greatest variation in average times across the sites. The longest average measured was at site 3 (Nelson 2), being 33.6 seconds. This average is significantly longer by over 10 seconds than either of the other sites. It is suspected that this is due to the significantly dense Douglas Fir regeneration growing under the pines in the understorey. After talking with the crew, I was informed that the stand that was being measured had undergone multiple previous rotations of Douglas Fir, and this was the first rotation of Radiata Pine for the stand. This with the combination of the low stocking, and steep slopes promoted the dense undergrowth of Douglas Fir regeneration, causing a notably longer average time taken to complete the first action. This was further reflected in the analysis of the reasons of the slowest 20% of action times, where 58% of the causes were due to extended amounts of clearing to and around the tree. The second longest Walk/Clear time measured was at site 1 in Napier, being 22.4 seconds. This like site 3, but to a lesser extent, experienced the presence of denser undergrowth as well around trees in some areas. This is likely due the operations nature, where it was a road lining operation on a ridge that was exposed, and on the edge of the stand, causing a greater undergrowth presence. This again was reflected in the reasons behind slowest 20% the times as the largest percentage, 48%, of the causes were from extended amounts of clearing to and around the trees. Walk time also played a part in making site 2's Walk/Clear times longer as due to the site and operation, the edge trees were not often evenly spaced, and different walk times were involved. Lastly, site 2 experienced the shortest average Walk/Clear time of 16.1 seconds. This is possibly due to the favourable stand characteristics, allowing the action to be completed quicker. Site 2 had the highest stocking, meaning the operator was able to reach the next tree more easily and fell it faster, site 2 also had a smaller piece size. The sites stocking also played a part in reducing the amount of undergrowth, as little was observed to have caused any prolonged times. This prediction coincides with the analysis of the causes of the slowest 20% action times, where only 6% were caused by clearing, and 67% due to a longer walk to the next tree to fell.

The Fell/Place action saw a much smaller variation in average times across the three sites. This is likely due to the stand characteristics having less of a direct effect on the action. Site 2 was seen to have the longest average Fell/Place time of 19.1 seconds. Although only slightly longer, this could be due to the operator noticeably taking more consideration into the action, making sure that the stem was in its most optimal position for extraction. Another factor to consider which may be impacting this time was stocking, as it was significantly higher than the other sites, the space may have been restricted for the operator forcing them to make slightly slower and more careful placements. Site 1 had the fastest average Fell/Place time of 17.8 seconds. This is likely due to that operator being the most experienced out of the three. Overall, the Fell/Place action times were very similar across the board, this is further reflected in all the standard deviations of the Fell/Place action times being significantly lower than the Walk/Clear standard deviations. The average total cycle times have a variation of 17 seconds, this variation in predominantly due to the Walk/Clear variation discussed above. With site 3 having the longest average cycle time, the operator was transparent in discussing with that he was still learning, and that he may be slower than other, more experienced operators. Although the operator came from a dangle head, which is considered to be challenging, he still handled it very well and still achieved fast cycle times at an individual level. Operator experience, seen with these results is likely a contributing factor to cycle time speed and in turn productivity.

Once the average cycle times were calculated, productivity and productivity per productive machine hour was then calculated incorporating delays. A range of delays occurred with a lot of them being inevitable across all sites. These included chain changes, walking to new areas and refuelling. Site 3 had the lowest utilisation of 71%. Again, this is likely due to the natural regeneration of Douglas fir in the understorey. There were multiple times where the operator had to halt felling to spend time clearing the understorey, with some of the trees being large and already felled, causing an increase in experienced delays. Site 3 also had the newest operator to fixed felling heads with only three months experience. Another example of delays experienced for site 3 were winch-assist related delays, like when the machine was moving to a new spot, both machines had to be moved, re-attached, and more which took longer than relocating the felling machine at other sites. Site 1 had the highest utilisation of 81%. Although this is evidently due to less delays occurring, operator experience and skill may have been a reason to why less delays occurred. The operator was exceptionally skilled with the fixed felling head, meaning that they were being able to be more efficient when felling and in their down time. Site 2 had a utilisation of 79%, which is not far from site 1. What was observed at site 2 is that an abnormal amount of chain changes occurred, as this was due to the chain often getting blunted by the uncemented gravels of the slope, rocks would pile up on the higher side of the stem and the chain would often nick them, causing more chain changes, contributing to the delays. Overall, the three sites experienced strong utilisation results.

Each of the extraction data results saw some significantly ranging data. Figure 35, the small end diameter distributions of the extracted stems for each of the three sites are shown.

