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Viability of Production Thinning in New Zealand

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FOREST ENGINEERING FINAL YEAR RESEARCH PROJECT

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ABSTRACT

In New Zealand plantation forests thinning is required to improve stand quality during its growing cycle. Most plantations are currently thinned-to-waste; production thinning is not a widely used form of silviculture. In regions like the USA and Europe production thinning is used commonly for one or even two thins of a forest before final harvest.

This research project aimed to determine the viability of production thinning through the evaluation of the productivity of production thinning crews, estimating daily and per tonne harvesting costs, and exploring stand and terrain effects on production thinning. Data for this project came from an industry questionnaire where 6 companies responded with details on 8 existing crews, and a time study performed on one of the 8 crews in Southland during early June 2021.

From the survey, most crews ran one or two harvesters, a forwarder and a loader at the landing. The crews averaged 3 workers and 3 or 4 machines per crew, indicating they were highly mechanised. Typical thinning volumes extracted were between 60 and 100 tonnes/ha, at an average extraction distance of 245m. The reported daily production ranged from 60 to 185, with an average of 125 tonnes/day. Daily operational costs were calculated in the range of $2,860/day – $5,150/day, with an average of $4,210/day. Harvesting rates in the range of $27.00/t – $64.40/t, with an average of $37.00/t were calculated based on daily production values given by the crews.

Harvester productivity from the time study ranged between 63 and 97 tonnes/day based on different tree piece sizes. Forwarder extraction productivity ranged between 66 and 106 tonnes/day based on different log piece sizes and different extraction distances.

It was concluded that production thinning will be a viable operation for New Zealand's plantation forests where the logging rates can be cost competitive relative to the value of the product extracted. Further research into the productivity of harvesting and extraction machines in specific scenarios throughout New Zealand will help to provide a clearer understanding of when production thinning might be a viable operation for forest owners.

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1. INTRODUCTION

Thinning is a common practice within the plantation forest industry to improve future crop quality and hence value. In New Zealand, most commonly trees are thinned-to-waste, which means they are simply felled and left. Production thinning refers to an operation that includes the commercial removal of trees. Production thinning is often overlooked due to the high cost in comparison to traditional waste thinning. It relies on the removal of higher numbers of trees to be profitable. More recently production thinning is also not common due to an industry change to a structural timber regime. A structural regime requires a higher final crop stocking, resulting in less trees being thinned.

However, production thinning provides an opportunity to recuperate establishment costs as well as provide alternative grades such as post and poles. With advances in techniques and availability of smaller and more versatile equipment there may be greater opportunity for New Zealand to increase its use of production thinning. However there is limited literature on production thinning within New Zealand, especially on productivity, costing, and effects on productivity. The most recent publicly available studies done on production thinning in New Zealand were over 20 years ago.

New Zealand is known for its difficult terrain which makes for tough forestry harvesting and operating conditions. This often means that waste thinning is the operation of choice. However, there are still substantial areas within New Zealand that could utilise production thinning. This research project will look at some of the current production thinning operations in New Zealand. The information gained from this study has the potential to encourage more production thinning in New Zealand.

2. LITERATURE REVIEW

Thinning is an integral part of a forest plantation silvicultural regime. There is a need for thinning to reduce the stocking from establishment to final crop stocking. According to Mead (2013), having a higher initial crop stocking than final crop stocking allows for selection in thinning and pruning operations. Mackintosh & Bunn (1976) found that a high stocking limits the size of the branches at the lower portion of the stem. A more recent study by Mead (2013) also found that a relatively high stocking can improve core wood quality and decrease branch size in the lower portion of the stem.

One of the methods of thinning a forest is production thinning. Production thinning is as an intermediate harvest where the merchantable wood removed can be sold to cover part or all the cost of harvesting. Smith (1986) defines production thinning (as cited in British Columbia Ministry of Forests, 1999) as "a thinning in which all or part of the felled trees are extracted for useful products" (p. iii).

The timing of production thinning can greatly affect the volume and piece size of the final crop in two ways. Firstly, through leaving the crop too long before thinning. Too much competition for the final crop will not increase the average piece size (Mackintosh & Bunn, 1976). Bose et al (2018) found that when thinning occurs too late the maximum volume growth potential has already been reached before the thinning has occurred. However, this is more acceptable as the industry moves towards a structural regime with a greater number of smaller trees instead of fewer larger trees. Secondly, if early thinning occurs then competition between the remaining trees will be reduced (Emmingham & Elwood, 1983). This allows for more nutrients, sunlight, and water which allow for better growth of the trees (Bose et al., 2018).

The potential growth of higher economic value pruned trees can be stunted with competition from unpruned trees in proximity. Production thinning may be justified when the unpruned trees can be thinned before they impact the growth of the pruned final crop (Mackintosh & Bunn, 1976). The long-term determining factor that decides whether you should production thin or not depends largely on whether unwanted trees can be extracted before they decline the volume growth of the final crop (Mackintosh & Bunn, 1976).

Looking at the latest information on Radiata pine production thinning in New Zealand, MPI found that 191,685 ha (12.8%) of New Zealand's Radiata pine plantation forest is production thinned (MPI, 2020). This is up 0.3% on 2019, however over the last decade production thinning of Radiata pine has generally declined (MPI, 2020). D. Evison (personal communication, October 18, 2021) suggested that one reason for this is due to the demand for pulp logs being met by final crop harvesting. Therefore, the need for production thinning to fill the gap in supply of pulp wood has not been needed in the last decade.

This can be compared to 1995 where 28% of Radiata pine forests were or were intended to be production thinned (MAF, 2004). In reality, the area of Radiata pine production thinning in New Zealand has been declining for the past two decades. Figure 1 shows the areas of production thinning, no production thinning, and total radiata pine area for 2003, 2010, and 2020.

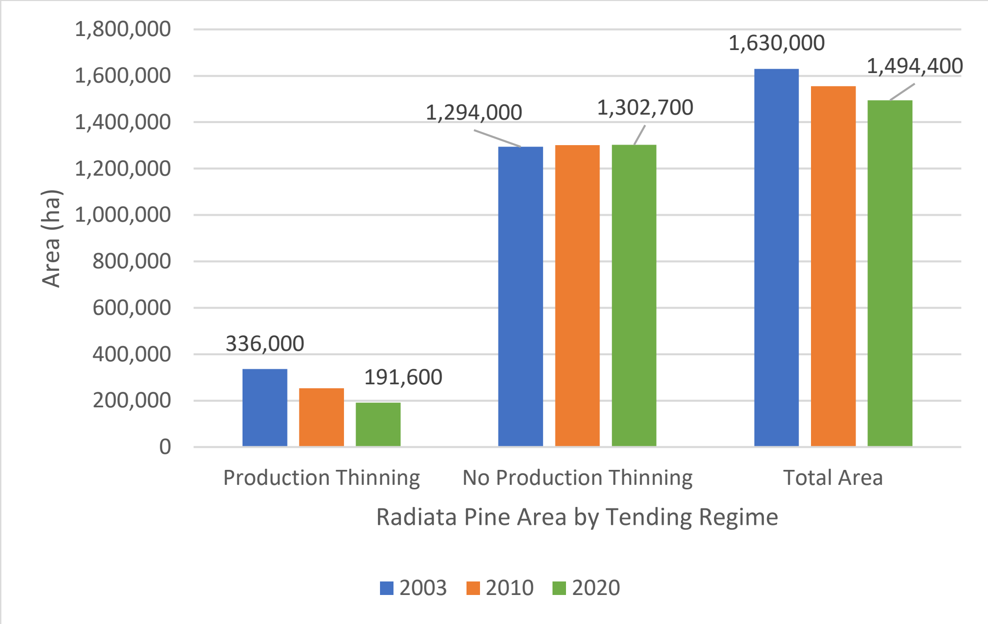

***Figure 1** – Radiata Pine Area by Tending Regime for 2003 (MAF, 2004), 2010 (MAF, 2010), and 2020 (MPI, 2020).*

The area of production thinning of Radiata pine in New Zealand decreases significantly from 2003 to 2020 (Figure 1). The total area also decreases over this period. Most of the production thinning area decrease between 2003 and 2020 is due to the total Radiata pine area decrease. An additional 8,700 hectares has been moved to non-production thinning area between 2003 and 2020 (Figure 1).

Most of the Radiata pine production thinning in New Zealand comes from stands that are pruned (Figure 2). However, there is a large area that is not production thinned, especially in unpruned stands. This could be an area to increase the use of production thinning.

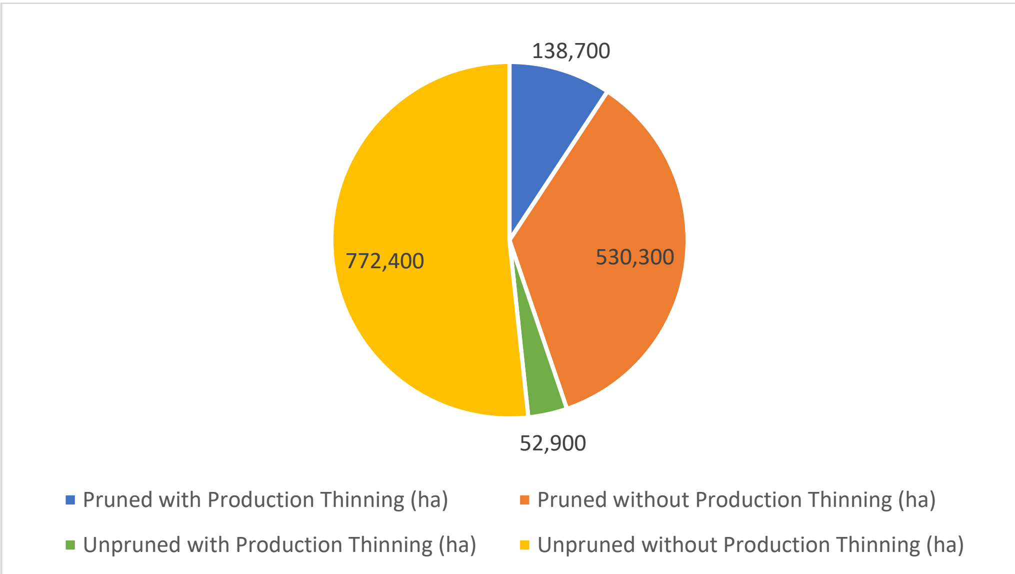

***Figure 2** – Radiata Pine Area by Tending for 2020 (MPI, 2020).*

There are many methods of felling and extraction within forestry plantations. Production thinning is no different. Figure 3 shows how Raymond, McConchie, & Evanson (1988) felled and extracted wood in their study.

