Battery-powered Chainsaw Productivity in New Zealand Thin-to-Waste Operations

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Executive Summary

Our society is moving towards a lower carbon future and battery-powered equipment is becoming more powerful, energy dense and commonplace, especially in areas with convenient electricity access. This gives motivation to many industries including plantation forestry in New Zealand to transition towards electrified equipment and move away from a reliance on fossil fuels. This study's objective is to investigate how the productivity of battery-powered chainsaws differs from the petrol-powered chainsaws currently used in commercial thin-to-waste operations in New Zealand pine plantations.

The significance of switching to battery-powered comes not only through reducing reliance on fossil fuels, but the proven ergonomic and health benefits. Multiple studies have shown that the noise level and vibrations caused by the battery-powered chainsaws are significantly less than from traditional petrol-powered chainsaws (Colantoni, et al., 2016) (Huber, et al., 2021) (Neri F. , et al., 2023) (MacDonald, Harvey, & Visser, 2023). Having no exhaust emissions has been shown to also be a positive aspect of battery-powered chainsaw usage (Dimou, Kantartzis, Malesios, & Kasampalis, 2019). However there have been far fewer studies looking at the productivity of electric chainsaws, especially in thinning operations, and other than the author's previous study (MacDonald, Harvey, & Visser, 2023) which assessed the productivity of three thinning crews, no further research has been published on thin to waste productivity.

To investigate how battery-powered chainsaws compare to their petrol-powered alternative, this study set up an in-forest trial where operators were observed felling with times for each activity broken down and analysed for both types of chainsaws, (petrol being (Stihl MS 462) and battery (Stihl MSA 220c)). Their trees per hour rate was also recorded to further add to the data collected in the author's last study. A controlled cutting test was conducted to further understand the differences in how the chainsaws cut, and which factors affect their cutting rate.

The results show that the petrol-powered chainsaws currently used in thin to waste operations in New Zealand are currently 1.8x more productive by the number of trees per hour felled, and they are 2.3x faster at felling a tree on average (excluding time between trees) than the battery-powered chainsaw tested. However, when the cutting rate was analysed using a measure of cm^2/s per kW of power output the battery-powered chainsaw proved to be very similar in rate in both the controlled test and in the forest. This shows that it is likely a battery-powered chainsaw with equal power to the commonly used petrol-powered chainsaws would likely perform just as well. The operators did not experience many delays when using the petrol-powered chainsaws, becoming jammed (chain stopped mid-cut) only twice in 62 felling observations. The battery-powered chainsaw experienced more delays, totalling 15 due to the chainsaw (either becoming jammed or the battery not sending power to the chainsaw) in 66 felling observations. However, when the delay times are normalised by averaging the time over all trees neither chainsaw caused a large proportion of delays (when compared with felling times), with 6% of felling time for electric and 1% of time for petrol. Delays were noted to come from larger trees for the battery-powered chainsaw.

The battery run times measured in this study combined with measurements from the author's previous study show that when used in a waste thinning operation they last on average 34 minutes. This would require an operator to carry nine batteries totalling 16.2 kg to complete five hours of thinning. This will impede the operator's ability to work and manoeuvre in a work environment that is often steep and difficult to travel through already. The cost of using the battery-powered-chainsaws is currently lower than petrol chainsaw by $5.85 per 1000 trees. However, the productivity of the battery-powered chainsaws will outweigh this advantage by having a much lower productivity, almost doubling labour costs to do an equal area, compared to the petrol-powered chainsaws.

Overall, this study shows that battery-powered chainsaw technology is not currently competitive with petrol-power in terms of productivity. However, with more powerful battery chainsaws having come to market, and more likely in pipeline for the near future, a lower carbon and safer transition could be happening soon.

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Introduction

With the ever-increasing capabilities of electric motors and battery cell technology more of what used to be petrol-powered is becoming electrified. Battery powered tools have been on the market for decades now, and a battery-electric car is in the top five bestselling globally (Carlier, 2023). Yet still the majority of power equipment, vehicles and machines used in the forestry industry are running on petrol or diesel. With climate change and carbon emissions at the forefront of many countries and companies' agendas, and improving health and safety being an important part of forestry operations, the benefits and drawbacks of switching to electric should be investigated within forestry.