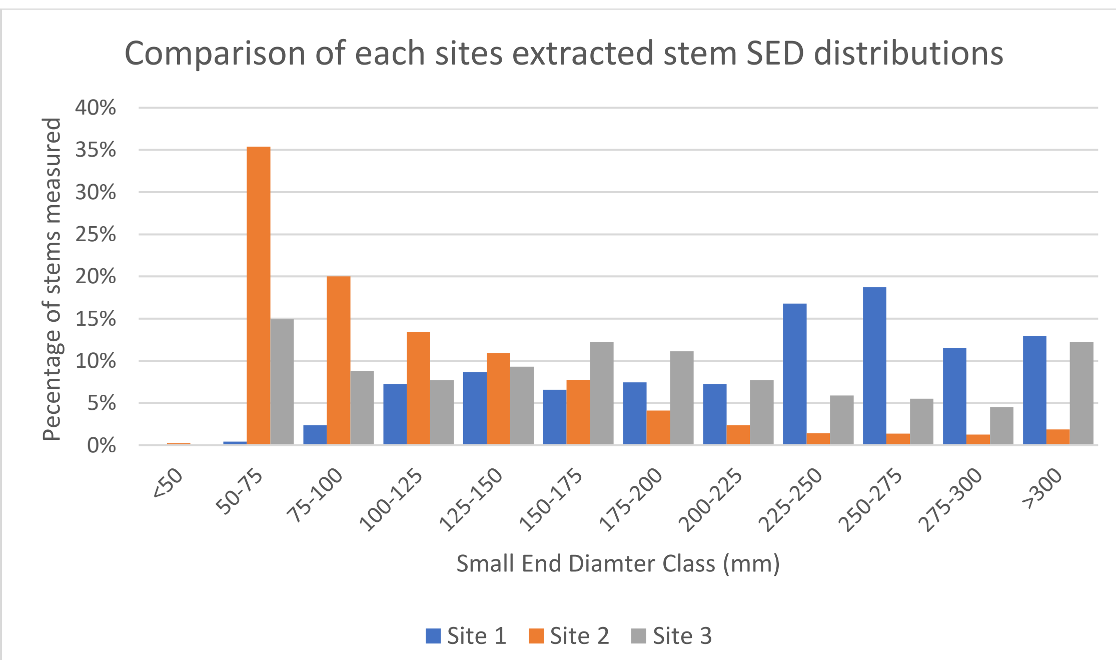


Figure 35: Comparison of each of the sites extracted stem SED distributions.

Site 1 visually had the majority of their extracted stems in higher small end diameter classes than the other two sites, with the average small end diameter being 230 mm. These larger small end diameters indicated that a significant number of stems were broken during processing. Interestingly, while conducting the time study at site 1, very few trees were observed to have broken while felling. When observing, there was a clear view of not only the machine itself, but also where the trees landed and were positioned. This means that potentially a number of stems may have broken during extraction. Site 1 was also the only site that was not being extracted by cable, meaning the trees were not as neatly presented for extraction as they did not need to be, this could have contributed to breakage during extraction. Besides from extraction, there were a number of varying stand characteristics that both site 1 and site three possessed that may have been unfavourable and could have contributed to breakage when felling. Site 1 had a piece size of 1.75 m^3, which is larger than site 2's 1.12 m^3 piece size, the stand also had a mean top height of 38 metres which is 4.5 metres taller than site two. For site 3, the distribution of small end diameters had improved compared to site 1 but was still not optimal. Site 2 had the largest piece size and mean top height of 2 metres cubed and 40 metres respectively. Site 3's average small end diameter was found to be 178 mm. It was observed while measuring at this site that some stems were breaking while felling, the above stand characteristics are likely to have been one of the factors. Another factor that may have caused breakage at site 3 was operator experience, as mentioned above in analysing the cycle times, the operator was still relatively new to fixed felling heads, and still learning, meaning that some trees broke while felling as a result. Site 2 is the most optimal example of a fixed felling head heavily reducing stem breakage which was evident from the small end diameter distribution. The average small end diameter was determined to be 114 mm, which was significantly lower than the other two sites, and over 75% of the small end diameters recorded were under 150 mm. Other contributing factors to this distribution were its favourable stand characteristics, including its low mean top height of 33.5 m, and low piece size of 1.12 m^3. Another potential factor would be the difference in species, where site 2 was Douglas Fir.

Table 8 shows a comparison of the time study reported here versus a time study performed in 2016 involving three felling machines with dangle felling heads in a similar region of New Zealand. Piece size and stems felled per productive machine hour were compared, in turn giving productivity of metres cubed per productive machine hour.

Table 8: Comparison of the study to a recent New Zealand time study on dangle head felling heads.

Machine type	Felling Head	operation type	region	piece size (m3)	Productivity (Stems/PMH)	productivity (m3/PMH)
Eltec 316 with Quadco 4400QB	Fixed Head	Clearfell	Hawkes Bay, NZ	1.75	73.3	128.3
Eltec 316 with Woodsman 1400	Fixed Head	Clearfell	Nelson, NZ	1.12	81	90.7
Tigercat 855 with Quadco 4400QB	Fixed Head	Clearfell	Nelson, NZ	2	48.9	97.8
Tigercat 655 felling machine	Dangle Head	Clearfell	Nelson, NZ	1.6	43.5	69.6
Sumitomo with Satco felling head	Dangle Head	Clearfell	Nelson, NZ	2.3	43.3	99.6
Tiger cat 655 felling machine	Dangle Head	Clearfell	Nelson, NZ	2.5	47.4	109.0

The three fixed head studies represent the studies recorded in this project. As shown in the table, all three of the fixed felling head studies felled more stems per productive machine hour. In terms of m^3/PMH, site 1 felled more than all the dangle heads, site 2 felled more than the Tigercat 655 with a piece size of 1.6 m^3, even though it had a smaller piece size of 1.12 m^3 and finally site 3 felled almost equal to the Sumitomo, even though it had a smaller piece size.