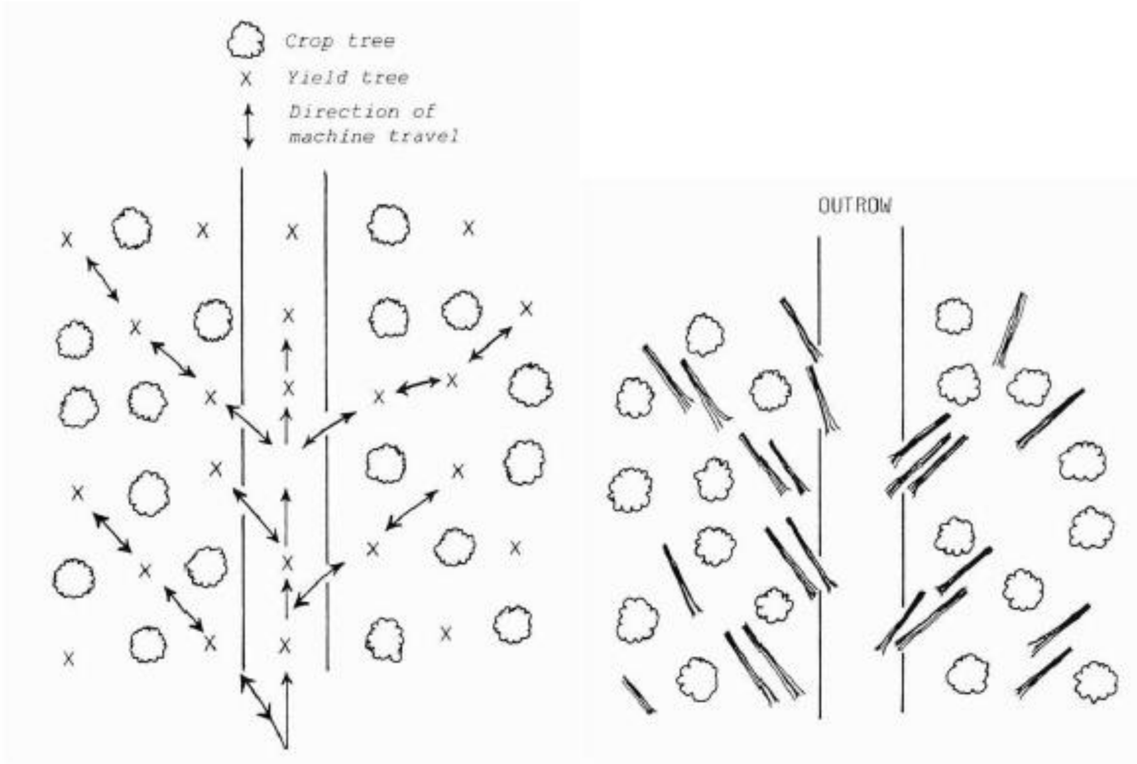

Figure 3 *– Felling and Extraction method using a Lako Harvester and Bell Skidder (Raymond, McConchie, & Evanson, 1988).*

This method of extraction used a Lako harvester to thin and process every seventh row. The adjoining three rows of each side were then selectively thinned and processed as the harvester moved through. Stems were semi bunched with butts placed in the direction of extraction to increase the productivity of the bell skidder during extraction (Raymond, McConchie, & Evanson, 1988).

In 1976 there was a study conducted by the NZ Forest Service into the economics of thinning plantations. Thinning is a more complex operation than clear felling, higher total yields foregone should be justified when production thinning (Fenton, 1976). According to Kerruish and Moore (1982) "early loss of volume production and financial returns are accepted in return for maximum financial yields over the rotation" (p. 350). The loss in total yields is offset by economic gains in harvesting larger trees (Kerruish & Moore, 1982).

2.1 Productivity of Production Thinning

The lack of current productivity data on production thinning harvesters within New Zealand is shown with only one study published over 30 years ago. Raymond, McConchie, & Evanson (1988) determined a productivity value of 28 m^3/PMH. Some of the available extraction productivity rates in New Zealand date back to 1976, Grayburn (1976) determined 49 – 71 tonnes/day and Rayomond, McConchie, & Evanson (1988) determined a productivity of 49.6 m^3/PMH.

There were different production rates in Grayburn (1976) for different age classes and extraction distances. It is difficult to compare the rates of (Grayburn, 1976) to the rate of (Raymond, McConchie, & Evanson, 1988) because of the different measurement factors. If a utilisation rate and productive hours were known in the Raymond, McConchie, & Evanson (1988) study, then a comparable production rate could be determined.

There is significantly more available data on felling and extraction from overseas studies. Table 1 shows some of the felling productivity data from a range of harvesters in time studies conducted internationally. The values range from 11.3 to 41 m^3/PMH, with an average of 27 m^3/PMH, with one value in tonnes per day of 371 tonnes/day.

***Table 1** – Productivity Rates for Felling in Overseas Countries.*

Research Paper	Year	Country	Production Rate
(Baek, 2018)	2018	USA	28.8 – 35.6 m^3/PMH
(Mederski, et al., 2016)	2016	Poland	21.4 – 22.0 m^3/PMH
(Visser & Spinelli, 2012)	2012	Italy	39 – 41 m^3/PMH
(Acuna, Strandgard, Wiedemann, & Mitchell, 2017)	2017	Australia	14.5 – 25.9 m^3/PMH
(Eriksson & Lindroos, 2014)	2014	Sweden	11.3 m^3/PMH
(Kellogg & Bettinger, 1994)	1994	USA	30.8 m^3/PMH
(Visser & Stampfer, 2003)	2003	USA	371 tonnes/day

Table 2 shows some of the extraction productivity data from time studies conducted internationally. The values range from 10.2 to 23.3 m^3/PMH, with an average of 16.7 m^3/PMH, with one value in tonnes per day of 286 tonnes/day.

***Table 2** – Productivity Rates for Extraction in Overseas Countries.*

Research Paper	Year	Country	Production Rate
(Baek, 2018)	2018	USA	22.4 – 23.3 m^3/PMH
(Eriksson & Lindroos, 2014)	2014	Sweden	12.9 m^3/PMH
(Kellogg & Bettinger, 1994)	1994	USA	10.2 – 14.5 m^3/PMH
(Visser & Stampfer, 2003)	2003	USA	286 tonnes/day

Based on the larger datasets of the international data in Table 1 and Table 2 the felling productivity in Table 1 is greater than that of extraction in Table 2. This is different to the literature in New

Zealand, where extraction has a higher productivity rate than felling. The tonnes per day values in Table 1 and Table 2 are again hard to compare to the other m^3/PMH values in the respective tables without utilisation rates or productive machine hours for each study.

2.2 Effects on Productivity of Production Thinning

There are many effects on the productivity of a production thinning operation. These can be stand, land, soil, and machine characteristics, among other things. The effects can be on both harvesting and extraction aspects of the operation.

For extraction productivity, one of the greatest effects is extraction distance (Baek, 2018; Ghaffariyan, Sessions, & Brown, 2012; Eriksson & Lindroos, 2014; Strandgard, Mitchell, & Acuna, 2017; Spinelli, Owende, Ward, & Tornero, 2004; Tiernan, et al., 2004). As well as, the effect of slope on extraction productivity (Ghaffariyan, Acuna, & Brown, 2019; Kellogg & Bettinger, 1994; Tiernan, et al., 2004). Slope does not have as great of an effect on productivity as extraction distance does. Especially when slope is not steep for the entire duration of a cycle (Strandgard, Mitchell, & Acuna, 2017).

Figure 4 shows the predicted productivity of forwarders based on distance and slope using Australian Logging Productivity and Cost Appraisal (ALPACA) (Ghaffariyan, Acuna, & Brown, 2019). The graph is representative of a large source of different time studies carried out around the world, through a literature review of different case studies.

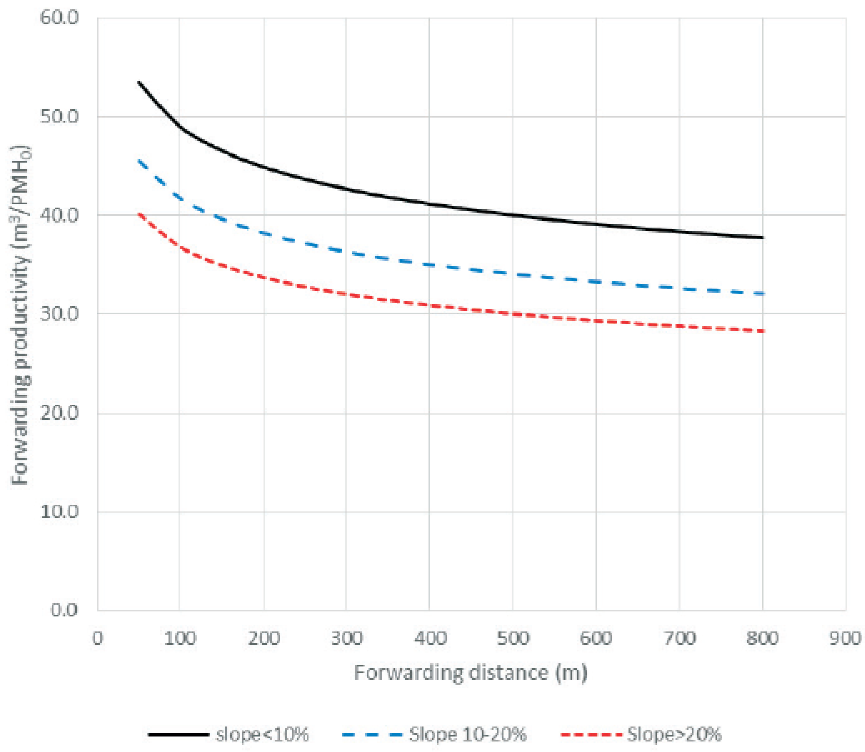

Figure 4 – Predicted Productivity of Forwarders based on Distance and Slope (Ghaffariyan, Acuna, & Brown, 2019).

The same data used in Figure 4 was used to show the predicted productivity of harvesters based on tree volume and slope. ALPACA used the inputs from a large range of literature review case studies (Ghaffariyan, Acuna, & Brown, 2019). The output for predicted productivity of harvesters based on tree volume and slope can be seen in Figure 5.

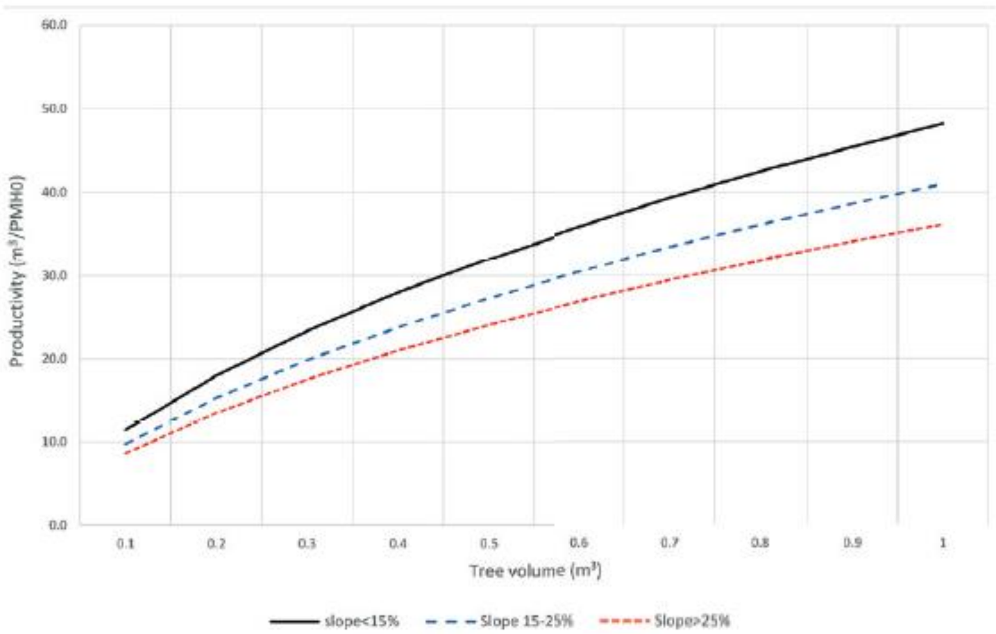

Figure 5 – *Predicted Productivity of Harvesters based on Tree Volume and Slope (Ghaffariyan, Acuna, & Brown, 2019).*

Although these are predicted models, they are based on actual case study data. To show that the trend in the predicted models is correct, Figure 5 can be compared to Figure 6. Figure 6 is the productivity of a harvester against tree volume (Acuna, Strandgard, Wiedemann, & Mitchell, 2017). The productivity trend with no forks in Figure 6 follows a similar trend to that in Figure 5 with a slope of <15%.