One area of forestry practice that currently depends on petrol driven chainsaws is thinning. Thinning is common practice in commercial conifer forests in New Zealand as it can increase the value of a tree crop (MacLaren & Knowles, 2005). Stands are usually planted at over twice the density of their intended stocking at harvest. Some of this stocking loss is due to trees naturally dying due to windfall, damage or competition with other trees within the stand; the majority of tree loss in production plantations is done through intentional thinning. For radiata pine (*Pinus radiata* D. Don) thinning to waste typically occurs at age 7-9, and less commonly production thinning typically at age 10-12 (Mead, 2013). The density of planting and the ratio thinned changes as silvicultural regimes come into and fall out of preference, with managing foresters, new science, location planted, and changing economic incentives all affecting the chosen thinning regime (Mead, 2013). As of 2018, silvicultural regimes including only thinning to waste were the most popular in New Zealand (Forest Owners Association, 2019).

Thinning to waste has long been an established technique in commercial forest growing in New Zealand, and during this time the method of how it is carried out has changed. In the 1950's modern chainsaws were introduced (Husqvarna, 2019) and in 1983 protective chainsaw chaps were introduced then later made a requirement (Sullman, 1996). The first chainsaw Andreas Stihl produced was electric (Stihl, n.d.) but for forestry operations petrol has been by far the dominant power source. In the early 2010's chainsaw companies were designing battery-powered chainsaws and quickly started to include lithium-ion batteries that lasted longer and enabled good power for their weight, i.e. had good energy density (Stihl, n.d.).

Photo 1: Stihl MSA 220c battery-powered chainsaw in use (Stihl, 2023)

Battery technology has been developing fast, especially regarding lithium ion (Manthiram, 2017) (Ziegler & Trancik, 2020). Since 2016 battery-powered tools have made up over half of the cordless power tool market (Pandur, Susnjar, & Bacic, 2021). This has allowed manufacturers to create chainsaws which they market toward professional forestry use. In the New Zealand both Stihl and Husqvarna are selling battery-powered chainsaws marketed towards professional use in forestry (Stihl MSA 220 and 300 C and Husqvarna 540i XP).

New Zealand forests often present a challenging workplace, and many machinery and operational aspects could contribute to how productive a thinning operation will be. This study aims to contribute by identifying where any differences in productivity exist between battery- and petrol-powered chainsaws in New Zealand thin to waste operations. This is to inform both the forestry industry and chainsaw manufacturers on the current state of chainsaw technology in professional thinning applications.

Literature Review

There have been a number of studies, predominantly from Europe, which investigate how battery-powered chainsaws perform in professional forestry use.

The use of battery-powered chainsaws in forestry comes with a variety of advantages. Most important to consider is the added safety regarding the long term health effects petrol-powered chainsaws can cause. This can include hand-arm vibration syndrome (HAVS) and carpal tunnel syndrome (CTS) from gripping a vibrating chainsaw for long periods (WorkSafe New Zealand, 2021). This risk is reduced when using battery-powered chainsaws (Neri, et al., 2023). The noise exposure reduction between the different chainsaw types (battery- vs petrol-powered) has proven to be significant, but not to the level where earmuffs are no longer required under EU and New Zealand employment requirements, (Huber, et al., 2021) although crew members did appreciate the ability to communicate with the reduced noise (MacDonald, Harvey, & Visser, 2023).

Advantages such as a lack of exhaust emission is also a positive change for health and the environment. A study by Dimou et al. (2019) showed CO and NO_2 concentrations during petrol-powered chainsaw use averaged 88.32 ppm and 0.07 ppm respectively. They also showed in certain situations such as when using poor quality fuels the European Union workplace CO exposure limit was exceeded (Dimou, Kantartzis, Malesios, & Kasampalis, 2019). A change to battery-powered chainsaws would remove this hazard (Ministry for the Environment, 2021). Because of the positive changes battery-powered chainsaws could bring to operators, research into their productivity should be undertaken. This should be done so the forestry industry and particularly the silvicultural workers can be informed on their feasibility for professional use.