Discussion

The three sites studied throughout this project had a range of differing characterises. The sites had terrains ranging from flat rolling country seen in site 1, to steep slope harvesting with winch-assisting in site 3. The fixed felling head was clearly seen to be capable across the board. Each site had notable differences in piece size, slope, stocking and mean top heights, meaning evaluation of the fixed felling heads performance under a range of conditions was possible. Piece size had a significant impact on the stems felled per productive machine hour, with lower piece size returning a higher productivity of stems felled. Another aspect to be considered was the fact that sites 2 and 3 were on moderately steep to steep slopes, with site 3 being winch assisted for majority of the study. This may have had an impact on productivity, as site one was seen to be more productive in terms of m^3/PMH, as it was able to fell a substantial number of stems at its respective piece size of 1.75, where site 3 felled significantly less stems/PMH at its piece size of site 2, which was on a much steeper slope. Overall, the fixed felling head was seen to handle a range of piece sizes, on a range of slopes. Comparing this study to a recent similar study involving its dangle head competitors (Table 8), shows that fixed felling heads are just as capable, if not more than its dangle head counterparts with similar piece sizes. On top of this, the operators were able to produce and maintain noteworthy utilisation values, and efficient tree positioning for extraction times with little variation.

Although the stem breakage analysis showed unique results over the three sites, site 2 in nelson highlighted the true capability that fixed felling heads can achieve in reducing stem breakage, and others indicated at the potential of this without the inclusion of extraction breakage. Another concept that plays an important part in fixed felling head breakage, is for the operator to understand the task and goal of using the fixed felling head to reduce breakage. They must understand how to optimally operate the machine to promote breakage reduction, and how that is the goal. Sites 1 and 2 had operators with extensive experience with fixed felling heads, and both were passionate in the use of them. They understood the goal of the machine, and the implications and advantages if correctly used across the whole system.

The operators were able to identify a range of advantages that were reinforced by their actions. The most evident advantage is the fixed felling head's ability to have better directional control when felling, which was recognised by all operators. As reflected in the productivity results, improved cycle times were another advantage of fixed felling heads. The bunching capability has a significant effect not only on the felling process itself but also across the whole harvesting system. The two sites that were in fully mechanised cable yarding operations found it extremely advantageous because of how they were able to position and prepare bunches to aid the extraction process, the operators of the yarders affirmed this also. Lastly all operators, including the operator that recently moved from dangle felling heads, emphasised that they were able to achieve a significant reduction in breakage.

Although there were a number of advantages identified, fixed felling heads do have disadvantages, with the most widely identified being its higher cost. Fixed felling heads were consistently more expensive to purchase than similar dangle head models. Shovelling limitations are often included in the disadvantages of fixed felling heads, but multiple operators were able to shovel with them when they had to. Due to fixed felling heads controlling the descent of the felled tree, larger piece sizes can be harder on the machine, which was identified in site 3 with the largest piece size. This could lead to the issue of higher and more frequent maintenance costs in the future.

When asked “Would you suggest other crews to get one?”, operators answered yes, they would, but it had to be suitable for them. It is not uncommon to compare fixed felling heads to dangle heads in actions other than felling. Fixed felling heads are excellent felling machines, and that is the main task they are built for. Dangle felling heads often possess processing capability and can be used for a range of other actions when its primary task of felling isn’t urgent. Fixed felling heads lack this versatility, meaning a predetermined opinion on them being worse is sometimes used. This does not mean that fixed felling heads are bad, just that they are better in certain applications than others. Operators praised how good the fixed felling heads were at felling, but emphasised the fact that they would suit certain operations more than others.

An important view on harvesting as a whole is identifying what the overarching goal of the system is. When harvesting, the aim should be to reduce the amount of breakage as much as possible, because every breakage, is a reduction in merchantable volume. Incorporating machinery that helps the harvesting system move closer to the target should be implemented.

Conclusion

This project showed the capability of fixed felling heads in forest operations on three different sites with varying stand characteristics, including piece size, slope and stocking. Compared to dangle head studies of similar piece sizes, fixed felling heads returned better productivity results. A range of data was collected and analysed from the processing machine to indicate stem breakage, with one of the sites exceeding the expectations of how much fixed felling heads could reduce stem breakage. Looking to the future, there is opportunity for greater investigation into stem breakage without the intervention and potential of extraction breakage skewing the data set. Some key findings and advantages that fixed felling heads presented are faster cycle times, the benefit of bunching and positioning for extraction, and the reduction in harvest residue on the slopes. There is significant opportunity in the industry for more fixed felling heads, and the study aids in proving their advantages, capabilities, and suitability.

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"Intelligence plus character – That is the goal of true education." - Martin Luther King

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Appendix

Time Study data sheet example.

#	WALKING & CLEARING	FELLING & PLACING	BUNCHING	Comments/ Delays