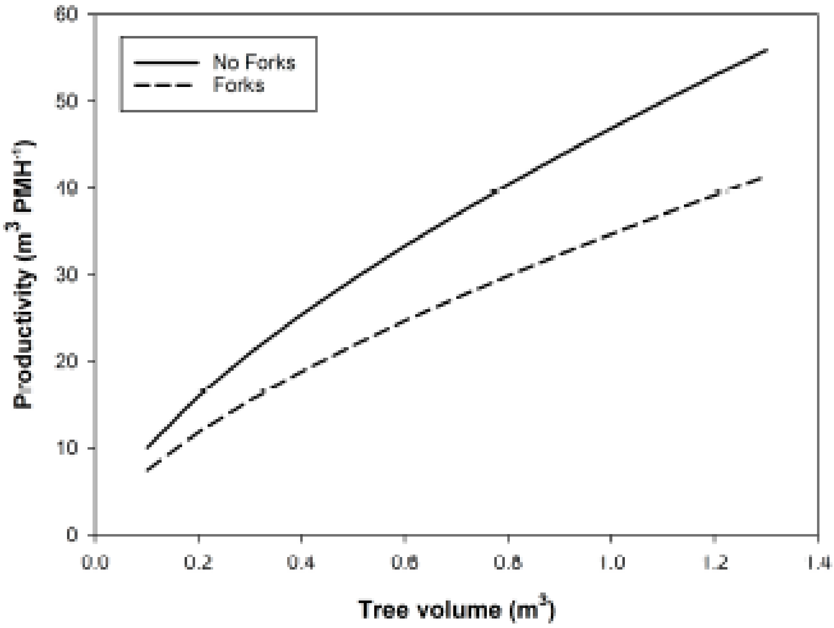

Figure 6 – *Productivity of a Harvester as a Function of Tree Volume (Acuna, Strandgard, Wiedemann, & Mitchell, 2017).*

The visual representation of Figure 4 confirms the negative effect of a greater extraction distance and higher slope on extraction productivity (Baek, 2018; Ghaffariyan, Sessions, & Brown, 2012; Eriksson & Lindroos, 2014; Strandgard, Mitchell, & Acuna, 2017; Spinelli, Owende, Ward, & Tornero, 2004; Tiernan, et al., 2004).

Some other effects on the productivity of extraction include the number of logs per cycle (Baek, 2018; Ghaffariyan, Acuna, & Brown, 2019), the time taken to load/unload logs (Baek, 2018), size of the forwarder (Ghaffariyan, Acuna, & Brown, 2019), and the driving speed (Strandgard, Mitchell, & Acuna, 2017).

Other effects on the productivity of harvesting include the number of unmerchantable trees in the stand (Kellogg & Bettinger, 1994), distance between trees (Ghaffariyan, Naghdi, Ghajar, & Nikooy, 2012), the number of logs produced by each stem (Baek, 2018), undergrowth (Baek, 2018).

Finally, operator experience can affect the productivity of both extraction and harvesting. Operators with less experience are not as efficient at processing and making decisions (Tervo, Palmroth, & Koivo, 2010).

2.3 Cost of Production Thinning

Extraction volume must be great enough to warrant production thinning, Maclaren & Knowles (2005) found that a volume of 75 to 125 m^3/ha is needed to ensure the cost of extraction is justified. However, it was a lower volume of 56 m^3/ha where production thinning would be postponed in Grayburn (1976).

Ghaffariyan, Acuna, & Brown (2019) said that "one of the suitable approaches to control the cost is developing machine productivity and cost-predicting models for the expected range of operating conditions" (p. 13). Knowing the productivity and cost of machines in a production thinning operation will ultimately tell the forest manager whether it is viable to production thin or not. The need for a productive crew is nothing without it being cost effective.

There are costing models such as the Australian Logging Productivity and Cost Appraisal (ALPACA) (Ghaffariyan, Acuna, & Brown, 2019), LIRA Costing Handbook (Raymond, McConchie, & Evanson, 1988), and most recently the LIRO costing model (Future Forests Research, 2009). As well as this, individual companies often have their own costing models.

To get an understanding of harvester cost data we can look to Raymond, McConchie, & Evanson (1988) who developed costs for their harvester productivity study with two scenarios as seen in Table 3. The first is a single operator working a 8 hour shift, the second is a double shift, both with 8 hours worked.

***Table 3** – Harvester Cost Data (Raymond, McConchie, & Evanson, 1988).*

	Scenario 1	**Scenario 2**
Total Cost	$207.80/PMH	$148.30/PMH
Cost per m^3	$7.40/$m^3$	$5.30/$m^3$

3. OBJECTIVES

This research project aims to determine the viability of production thinning in New Zealand by:

- Evaluating the productivity of production thinning crews in New Zealand,
- Determining a $/day and $/tonne operational cost for production thinning in New Zealand,
- Exploring the effects on production thinning.

4. METHODOLOGY

There were two main parts to this research project in determining the viability of production thinning in New Zealand: an industry questionnaire and a time study.

4.1 Industry Questionnaire

The main methodology used to determine the viability of production thinning in New Zealand was an industry questionnaire. Areas of effect on production thinning were identified through initial research, which was covered in the literature review. Some of the areas of effect identified were then developed into questions to put forward to industry. The questions were developed so that they would capture a broad sense of effects on production thinning viability. As well as this, a few questions were developed to draw on industry knowledge, and gain ideas of what could be done better or changed to increase the viability of production thinning.

Various forest management companies throughout New Zealand were contacted to gather data on productivity, machines, and industry knowledge. The questionnaire was sent out to the forest managers to either fill out themselves or give to their contractors. Answers were received from six different companies, including Ernslaw One, Forme (answers from Forest Enterprises), NZFM, Pan Pac, Rayonier, and Timberlands. The questions developed for the questionnaire are as follows.

- What are the machines that are used for operations and the number of people in the crew?
- Average productivity data for the operation
    - Tonnes/day, hours worked
    - Typical piece size
    - Typical extraction distance
    - Typical stocking before and after thinning
- Is there a maximum slope you'll still production thin on?
- Is there a maximum distance to the mill that you would still production thin?
- Is there a minimum m3/ha recovery for you to production thin?
- What percentage of merchantable material is pulp, post/poles, sawlog? Are these all the grades that are cut?
- Do you row thin? Which rows do you thin? Is there any selection thinning?
- Have you increased/decreased or held production thinning areas the same in the last decade?
- Are there any other factors that encourage production thinning?

- Are there plans to production thin before the stand is established? Are there adjustments made to allow for production thinning?
- What could be done better at/before establishment to make production thinning more productive/viable?

When all industry questionnaires were received and reviewed the information from each questionnaire was collated into an excel document. Each industry questionnaire was given an individual crew number. This was done to keep the information from each company and crew private, whilst keeping information consistent for comparisons. The collation into a single excel document allowed for ease of viewing and comparison.

After comparisons were made between the questionnaires the results were compared to some of those found in the literature review. And finally, some results and conclusions were drawn about New Zealand's production thinning compared to operations overseas.

4.2 Time Study

To gain a more accurate production rate for production thinning it was decided that a time study would be completed. This secondary methodology of a time study would give a more accurate level of current production thinning productivity for a certain forest. This value could then be compared to that of the typical values given in the industry questionnaire.

A production thinning crew in Southland was chosen for the time study. The crew was chosen for its smaller size and the time availability of the study. The 20 to 22-year old *Pinus* radiata forest is located 53 km east of Invercargill. The study was conducted over two and a half days from the 1st to 3rd of June 2021. A pre-assessment and planning day was conducted on the 31st of May 2021. The weather during the study was a mixture of rain and sunshine. On the first day of the study, the weather was mostly overcast and cold. The next day and a half consisted of passing showers.

4.2.1 Site and Stand Characteristics

Online soil information for the forest is unavailable, however, soil information for the area surrounding the stand shows that the dominant soil type is Tokanui soil. The soil is silty, firm, and stoneless. The stand is located on rolling hill country with low erosion susceptibility and land use capability (LUC) of 3e and 5c according to the NES-PF erosion susceptibility classification and fish spawning online tool. Based on the LUC the land is suitable for pastoral grazing and production forestry, with limiting factors of erodibility and climate (Lynn, et al., 2009). Ground conditions during the time study were saturated, with large rutting in areas of forwarder movement.

The production thinning operation was the first thinning operation in the stand, with a planted stocking of 1000 stems per hectare (sph), and an estimated 850 – 900 sph pre-thinning. The target production thin was down to 477 sph. Some areas of the stand have previously been pruned. There is poor genetics throughout the forest with large numbers of double leaders, and dead trees at the time of thinning. The stand has an estimated recoverable piece (tree) size of 0.5 – 0.7 m^3.

4.2.2 System Description

The Southland crew was made up of two members. One member is a full-time harvester operator, and the other member operates the forwarder and loader. The machines used in the crew include:

- Harvester – Hyundai Romex zero swing 14 tonne, with a Satco 214 harvester head (Figure 7),
- Forwarder – John Deere 1210E (Figure 8),
- Loader – Hitachi Z-Axis 225 (Figure 9).

Figure 7 *– Harvester: Hyundai Romex zero swing.*

Figure 8 *– Forwarder: John Deere 1210E.*

Figure 9 *– Loader: Hitachi Z Axis 225.*

The crew also has an old harvester and John Deere 810 forwarder. These machines are used when the Hyundai Romex and John Deere 1210E break down.

The harvester operator would create an entry/exit path into the stand at a right angle to the road. From here he creates a pathway for itself and the forwarder to follow that is perpendicular to the road. The operator goes through and selectively thins the stand. One of his thoughts whilst selectively thinning is how the forwarder can fit through the stand. As well as how the forwarder can turn around. It is all about creating an efficient path for himself as well as, for the forwarder to pass through.

The operator would typically fell, delimb, and buck a single stem before moving on to the next. After he felled a few trees he would sometimes need to restack some of the logs, this was covered in the processing cycle element. There were also a substantial number of double leaders. How the operator went about felling a double leader depended on how far up the tree the stem split into two. He would either rip the second stem off or fell the tree at the base before separating the two. This meant that it was variable in the way that he processed the double leader. Sometimes he would fell and process one side of the tree at a time, and sometimes he would fell both sides before processing both sides of the double leader. When he felled and processed one side of the stem first it was recorded as two separate fell and process elements, with it noted as a double leader on the first felling element. Where he felled both sides before processing both sides there was only a single fell and process element recorded, with it noted as a double leader.

The forwarder operator is in lag of the harvester operator by about 4 to 5 days. The operator works methodically through the stand typically collecting the oldest cut wood. Depending on the stock of grades at the skid and what the next loadout of wood was determined what grade of wood the operator collects from the stand.

The forwarder operator uses the loader to unload the forwarder rather than using the forwarder crane to unload the machine. This is because it is more efficient for him to use the loader to unload, it also creates neater log sorts and allows the operator to stretch his legs. This in turn keeps him fresher and lowers the chance of fatigue setting in from staying in the forwarder all day.