Previous Productivity Studies with Battery-powered Chainsaws in Thinning Operations

In Tuscany Italy a study by Neri et al. (2023) analysed two chainsaws of similar power, weight, chain and bar specifications, one being petrol-powered and the other battery-powered. They showed that the two chainsaws had productivity values with no significant statistical difference as shown in Figure 1. The battery-powered chainsaw was found to have a productivity of 1.34 m^3 /hour while the petrol had a productivity of 1.21 m^3/hour (Neri, et al., 2023). This study was undertaken in a 70 year old Douglas Fir stand with DBH (diameter at breast height) ranges from 20 to 26 cm. Operators observed were also required to buck and delimb (process) the stem in this operation. Because of this the study is not entirely representative of a typical New Zealand thinning operations, as the majority of thinning in New Zealand in thin to waste (Taylor, 2021). However, with similar productivity achieved, it does show that battery-powered chainsaws are worth considering as a substitute for petrol-power in professional settings.

The measure of productivity used in this study is also not well suited to waste thinning, as the volume of the trees in not important in waste thinning operations. Because the trees thinned are usually smaller, poorly shaped and done quickly this measurement would be difficult to record in a thin to waste study.

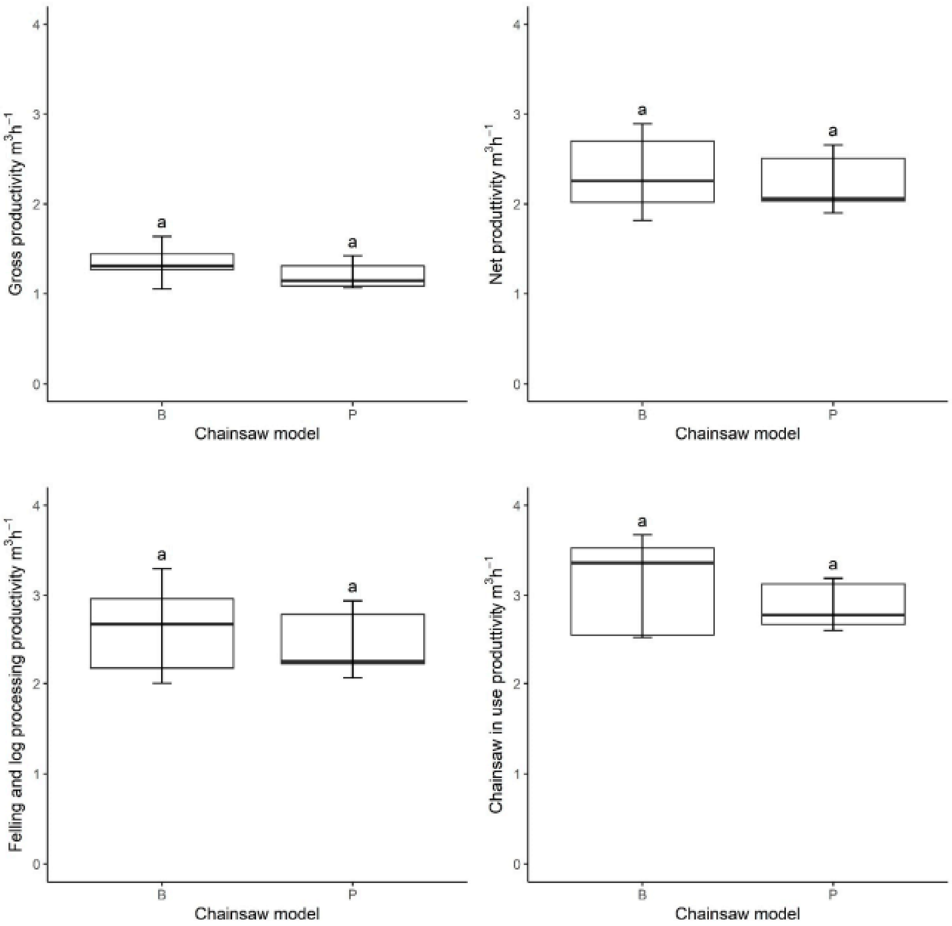

Figure 1: Productivities analysis (gross, net, felling, and processing, and chainsaw "in use") applied 252 to the two models of chainsaw (B = battery MSA220 C-B; P = petrol MS201 C-M). The median and 253 spreading-range values of productivity are represented. Similar lowercase letters reported above 254 each boxplot show the absence of a significant difference (p value > 0.05) between chainsaws 255 according to the ANOVA test and the multiple comparison using the HSD test (Neri, et al., 2023).

A study by Laschi, et al. (2023) showed that when cut to length clearcut harvesting in the Montebello Forest in Italy, the Stihl MSA 300 c battery-powered chainsaw was not statistically different to the similarly weighted and powerful petrol Stihl MS 261 C-M using the same chain and bar. In this study the felling and processing of 50 year old Scots Pine with an average DBH of 28 cm was observed. Both chainsaws averaged 20 trees per day in an average 7.4 hour work day (gross time), (equating to 2.7 trees per hour). This study also found that a battery Stihl AP 500 s lasted an average of 0.88 hours (52 minutes and 48 seconds), while a tank of petrol lasted 9% longer at 0.97 hours (58 minutes and 12 seconds) (Laschi, et al., 2023). The productivity results from this study are consistent with the other Italian study by Neri et al. (2023) and showed that chainsaws of lower power (<=3 kW) have productivities independent of their power source. These two studies are relatively similar in that trees were of 20 – 30 cm DBH and all trees felled were delimbed and cut to length.

A New Zealand study undertaken by the author (MacDonald, Harvey and Visser, 2023) showed that battery-powered Stihl MSA 220 Cs were not as productive when thinning to waste as the current large and powerful petrol chainsaws currently used by thinning crews. In the study, battery-powered chainsaws (Stihl MSA 220c) were compared against petrol chainsaws as powerful as the Stihl MS 500i (5 kW) in radiata pine plantations with average stump diameters of between 12 and 20 cm. The battery-powered chainsaws used in this study had 16 inch bars while the petrol chainsaws ranged from 16 to 20 inch. The chains used on the battery chainsaw were half-chisel, while most petrol chainsaws had full chisel. The productivity data collected in this study produced an interesting trend where in stands which had larger diameter trees the battery-powered chainsaws had a productivity value (trees per hour) closer to the more powerful petrol chainsaws; in stands with small diameter trees the productivity differences were far greater (Figure 2). For both chainsaw types in the study larger trees resulted in lower productivity (trees per hour). This is a result which European studies have not produced, and seems counter intuitive due to the higher power of the petrol chainsaws.

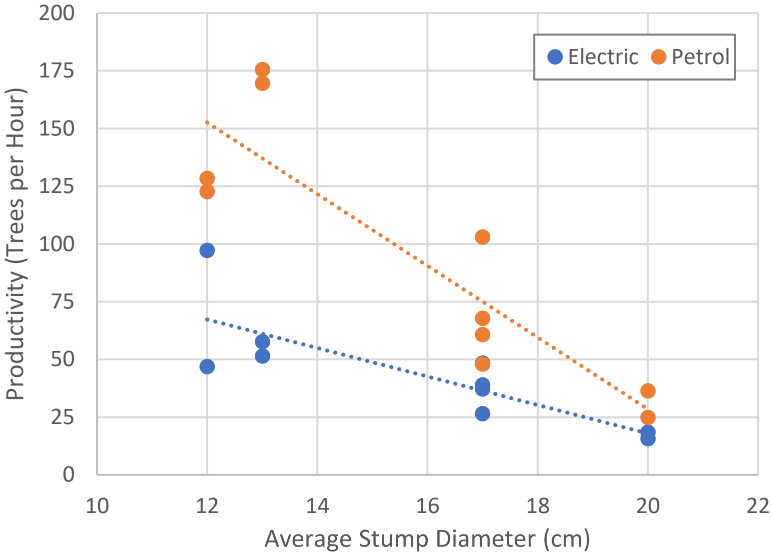

Figure 2: Productivity (trees per hour) of battery-powered and petrol-powered chainsaws, (MacDonald, Harvey, & Visser, 2023).