4.2.3 Time Study Elements

It was decided to keep the elements studied on the harvester as simple as possible, whilst still capturing as much information as possible. Therefore, it was decided to study the following elements on the harvester:

- Felling – Measured from the time the harvesting head grabbed a tree until the time the stem hit the ground.
- Processing – Measured from the time the stem touched the ground until the harvesting head grabbed the next tree or until the tracks started to move.
- Positioning – Measured from the time the tracks started to move until the harvester head grabbed a tree.
- Clearing –This element included the clearing of previously fallen dead trees, organising of processed logs, and ripping of dead stumps. The element time was measured from the time the harvester head grabbed the tree or log until another element was started.
- Delays – Measured from the time the harvester became stationary for more than a few seconds or the machine was switched off. Delays mostly consisted of the operator looking around, occasionally communicating with the forwarder operator, and refuelling.

Continuing to keep things simple whilst capturing as much information as possible on the forwarder it was decided to capture the following elements:

- Unloaded travel – Measured from the time the forwarders front wheels left a set point on the skid to the time the grapple started to move off the bunk.
- Loading – Measured from the time the grapple started to move to the time the grapple was stationary and placed over the logs in the bunk. Some positioning time was included in the loading element when the forwarder only moved a few metres to the next log stack.
- Positioning – Measured when there was a major forwarder movement to a new area of pick-up. The element time was ended when the grapple started to move again.
- Fully loaded travel – Measured from the time the grapple was stationary and place over the logs in the bunk until the forwarders front wheels passed a set point on the skid.
- Unloading – Measured from the time the forwarders front wheels passed a set point on the skid until the wheels passed that set point again after unloading.
- Delays – Measured from the time the forwarder became stationary for more than a few seconds or the machine was switched off. Delays consisted of maintenance on the backup forwarder, general skid work (QC and log marking), loading out of trucks, and laying corduroy on the skid.

4.2.4 Data Collection Method

Two data collection methods were used during the two and a half days of the survey. The first being a hand method – running stopwatch, with pencil and paper. The second was the use of an iPad, utilising the Workstudy+ app.

Both methods were used in data collection for the harvester and forwarder on separate days. This was done because the Workstudy+ app was a more consistent way of capturing the data. The Workstudy+ app is a more consistent method of capturing data because the time to press a button on the iPad was more consistent than looking at a stopwatch when elements changed quickly. The errors in time collection related to the stopwatch were greater with quick changes in elements compared to the iPad.

The use of two different methods of data collection for each machine required the two data sets to be manually combined. To make this easier, the data that was collected by hand was entered into excel in a similar format to that of the export from the Workstudy+ app. This allowed for easy amalgamation of the two data collection methods.

From here the data was analysed to get average element times for each of the elements. The average times could then be totalled for an average total cycle. For the harvester, this was the average time taken to fell a stem, for the forwarder this was the average time to complete a full cycle from skid to skid.

Delays were recorded as part of the time study, but it is unlikely this small sample size of delays accurately represents the crew's actual unproductive time. Therefore, an average time allowance was added to the data based on historical studies for machine utilisation. Typical utilisation rates are 65 – 75% (Spinell & Visser, 2009), making delays in the range of 25 – 35% of the time. Typical delays can be put into three categories mechanical, operator, and other (Spinelli & Visser, 2008). A delays allowance of 29% was chosen based on typical delay values (Spinelli & Visser, 2008).

Productivity values were calculated for the harvester and forwarder based on different variables with the delays allowance added to the typical cycle time.

4.3 Daily Operational Cost

A daily cost for each operation can be determined by inputting the information acquired from the industry questionnaire on machine use in each operation and the machines that were used during the time study into the LIRO costing model. 2019 INFORME costing data was also used in the costing model. Costing for each crew will vary even with some machine inputs the same for the crews. The cost will vary with hours worked and production per day. A breakdown of the cost consumptions used in the LIRO costing model is referenced in Appendix A.

5. RESULTS

5.1 Industry Questionnaire

From the industry questionnaires sent out, information for 8 different crews from 6 forest management companies in 6 regions was received. To keep the questionnaire anonymous and consistent throughout the analysis a crew number has been allocated to each of the crews. Although no analysis was conducted on a regional basis, the regions involved were Auckland, Bay of Plenty, Central North Island, Hawke's Bay, Otago, and Southland.

5.1.1 Production Thinning in the Last Decade

Over the last decade, all the production thinning crews have increased their production thinning operations in some form. One of the crews has increased production steadily over the last decade, whilst another has stayed consistent with a spike in production in the middle. Four of the crews started their production thinning operations in the last few years or have only had one operation in the last decade.

Two crews have taken the opportunity to production thin when there was an opportunity to production thin. The dependant variable in the decision to production thin was forest location to the mill or port and the market price. One of these crews will be increasing their production thinning operation in the next few years through Douglas-fir planted in the mid to late 90s.

5.1.2 Productivity and Hours Worked

Companies provided ranges of productivity values as well as target productivity values, (Figure 10) shows the average of the productivity values received for each of the crews, with the lowest and highest productivity being 60 tonnes/day and 185 tonnes/day respectively. The average productivity value across the crews was 125 tonnes/day.

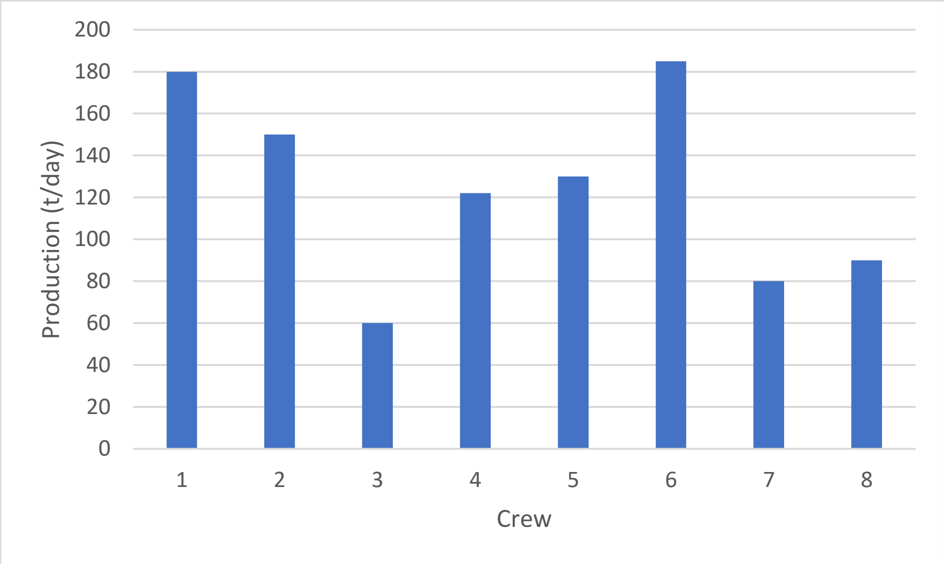

***Figure 10** – Typical Productivity Levels.*

Most of the crews worked 8-hour or 9-hour days except for one crew which worked between 8-hour and 12-hour days. Workday information from one of the crews was not received so the average hours worked of 9 hours was used for this crew. The longest day modelled in the analysis was 9 hours.

5.1.3 Extraction Distance

All crews surveyed used a forwarder for their extraction. However, the model and size of the forwarder varied, with the most common being the John Deere 1210 or 1510 being used in three of the six crews that responded with their forwarder model. All typical extraction distances were 400 metres and under. With the lowest typical distance at 120 metres. One of the crews were extracting out to 1000 metres at one point but suggested a maximum distance of 400 metres. The typical extraction distances averaged out to be 245 metres.

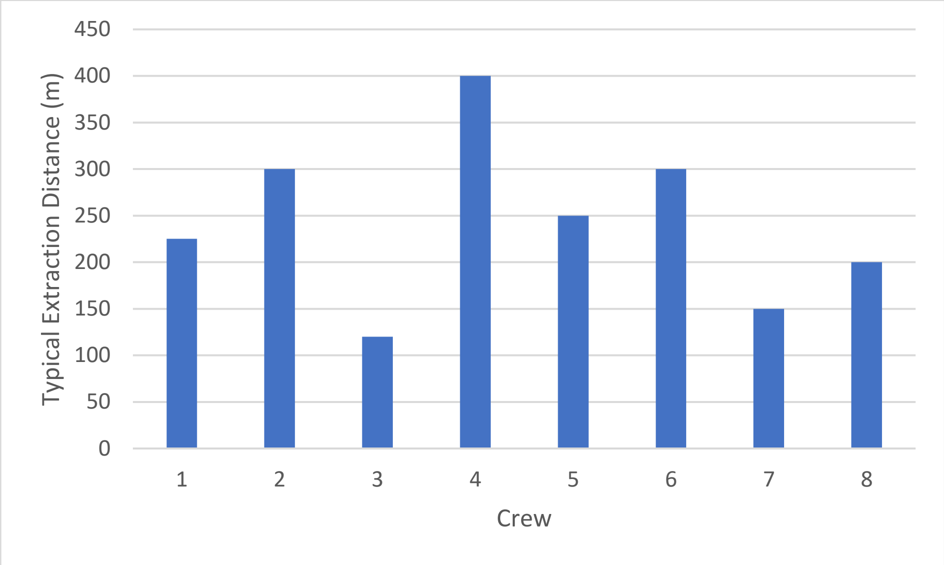

Figure 11 *– Typical Extraction Distance.*

5.1.4 Stocking

The stocking before production thinning in the stands of the crews ranged the most. Due to some stands having a thin to waste before the production thin, and some stands not being thinned before the production thinning. The age at which some of the stands were thinned also varied, the later the thin the lower the initial stocking. Initial stocking ranged from 650 to 1400 sph for Radiata pine and 1200 to 1500 sph for Douglas-fir.

Final stocking ranged from 425 to 525 sph, with an average of 475 sph for unpruned Radiata pine. Two crews gave final stockings for pruned Radiata pine stands that were equal to 330 sph and 388 sph. As for Douglas-fir, the final stocking information ranged from 600 to 700 sph.

5.1.5 Slope

The lowest given maximum slope was 10 degrees where the forwarder was limited by the soil. The maximum slope is dependent on the smoothness of the terrain, soils, and machine used. Another crew said that 17 degrees was the maximum, while most of the answers said that the maximum slope is 22 degrees. This is the maximum safe working slope of a tracked machine. Where there are small areas of greater slope it is still possible to work but it needs to be under the right conditions. This is where the soil is not loose and has a low moisture content.

5.1.6 Mill Distance

There were variable answers given when asked about the maximum distance to the mill. With some crews not providing a maximum distance or not knowing a maximum distance. This is due to the multiple variables that go into calculating a maximum distance to the mill. The maximum distance is dependent on the grades that are cut, current market conditions, and cartage cost.

Two crews gave suggestions that the maximum distance to the mill would be 125 and 130 kilometres respectively. Between four crews there were ranging answers of current distances to mills of 30 to 250 kilometres away from the respective forests. It should be noted that the distance of 250 kilometres can be achieved through an off-highway network resulting in lower cartage costs. The next highest current mill distance was 150 kilometres to the port. No information was received from one of the crews.

5.1.7 Minimum Recovery

Minimum recovery viability ranged between 60 and 100 m^3/ha with no answers from two of the crews. Two of the crews responded saying that cost is very responsive to volume recovered per hectare and that it is dependent on day cost. If the company wants to have a cash positive production thinning operation with a certain profit margin, the minimum recovery will be higher than an operation that can go cash negative.

One crew said that they have a minimum recovery if the production thinning operation is recognised as a harvesting operation but if the operation was recognised as a silvicultural operation then it could go under this minimum recovery. The reasoning for this was that silvicultural operations are not performed to make a profit at the time of occurrence, whereas harvesting operations are.

5.1.8 Log Grades

Most of the wood produced by the crews are Pulp grade, as expected. With around 10 – 20% of the rest of the wood either export Pulp grades, or low numbers of sawlogs. A summary of the grade mix from the survey is shown in Table 4.