A study conducted by Tomczak and Naskrent (2022) on work efficiency of battery-powered chainsaws in commercial pine stands in Poland recorded that petrol chainsaws had a productivity of 100 m^2/h higher than electric chainsaws over the course of the study. The measurement used in this study was of cross-sectional area cut rather than m^3 of wood processed. This study was investigating production thinning so therefore includes the time spent processing stems into logs, and was undertaken in a mixed stand of mostly Scots Pine which was at 14 years of age. This study showed that battery-powered chainsaws are not yet as productive as petrol-powered chainsaws in forestry settings, unlike the other European studies in this literature review which show them to be similar. This may be due to the different chainsaws used in this study (petrol Dolmar PS-5000 at 2.8 kW and electric Echo ECCS-58V of 1.7 kW), the operational aspects of the thinning or more specific stand details. In a waste thinning context this is likely a more useful measurement than wood volume felled/processed as measured in other studies, and will be an interesting way to compare the two chainsaw types in a New Zealand context.

The final piece of published research specifically comparing battery-powered to petrol-powered chainsaws in a thinning or felling operation was undertaken by Poje, Potocnik and Mihelic (2018). In their research they compared the efficiency and safety of the two chainsaw types (1.35 kW Makita EA320035B Petrol and 0.8 kW Makita DUC302Z Battery) in a young spruce stand in Slovenia with DBH ranges of 5 to 30 cm. Like the other European studies this was also a production thinning where the chainsaw operators processed the stems where they were felled. The trends produced in this study show that productivity differences for the two chainsaw types was statistically insignificant, and that larger trees decreased the time per volume of wood felled and processed (Figure 3). The chainsaws used in this study are far less powerful than other chainsaws studied and used by silvicultural contractors in New Zealand.

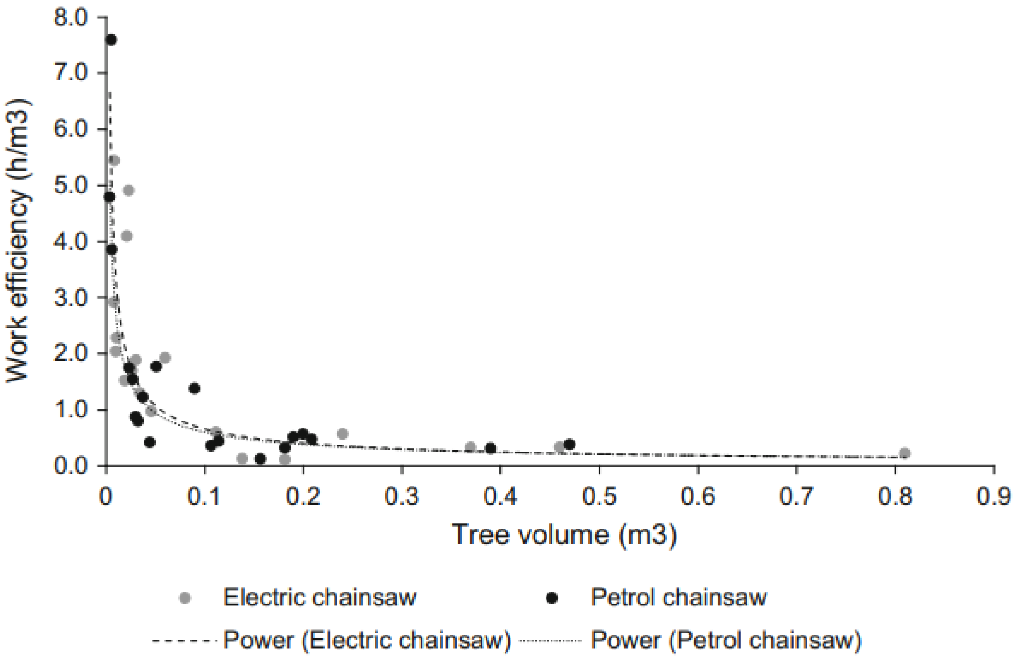

Figure 3: Tree volume and efficiency of electric and petrol chainsaw (Poje, Potocnik, & Mihelic, 2018).