***Table 4** – Summary of Crew Log Grades Produced.*

Crew	Grade Mix
1	Pulp 70 – 75% KIS 25 – 30%
2	Sawlog – 50% Firewood/chip – 50% (stand dependant)
3	S20 – 10% R10 – 76% KX – 14%
4	Some Post and Poles K, KX, and UA (block and age dependant)
5	Pulp – 80% Other – 20% (Some A grade in good stands)
6	Sawlog – 25% RR – 75%
7	Pulp – 100%
8	Export – 13% (KX) Pulp – 87%

5.1.9 Other Production Thinning Factors

The most common response for other production thinning factors was suitable terrain and slope. Contractor availability with experienced contractors is often crucial for a successful operation. Not only does inexperience result in the removal of crop trees but if the operator hits any crop trees this can damage the value of the final crop.

Where the stand has been left too long without a thinning it can increase the risk of performing a thin to waste operation. Production thinning is an alternative silvicultural operation that significantly reduces crew risk by placing them in machines. Alternative motives or interests from owners of the forest can result in encouragement of production thinning over thinning to waste. This may be from the owners having other business interests such as owning a local pulp mill and wanting consistent supply.

Some other factors include the market price for the wood, distance to market, stability of the market, and current cost of thinning to waste. A negative factor for production thinning is that there is a tendency to have higher final crop stockings in New Zealand, this leaves less of an opportunity to production thin down to a stocking that allows for a profit.

The first thing that can be done before establishment is buying favourable terrain. Following this, planting at a higher stocking to get the most out of the mid-rotation crop. Rows should be planted perpendicular to the road with increased spacing between rows and reduced spacing within the row.

For this to occur communication with planters and supervision over planters must occur. Planters have their own way of planting, so it is sometimes difficult to control how the site is planted. Cooperation between the forest manager and planters will be key to getting the most out of the trees.

Orientation of windrows should also be adjusted for suitable machine access. Other factors include seedling genetics, regen control, infrastructure design and destination market.

5.2 Time Study

5.2.1 Harvesting

A harvester was observed for 512 minutes over two study periods during a time study in Southland. There were five elements observed during the study periods including, felling, processing, positioning, clearing, and delays. Processing was the largest portion of operator time at 46%, followed by felling at 22% during the study period. A percentage breakdown for the harvester operator time is shown in Figure 12.

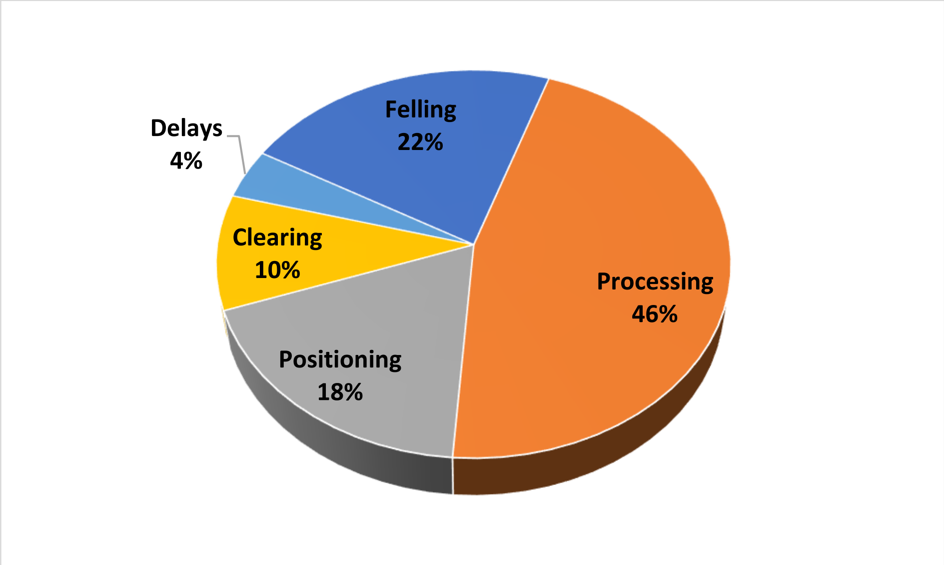

Figure 12 *– Harvesting Element Breakdown as a Percentage of Total Study Time.*

5.2.1.1 Felling

The felling element had an observed study time of 22%. Each felling element was the felling of a single tree including double leaders, whether the stem was dead or alive. Over the study period, 174 stems were felled, with an average time to fell a stem of 0.6 decimal minutes, as seen in Table 5.

Table 5 *– Harvesting Element Breakdown for Felling.*

	Total Time (min)	Tree Count	Time/Tree (min)
Fell – Total	112.0	174	0.6
Fell – Live	99.8	153	0.7
Fell – Dead	12.2	21	0.6

5.2.1.2 Processing

The processing element was observed 46% of the study time, this equated to 236 minutes of the study. During this time 157 trees were processed, with an average process time of 1.5 decimal minutes as seen in Table 6. From the 157 processed stems, 523 logs were cut for an average of 3.4 logs per tree.

Table 6 *– Harvesting Element Breakdown for Processing.*

	Total Time (min)	Tree Count	Time/Tree (min)
Process – Total	235.6	157	1.5
Process – Live	227.0	148	1.5
Process – Dead	8.7	9	1.0

The time taken to process a tree and the number of logs produced was graphed in Figure 13 to better understand the relationship between the number of logs processed and the time to process them. A linear line of best fit was taken with an equation of $Time = 0.25 + 0.37 * No. of\ Logs$, and a variance ($R^2$) of 0.42.

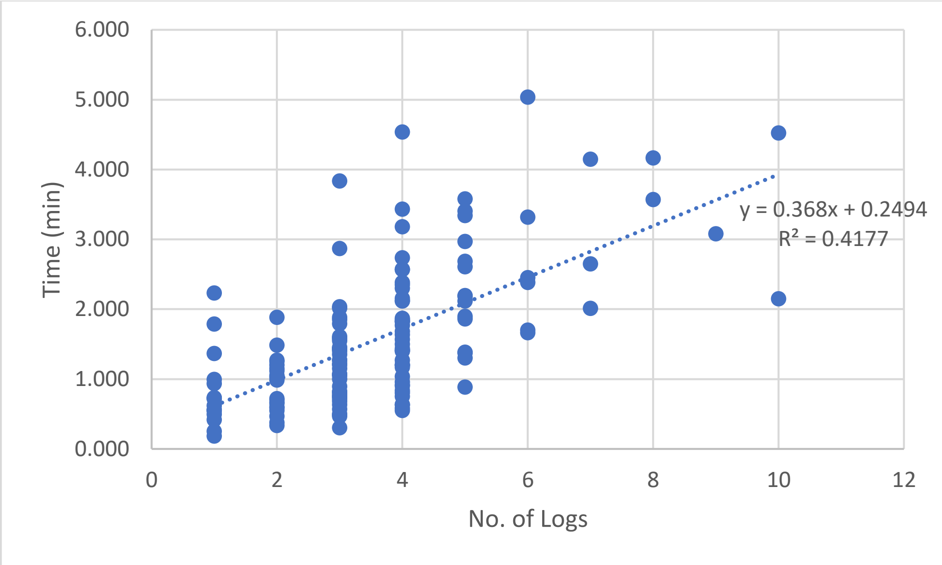

Figure 13 *– Harvesting Processing Time Relationship to Number of Logs Processed.*

5.2.1.3 Positioning, Clearing, and Delays

Positioning, clearing, and delays had the fewest observation time during the harvester study. Table 7 summarises the breakdown for these three elements.

Table 7 *– Harvesting Element Breakdown for Positioning, Clearing, and Delays.*

	Percentage of Time	Total Time (min)	Occurrence	Time/Occurrence (min)
Positioning	18%	94.3	131	0.7
Clearing	10%	49.2	60	0.8
Delays	4%	21.1	5	4.2

5.2.1.4 Harvesting Productivity

A productivity value was calculated for the harvester during the time study using three different stem piece size. Two of the productivity estimates were done using the estimated stem piece size by the forest managers. The third productivity estimate was based on the average stem piece size during the time study.

An average log piece size of 0.227 tonnes/log was calculated using the number of logs loaded onto the forwarder divided by an assumed 12-tonne payload per cycle. This estimate of a 12-tonne payload per cycle was used instead of measuring the actual payload per cycle. A breakdown of each forwarder cycle with the number of logs and the equivalent piece size is shown in Table 8.

Table 8 – Estimated Piece Size of Logs in each Extraction Cycle.

Cycle	Number of logs	Piece size (tonnes/log)
1	55	0.22
2	47	0.26
3	54	0.22
4	49	0.25
5	65	0.19
7	60	0.20
8	39	0.31
9	57	0.21
10	61	0.20
11	50	0.24
12	58	0.21
13	51	0.24
14	50	0.24
15	57	0.21
Average	**54**	**0.23**

Using the average number of logs processed by the harvester per stem (3.4 logs) and the average piece size per log (0.227 tonnes/log) an average stem size of 0.775 tonnes was calculated. Both stem piece sizes given by the forest managers are less than the estimated average stem size of 0.775 tonnes.

The productivity values calculated for the harvester in the time study are shown in Table 9. The harvester productivity values increase with tree piece size from 62.7 tonnes/day to 97.1 tonnes/day.

Table 9 – Harvesting Daily Production Estimates.

		Units
Fell – Live Stem	0.6	min/tree
Fell – Dead Stem	0.07	min/tree
Process – Live Stem	1.4	min/tree
Process – Dead Stem	0.06	min/tree
Position	0.5	min/tree
Clear	0.3	min/tree
Total Cycle Time/Stem	**3.0**	**min/tree**
Total cycle time plus delays allowance (+29%)	3.8	min/tree
Cycles/day – (Day = 480 min (8 hrs))	125	trees/day
Productivity (.5 tonnes/tree)	**62.7**	**tonnes/day**
Productivity (.7 tonnes/tree)	**87.7**	**tonnes/day**
Productivity (.775 tonnes/tree)	**97.1**	**tonnes/day**

5.2.2 Extraction

A 12-tonne payload forwarder was studied for 735 minutes over three study periods, with 15 cycles measured. The average cycle time of the forwarder was 49 minutes. The percentage of total study time for the six elements measured is shown in Figure 14. Loading was observed as the largest portion of operator time (39%), followed by unloading at 24% of the study period time.

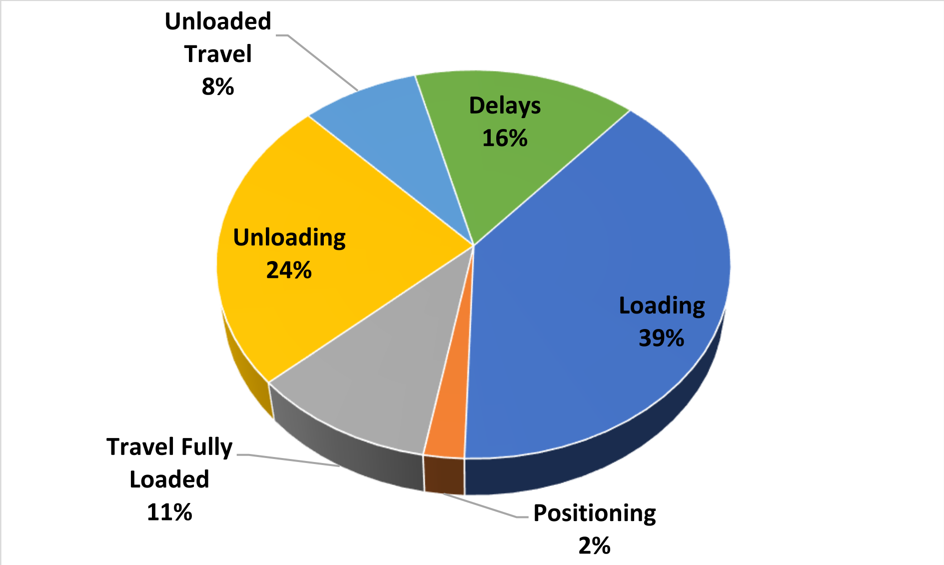

Figure 14 *– Extraction Element Breakdown as a Percentage of Total Study Time.*

5.2.2.1 Unloaded Travel

The unloaded travel element was observed for 59.7 decimal minutes, accounting for 8% of the time. During the time study, 16 unloaded travel times with the travel distances were recorded and are shown in Figure 15. The equation showing the relationship between unloaded travel time and distance travelled is $Time = 1.10 + 0.013 * Distance$, with an R^2 value of 0.87. This equation from Figure 15 is used in the calculation of forwarder productivity, referenced in Table 10.