Table 1 shows how all previous research into battery-powered chainsaws in thinning and felling operations have performed. From the table it can be identified that there is a correlation with the size of chainsaw and the cutting, felling and processing efficiency that they can achieve. The two Italian studies show that battery-powered chainsaws are an equal match for petrol-powered for outright productivity when both are at an equal power output; an output lower than typically used in New Zealand (Stihl MS 462 at 4.4 kW). The New Zealand and Polish studies showed that petrol chainsaws with more power did have a higher overall productivity, while the study in Slovenia showed no statistical difference in chainsaws which had a power difference of 0.55 kW. The result found in the New Zealand study shown in Figure 3 is not found/shown in other literature, and suggests that stump diameter influences the productivity potential of different power levels differently.

Table 1: Findings of current research into battery-powered chainsaw productivity in thinning operations.

Study by	Location	Operation Type	Tree Type and Size	Key Productivity Finding
Neri et al. (2023)	Italy	Production	Douglas Fir with DBH of 20-26 cm	No statistical difference between similarly powered battery and petrol chainsaws.
Laschi, et al. (2023)	Italy	Cut to length clear-felling	Scots Pine with average DBH of 28 cm	No statistical difference between similarly powered battery and petrol chainsaws.
MacDonald, Harvey and Visser (2023)	New Zealand	Thin to waste	Radiata pine with Stump sizes of 12-20 cm	More powerful petrol had greater productivity than less powerful battery. Larger

				difference in productivity observed among smaller trees.
Tomczak and Naskrent (2022	Poland	Production	Scots Pine, 14 years old	2.8 kW petrol chainsaw more productive than 1.7 kW battery chainsaw when measuring cross-sectional area cut.
Poje, Potocnik and Mihelic (2018)	Slovenia	Production	Young Spruce with DBH of 5-30 cm	No statistical difference between 0.8 kW battery and 1.35 kW petrol.

Other Studies Relating to Chainsaw Productivity

No other studies found during this literature review have measured the productivity of battery-powered chainsaws in forest environments. However, information on related topics can help understand the differences in productivity thinning operations experience. For example, a study by Lebel and Dubeau (2007) set out to identify thinning productivity differences based on site characteristics in Quebec Canada. The aim was to ensure piece-rate contracts were fairly priced. They found that when thinning with brush saws (scrub cutters) the only site characteristic that affected productivity (measured in hours per hectare) was initial stocking (Lebel & Dubeau, 2007). A study by Uotila, Saska, Rantala, and Kiljunen (2014) in Finland also found stand age and therefore average DBH negatively affected productivity when thinning with brush saws (Uotila, Saska, Rantala, & Kiljunen, 2014). This shows that stand details (such as age, DBH and stocking) are the key contributing factors to how productive a thinning operation can be, rather than terrain details in a brush saw operation. This likely reflects chainsaw thinning operations as well.

A study into motor-manual and mechanical felling in radiata pine thinnings by Moore (1988) showed that when production thinning on a flat site in Kaingaroa Forest motor-manual felling with petrol chainsaws (unspecified models) achieved a rate of 36 trees per hour. This type of thinning is less common in New Zealand currently (Taylor, 2021), with most production radiata pine stands being thinned to waste at ages 7-9 (Mead, 2013). In this case the trees were 18 years old with an average DBH of 28 cm. The initial stocking was 600 stems per hectare being reduced to 350 stems per hectare. When the fallers were made to delimb the stems prior to extraction this reduced their productivity to 11 trees per hour. During felling this study observed that operational delays amounted to 13% of the cycle time when felling a tree (Moore, 1988).

Battery-powered chainsaws have been investigated in areas other than felling and thinning productivity. A study by Poje and Mihelic (2020) investigated the influence of chain sharpness and tension on a range of corded and battery chainsaws. The key results from this were that the battery chainsaws (Makita DUC353Z, Stihl MSA 200 C -BQ and Husqvarna 536Li XP) were 1.9 to 2.8 times less efficient (measured in cm^2/second) than the petrol-powered chainsaws tested (Husqvarna 365) by Ciubotaru & Campu (2018). This was found by crosscutting a 0.2 metre sided square spruce beam. The average cutting rate recorded for the battery-powered chainsaws was 29.13 cm^2/second (Poje & Mihelic, 2020). At this rate a tree with a 10 cm diameter stump could be sawn through in 2.7 seconds. Because this study was done recording cross cutting time instead of felling this estimate may be an underestimate due to having a different cutting orientation.