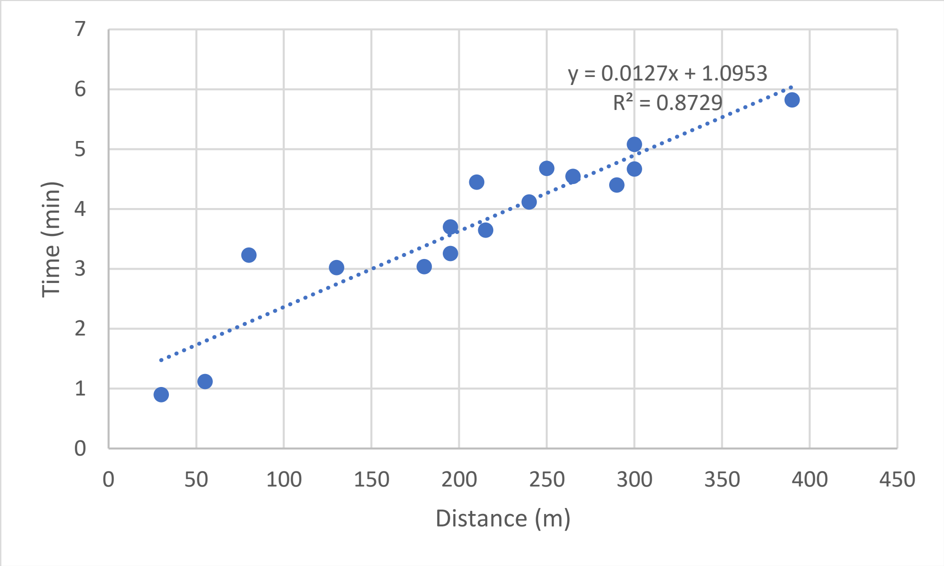

***Figure 15** – Extraction Unloaded Travel Time in Relation to Distance Travelled.*

5.2.2.2 Loading

Forwarder loading had the highest extraction time at 39% of the study time. During the loading time of 287.8 decimal minutes, 792 logs were loaded over 16 element observations. Figure 16 was produced to gain an understanding of how loading times may vary with the number of logs loaded. The graph has a linear trendline with an equation of $Time = 1.54 + 0.33 * No. of\ Logs$, and an R^2 value of 0.86.

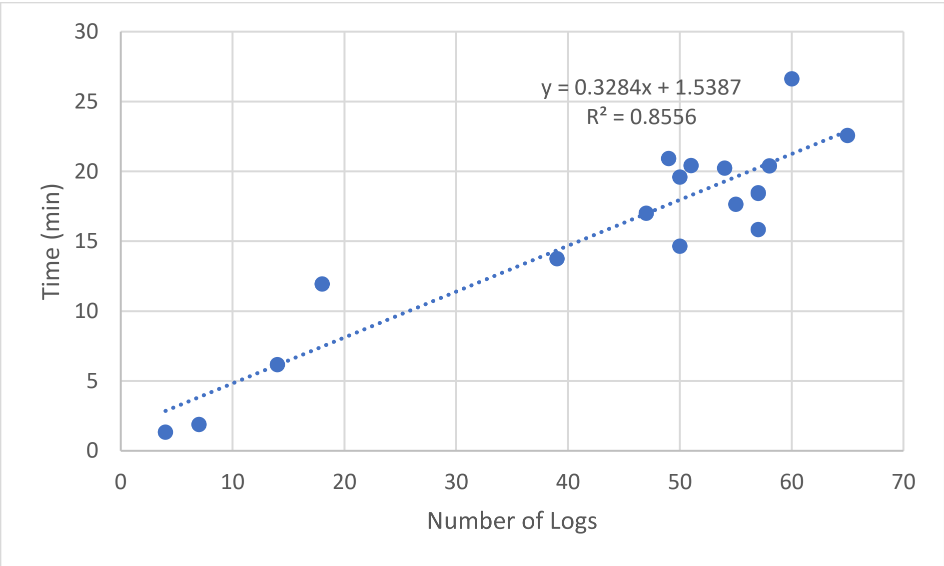

***Figure 16** – Extraction Loading Time in Relation to Number of Logs Loaded.*

5.2.2.3 Fully Loaded Travel

The forwarder element for travel fully loaded had a total time of 77.8 decimal minutes over 15 time and distance measurements. The equation showing the relationship between fully loaded travel time and distance is $Time = 0.9 + 0.022 * Distance$, with an R^2 value equal to 0.72. This equation from Figure 17 is also used in the calculation of forwarder productivity, referenced in Table 10.

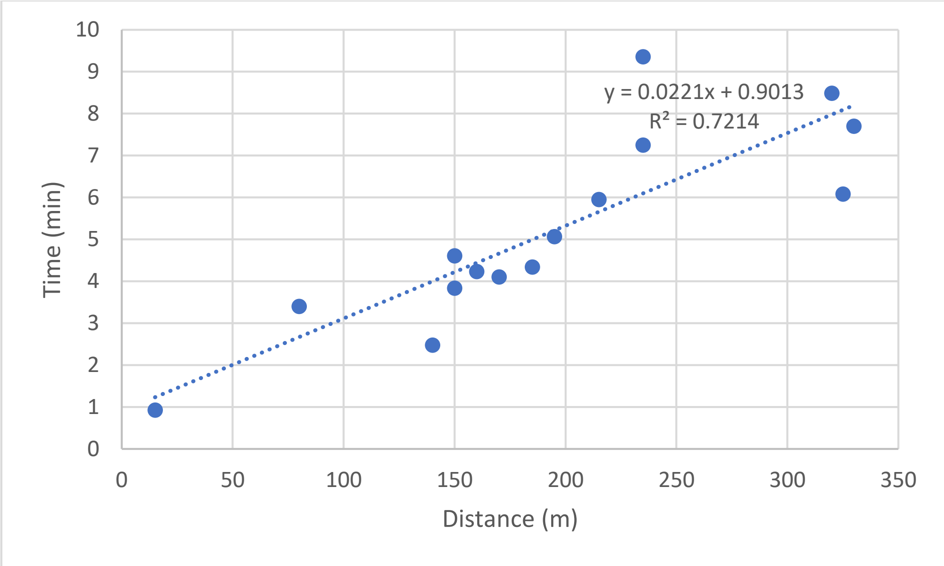

***Figure 17** – Extraction Travel Fully Loaded Time in Relation to Distance Travelled.*

5.2.2.4 Unloading

Forwarder unloading had the second highest extraction element time of 179.5 decimal seconds. In that time 753 logs were unloaded over 15 full cycles. Figure 18 represents the unloading time in relation to the number of logs unloaded. The equation representing the relationship between unloading time and the number of logs unloaded is $Time = -1.24 + 0.26 * No. of\ Logs$, with an R^2 value of 0.11.

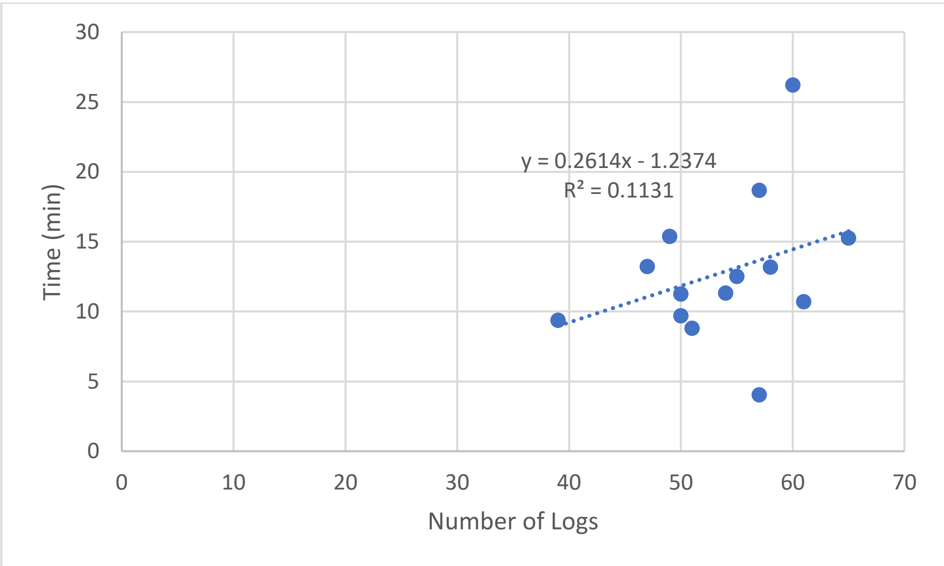

***Figure 18** – Extraction Unloading Time in Relation to Number of Logs Unloaded.*

5.2.2.5 Positioning, and Delays

Positioning and delays were observed for 17.2 and 113.6 decimal minutes, respectively over the course of the extraction time study. Some positioning was included in the loading element of the study where the forwarder only moved a few metres to the next stack of logs. This resulted in a low positioning time for the cycles and an overall observation time of 2%. An average positioning time of 1.7 decimal minutes per cycle was determined.

Delays were much higher in the forwarder observations than in the harvester. The forwarder operator was required to do more than extracting the logs from the stand resulting in a much higher delays time observed. Some of the delays included maintenance on the backup forwarder, general skid work (QC and log marking), loading out of trucks, and laying corduroy on the skid.

5.2.2.6 Extraction Productivity

An extraction productivity value for the forwarder was calculated using the variables of log piece size and extraction distance. Three log piece sizes were used in the productivity calculations. The log piece sizes were based on the stem piece sizes used in the harvester productivity calculations. Using the average number of logs processed per stem (3.4 logs) and the three stem piece size values (0.5, 0.7, and 0.775 tonnes/stem) three log piece size values were calculated and rounded to 0.150, 0.200, and 0.225 tonnes/log for use in the daily productivity estimates for extraction.

Extraction distances of 175, 200, and 250 metres were used as the second variable in the forwarder productivity calculations. The effects of piece size and extraction distance on extraction productivity is seen in Table 10.

***Table 10** – Extraction Daily Productivity Estimates*

	175 m	**200 m**	**250 m**	**Units**
Travel unloaded (Time = 1.1+0.013*distance)	3.3	3.6	4.3	min/cycle
Position	1.7	1.7	1.7	min/cycle
Loading	19.2	19.2	19.2	min/cycle
Travel loaded (Time = 0.9+0.022*distance)	4.8	5.3	6.4	min/cycle
Unloading	12.8	12.8	12.8	min/cycle
Total cycle time	**41.8**	**42.7**	**44.4**	**min/cycle**
Cycle time plus delays allowance (+29%)	53.9	55.1	57.3	min/cycle
Cycles/day – (Day = 480min (8 hrs))	8.9	8.7	8.4	cycles/day
Productivity (.150 tonnes/log)	**70.5**	**69.1**	**66.3**	**tonnes/day**
Productivity (.200 tonnes/log)	**94.0**	**92.1**	**88.5**	**tonnes/day**
Productivity (.225 tonnes/log)	**105.7**	**103.6**	**99.5**	**tonnes/day**

A visual representation of the tabulated forwarder productivity values in Table 10 is shown in Figure 19. This shows that as the extraction distance increases, productivity decreases. As the piece size per log increases the productivity increases, both are to be as expected.

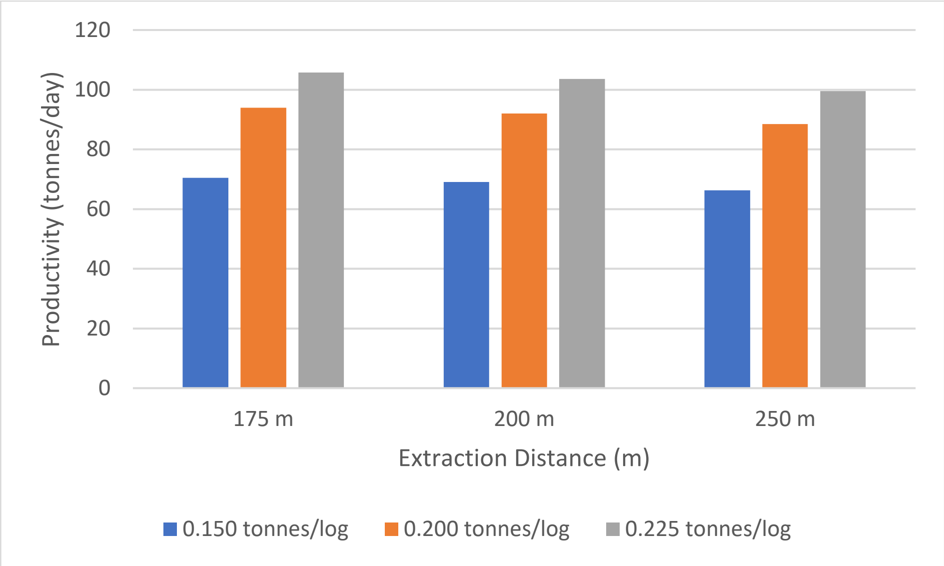

Figure 19 *– Extraction Daily Productivity Estimates.*

5.3 Daily Operational Cost

Based on the information supplied by the crews and the assumptions covered in the method and Appendix A, a daily operational cost was calculated using the LIRO costing model. Figure 20 shows the estimated total daily cost for each crew including an 8% profit margin. The highest estimated daily cost was $5,150/day, compared to the lowest daily cost of $2,860/day, and an average daily cost of $4,210/day.

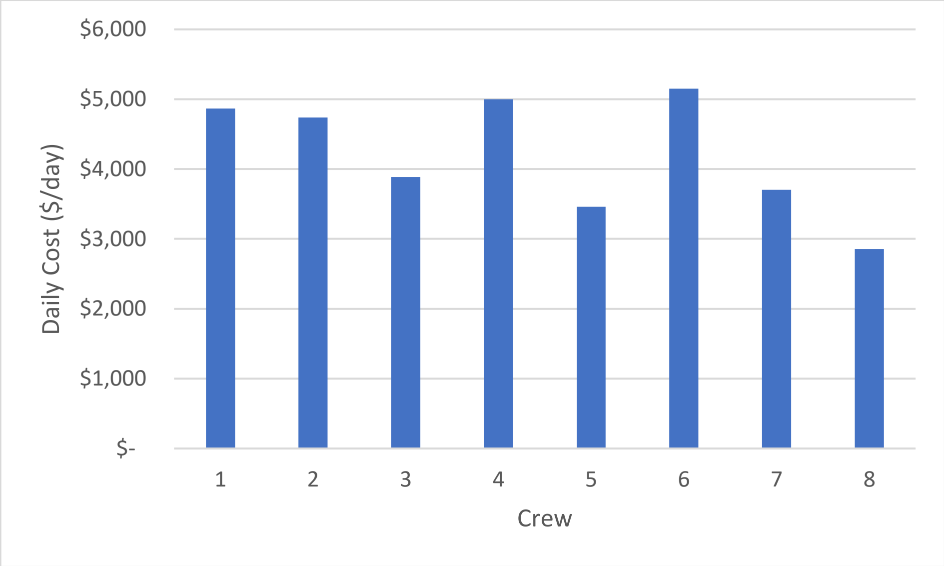

***Figure 20** – Estimated Total Daily Crew Cost.*

Using the provided production values per day for each crew an estimated harvesting rate ($/t) was predicted for each of the crew. This was then graphed in Figure 21. The highest estimated harvesting rate was $64.50/t, compared to the lowest rate of $27.00/t, and the average harvesting rate of $37.00/t.

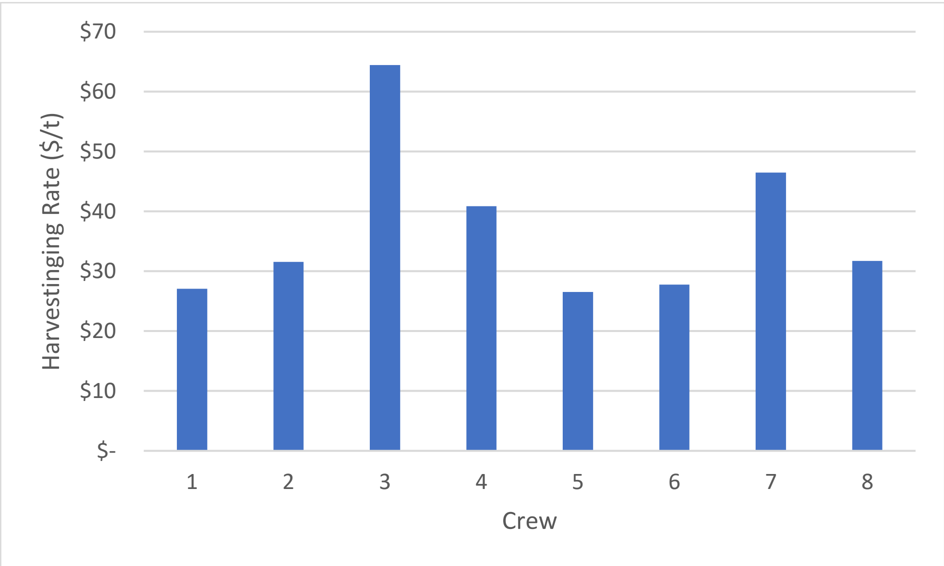

***Figure 21** – Estimated Crew Harvesting Rates ($/t).*

The values used to create Figure 20 and Figure 21 are shown in Table 11.

***Table 11** – Estimated Crew Harvesting Day Costs and Harvesting Rates.*

Crew	Total Day Cost	Tonnes per day	Rate per tonne $/t
1	$ 4,869	180	$ 27.05
2	$ 4,738	150	$ 31.56
3	$ 3,886	60	$ 64.44
4	$ 4,999	122	$ 40.85
5	$ 3,461	130	$ 26.56
6	$ 5,149	185	$ 27.79
7	$ 3,702	80	$ 46.49
8	$ 2,856	90	$ 31.73

5.3.1 Daily Operational Cost Correction

To get an understanding of how accurate the costs in Table 11 were, the crews were contacted again with their estimated daily cost and harvesting rates. The crews were then asked if they could comment on how accurate the values provided were, or even if the value was high or low. Of the 8 crews, 5 crews responded. Some of the feedback gave ballpark accuracies of how the estimate compared, and some crews gave actual figures.

Of the responses, two crews said the harvesting rate ($/t) in Table 11 was less than their actual harvesting rate. One crew said that the harvesting rate in Table 11 was too high compared to their actual harvesting rate, and the other two crews said that it was in the ballpark of their harvesting rate value.

The crew that identified their harvesting rate in Table 11 was too high suggested some of the reasons as to why the value predicted for their crew by the LIRO costing model was overpredicted. The first reason was that most of their machinery is old and has fully depreciated so it has paid itself off. However, a machine replacement cost is still being provisioned into their rate to cover a future machine replacement. Productivity was lower than it could be because the crew was asked to cut to length post material produced by the mill. The crew is also allowed to operate at a loss because of external reasons.

It was identified that the machinery values used in the LIRO costing model most likely gave the highest variance in daily cost, followed by wages. It was difficult to gather accurate current machine prices for each of the machines used in the crews. The wages value is also likely to be highly variable between each of the crews. The wages value used in the LIRO costing model is based on 2019 INFORME data, and the average forestry wage has increased since then.

6. DISCUSSION

6.1 Industry Questionnaire

One of the issues that production thinning faces is infrastructure costs. Production thinning can be either a silvicultural operation or a harvesting operation. As a harvesting operation production thinning faces the issues of infrastructure costs. Having to place roads to skids and punching in skids can be expensive depending on where you are in New Zealand. And with production thinning the profitability is low so keeping infrastructure costs low is key to being profitable. Placing fewer skids means longer extraction distances. The dilemma of building another skid and increasing extraction distance needs to be considered and modelled.

Maclaren & Knowles (2005) found that a volume of 75 to 125 m^3/ha is needed to cover the cost of production thinning. Similar minimum recovery values were suggested through the industry questionnaire. Minimum recovery values of 60 to 100 m^3/ha align with initial research and suggest that the minimum recovery needed for production thinning may be declining. If the minimum recovery needed is declining as technology and productivity increases, then the profit margin on production thinning increases. In turn, making production thinning more viable in New Zealand.

Production thinning is a harvesting operation but is also considered a silvicultural regime. If it is treated as a silvicultural regime it can then make a loss if the operation is not effective enough to make a profit. Production thinning can still be a viable thinning option when it does not make a profit if it is more beneficial and cost effective than thinning to waste.

One of the crew responses from the questionnaire said that it is not possible to achieve a final crop stocking above 400 sph. If it is any higher the production thinning operation will not make a profit. A significant variable involved in this is the market at the time of harvest for both the thinning operation and final harvest. If the log price is high at final harvest this will compensate for having a lower final crop stocking. However, if the log price is lower at the time of final harvest then a higher crop stocking will be required to get the most out of the more profitable final crop trees. Revenue is increased, and transport costs decreased with a forest located near the chosen market location for the production thinning operation. This results in the ability to have a higher final crop stocking.

6.2 Time Study

Performing a time study gave a point of reference to the productivity rates given in the industry questionnaire. It would have been beneficial to complete multiple time studies, but this was not possible due to outside factors and time constraints. Having multiple time studies would have given a better basis for productivity levels that could have been compared more accurately to the typical production levels that were given in the industry questionnaire.

To compare the harvesting productivity data from the time study to the literature review some assumptions were needed. The data in the literature review was mostly in the units of m^3/PMH, whereas the data from the time study is in tonnes/day. It was assumed that m^3 to tonnes was 1:1 and that there are 6.5 PMH in a day.

The average productivity from the literature review came out to be 192 tonnes/day. This is between two and three times larger than the time study data depending on the piece size used to calculate productivity for the time study. Two of the literature review study results were in the range of the time study data. With productivity values of 73.5 tonnes/day (11.3 m^3/PMH) (Eriksson & Lindroos, 2014), and 94.3 tonnes/day (14.5 m^3/PMH) (Acuna, Strandgard, Wiedemann, & Mitchell, 2017).

One of the possibilities for the productivity in the time study being so low in comparison to most of the literature review data is because of the lack of previous thinning. The stand was planted to 1000 sph but had an estimated stocking of 850 – 900 sph at the time of production thinning. This meant that the harvest operator spent a lot of time removing dead stems and clearing fallen trees. Clearing resulted in 10% of the harvester's time. Less mortality before the production thin may have resulted in higher productivity of the harvester.

The same assumptions from the harvesting productivity of a 1:1 relationship between m^3 and tonnes and 6.5 PMH in a day were used for comparing the extraction productivity. Based on these assumptions the average productivity from the literature review was 134 tonnes/day. However, two of the six machines in the literature review are skidders. The two skidder values were the highest of the literature review. The forwarder values of the literature review come to an average of 94 tonnes/day.

The time study extraction was much more consistent with that of the literature review. The range of values 66 – 94 tonnes/day (10.2 – 14.5 m^3/PMH) (Kellogg & Bettinger, 1994) are consistent with the range of values for the time study when the piece size is 0.15 & 0.20 tonnes/log, and an extraction distance are 175 to 200 metres. The literature review value of 84 tonnes/day (12.9 m^3/PMH) (Eriksson & Lindroos, 2014) is in the middle of all the time study estimated productivity values.

Assuming that the typical production per day given in the industry questionnaire is equal to the production of the extraction machine in the crew then the production can be compared to the extraction productivity in the time study. The average production per day from the industry questionnaire is equal to 120 tonnes/day. This is roughly 30 tonnes/day greater than the mid-range value in the time study. The time study production is in the middle of the industry questionnaire production results.

Three of the four crews that have a production higher than that of the time study use forwarders that are considered large, such as the John Deere 1510. Of the mid-range forwarder production values (such as the John Deere 1210) the time study results are the highest. Results from the short time study show that a 2-man crew with a mid-range forwarder can compete with larger production thinning crews.

During the time study, the loading element was on average longer than the unloading element. This will be because the operator needs to move around whilst loading the forwarder as some positioning was included in the loading element, whilst unloading the forwarder is in one place. The other reason for the shorter unloading element was due to the forwarder operator using a separate loader machine to unload the forwarder. The loader has a larger grapple and can unload the forwarder much faster than the smaller grapple on the forwarder.

6.3 Daily Operational Cost

The LIRO costing model was able to accurately predict the harvesting rate ($/t) of two of the crews within a ballpark figure. It was difficult to determine the actual accuracy of the LIRO costing model as costing information is sensitive and most crews did not want to confirm what their harvesting rates were. Two crews gave their actual harvesting rates, these rates were within $10/t of that estimated using the LIRO costing model. This difference of within $10/t is still quite high and further development of the costing model is required.

Using an actual cost sheet for one of the crews it was determined that the biggest difference between the LIRO costing model and crew cost sheet was machine price. For this research project, it was decided to use the same machine prices from 2019 INFORME data for each of the crews based on the power (kW) size of the machine. This meant that most machine prices were consistent through each of the crews. This method was used instead of contacting machine suppliers for actual current machine prices because of time constraints during this research project. Most of the pricing information used in the LIRO costing model was 2 years old (2019 data). Some of the pricing information will now be outdated. It was identified that the machine pricing, wages, and diesel pricing would be most affected by the old pricing information. Using updated pricing information has the potential to make the LIRO costing model outputs more in line with actual crew costs.

Hiesl, Benjamin & Roth (2015) determined a cost range of USD $20.56/tonne to $50.66/tonne, with an average of $33.46/tonne for a harvester and forwarder operation that included trucking costs. Based on September 18, 2021 USD to NZD conversion rate of USD$1/NZD$1.42 the costs of Hiesl, Benjamin & Roth (2015) convert to NZD $29.20/tonne to $71.94/tonne, with an average of $47.51/tonne. Baek (2018) determined a stump to truck cost of USD $17.10/tonne and $22.80/tonne for two study areas. Note the cost calculations in this study did not include move in/out cost, overhead, and profit-and-risk allowance. The costs from Baek (2018) converted to NZD $24.28/tonne and $32.38/tonne.

After currency converting to NZD the studies of Hiesl, Benjamin & Roth (2015) and Baek (2018) showed that they were in similar ranges determined in this research project. Although the studies of Hiesl, Benjamin & Roth (2015) and Baek (2018) use slightly different cost assumptions to those used in this study the harvesting rates determined for New Zealand production thinning crews are still comparable. This further shows the viability of production thinning in New Zealand.

6.4 Further Research

This research project has shown the viability of production thinning in New Zealand. It has also confirmed the lack of available information in New Zealand on the productivity and cost of production thinning machines. There is the opportunity for further research into either of these information areas. Research into the productivity of harvesting and extraction across New Zealand with a wider data set of information to form productivity equations would be the next steppingstone. Using a wider data set to form harvesting productivity equations based on DBH, logs produced per tree, and distance between trees. As well as, forming extraction productivity equations based on extraction distance, slope, and piece size.

Another area of further research could be into the current crew costs including machine costs, and wages for each of the crews. This could then be used in the LIRO costing model to potentially predict crew harvesting rates more accurately. The LIRO costing model could then be used as a silvicultural analysis to determine the viability of production thinning over waste thinning.

Alongside this, log pricing, cartage costs and infrastructure costs could be surveyed to get an overall picture of the economic revenue/cost of production thinning. This could then be compared to the cost of thinning to waste, how it varies with stocking/stand characteristics, and the availability of thinning to waste crews compared to production thinning crews.

7. CONCLUSION

Production thinning is a common form of silviculture overseas. It has often been overlooked and not considered in New Zealand because it is not seen as economically viable. The practice of production thinning has not been viewed as economically viable for many reasons including stand terrain, distance to market, available machinery, and experienced crew. The purpose of this project was to determine the viability of production thinning in New Zealand. This was achieved through evaluating the productivity of production thinning crews, exploring the effects on productivity of production thinning, and determining a daily operational cost. Results were achieved by sending a questionnaire to the industry, as well as conducting a time study on a production thinning.

Results for the industry questionnaire were received from 8 different crews (6 companies), including the crew that the time study was conducted on. Typical productivity values given were between 60 and 185 tonnes/day, with an average of 125 tonnes/day. The minimum recovery ranged from 60 to 100 m^3/ha. This minimum recovery value is largely dependent on the day cost. A response also suggested that if the production thinning operation is recognised as a silvicultural regime then the minimum recovery can be much lower. Rather than breaking even the production thinning operation must only account for costs so that it is cheaper than an equivalent thin to waste.

Of the crews that were surveyed one crew has increased production in the last decade, one crew has had a consistent production with a spike in the middle. The other crews are either on their first operation or only started production thinning in the last few years. The main factors affecting the productivity of production thinning in the responses was suitable terrain and slope. Alongside this was contractor availability and experience. Leading on from this, buying suitable land, planning infrastructure, and guiding planters before and during establishment were the most common responses to increasing productivity of production thinning based on establishment techniques.

Harvesting productivity values for the time study equalled 63, 88, and 97 tonnes/day for tree piece sizes of 0.5, 0.7, and 0.775 tonnes/tree, respectively. The results of harvesting productivity were low compared to the literature review values. The low harvesting productivity values were probably due to the high stocking of the stand, with large numbers of dead trees.

Extraction productivity values for the forwarder in the time study ranged between 66 and 106 tonnes/day based on three different log piece sizes, and three different extraction distances. The time study forwarder extraction productivity values were more comparable than the harvesting values to that in the literature review.

Daily operational costs of the surveyed crews ranged between $2,860/day and $5,150/day, with an average of $4,210/day. Based on daily productivity values the estimated harvesting rates ranged between $27.00/t and $64.40/t, with an average harvesting rate of $37.00/t. The harvesting rates of this study were comparable to similar studies by Hiesl, Benjamin & Roth (2015) and Baek (2018). These studies determined harvesting rates of NZD $29.20/tonne to $71.94/tonne, and $24.28/tonne and $32.38/tonne, respectively.

This research project into the viability of production thinning was successful because it showed that production thinning can be successful in New Zealand. Minimum recovery yields (m^3/ha) from the industry questionnaire were lower than those found in Maclaren & Knowles (2005) during initial research. This suggests that there could be a larger profit margin for production thinning in New Zealand in the future. Production thinning can be viable where the terrain of the stand is suitable and the distance to market is low. Further research into productivity on specific slopes, and transport distances would give forest owners specific details as to whether their forest would be suitable for an economically viable production thinning operation.

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10. APPENDICES

10.1 Appendix A – Cost Model Assumptions

There were a variety of cost assumptions used as inputs for the LIRO costing model. The main assumption made is for the fuel usage value. It represents the fuel consumption rate of a machine based on the number of litres used per kilowatt-hour (L/kWhr). Therefore, the fuel usage value changes with each machine surveyed because of the variable fuel consumption, power of the machine, and the number of hours the machine is used. A different fuel consumption value was developed for harvesters, forwarders, and loaders in the LIRO costing model based on research and fuel consumption given by the Southland time study. Researched fuel consumption values for the different machines are tabulated in Table 12.

***Table 12** – Fuel Consumption Values for Production Thinning Machines.*

Research Paper	Harvester (L/kWhr)	Forwarder (L/kWhr)	Loader (L/kWhr)
(Oyier, 2015)	0.24	–	0.38
(Holzleitner, Stampfer, & Visser, 2011)	Avg. – 0.095 0.077 – 0.119	Avg. 0.098 0.011 – 0.146	–
(Fulvio, et al., 2017)	0.15 0.1 (Wheeled Harvester)	–	–

Information gathered from the Southland time study crew showed that on average they used 60 L of fuel for the harvester and loader daily, and 80 L of fuel for the forwarder daily. Based on a diesel fuel cost of $1.15 per litre in the LIRO costing model, and the power (kW) of the machines we know what the typical fuel cost per day for each machine is. This combined with the fuel usage values from Table 12 helped to determine the fuel usage values for each machine used in the LIRO costing model. The fuel usage values used in the LIRO costing model are shown in Table 13.

***Table 13** – Fuel Usage Values used in the LIRO Costing Model.*

	Fuel Usage Value (L/kWhr)
Harvester	0.115
Wheeled Harvester	0.100
Forwarder	0.103
Loader	0.170

The assumption for the number of workdays in the year is 226. The assumption starts with 260 total paid days for the 5 working days in 52 weeks of the year. Five days are added for occasional Saturday work. Annual holidays, statutory holidays, wet days, and sick leave are then taken off to give 226 workdays. The working for this is referenced in Table 14.

***Table 14** – Workdays per year.*

Total paid days	260
Saturdays added	5
	265
Less:	
Annual holidays	20
Statutory holidays	11
Wet days	3
Sick leave	5
Total Workdays Per Year	**226**

Other cost variables used in the LIRO costing model are as follows in Table 15.

***Table 15** – Cost Variables Used in the LIRO Costing Model.*

Loan Interest Rate	7%
Owner's Interest Rate	5%
Proportion of ACI as loan	75%
Proportion of ACI as owners' equity	25%
Insurance	3%
Diesel Price	$1.15
Petrol Price	$1.67
Oil as a % of Fuel	20%
RUC/1,000km	$59.14
Resale value (as % of cost)	25%
Hours to be owned	10,000
R + M as a % of depreciation	80%
ACC Levy	$3.38
Kiwi Saver	3%
Operating Cost Per Workday	$132.71
Overhead Cost Per Workday	$96.61
Profit	8%

The tyre and track life/price used in the LIRO cost model are shown in Table 16.

***Table 16** – Tyre and Track Life/Price.*

	Life (hours)	**Price ($)**
Tyre	15,000	$45,000
Track	6,000	$24,000