A study by Neri et al. (2022) produced similar results to the previous study mentioned. They showed that when cross cutting 15 cm sided square beams of five different species, a battery powered chainsaw (Stihl MSA 220 C) was on average 17.5% (1.18 times) slower than a similarly powered petrol chainsaw (Stihl MS 201 C), and 82.2% (1.82 times) slower than a chainsaw typically used by forestry professionals for trees of small and medium diameter (Stihl MS 261 C). The average rate at which the battery-powered chainsaw crosscut Black Pine (*Pinus nigra*) was 36.0 cm^2/s while the similar powered-petrol chainsaw took 36.7 cm^2/s and the more powerful petrol chainsaw 56.3 cm^2/s. These times will be the most representative of radiata pine from the studied timbers. This study also noted that the more powerful chainsaw appeared to not be affected by defects in wood as much as the lower powered chainsaws (Neri, et al., 2022).

In a pruning productivity study by Colatoni et al. (2016) many different chainsaws were timed on varying branch sizes on many different tree species. Key results from this study show that the 1.5 kW battery-powered Pellenc Selion C15 was similar in productivity to the 1.7 kW petrol-powered Stihl MS200 when sawing branches under 7 cm in diameter. Above this diameter range the difference in productivity increased, with the battery chainsaw being just over 3 times less productive on branches of 13 cm in diameter (Colantoni, et al., 2016). This shows the opposite result to the thinning study by MacDonald, Harvey and Visser (2023) where larger diameter trees had less productivity difference, but is situationally different in that this study was only measuring pruning cut times, not thinning operation productivity.

From the studies above, the need for further research into the productivity of battery-powered chainsaws in thin to waste operations in young radiata pine stands has been identified. This is due to the majority of current literature taking place in production thinning operations in stands of different species (not radiata pine) that are significantly older than the 7-9 years typically thinned in New Zealand. The one study which took place in a New Zealand radiata pine stand produced a unexpected result with the largest productivity differences between petrol and battery-powered chainsaws being associated with smaller diameter trees (MacDonald, Harvey, & Visser, 2023). Cross cutting studies suggest that battery-powered chainsaws are less productive when considering area cut per second, while two out of three studies in Table 1 suggest they have no statistically significant difference when in a production thinning operation. Because of the range in results and unexplained trends in current literature a time study analysing delays and cutting times would be beneficial to properly understand how battery-powered chainsaws perform in New Zealand thin-to-waste operations.

Study Objectives

The study aims to examine the productivity differences between battery-powered chainsaws and petrol-powered chainsaws currently used in commercial thin-to-waste operations in New Zealand pine plantations?

To understand these differences the following hypotheses will be resolved:

1. Battery-powered chainsaws will have lower productivity values than petrol when cutting trees of all diameters.
2. The productivity of the battery-powered chainsaws will have a larger difference relative to cutting time on smaller diameter trees when recording on a per tree basis, due more delays experienced.
3. There is a linear relationship between cutting rate and chainsaw power output.
4. More powerful chainsaws have fewer small delays during felling.
5. There is no significant economic benefit to using battery-powered chainsaws.

Methodology

The productivity of the battery-powered chainsaw was analysed by supplying experienced thinning crew members with two Stihl MSA220-C cordless electric chainsaws (Table 2). While thinning they were observed in a way that allowed for the observers and operators safety (e.g., standing two tree lengths away), ensured a good range of stump diameters were cut, and maintained real-world conditions as best as possible. Measurements of productivity were recorded for operation of both the battery-powered chainsaws and the operators' usual petrol-powered chainsaw such that differences could be statistically identified. After using the chainsaws for two days the operators were surveyed regarding their experience with them. In addition to this a controlled test of the cutting rates was performed to compare the two chainsaw types. This was done to remove environmental effects on productivity.

The productive and delay times measured in this study's in-forest trial are defined below.

Productive time

a. Pre-felling - planning cuts and clearing branches from around trunk. Starts when operator reaches desired tree, stops when felling starts.

b. Felling – Starts when operator begins 'revving' chainsaw before making first cut into the stem. Finished when tree first hits the ground, or becomes 'hung-up' in adjacent trees.

c. Post-felling – Starts when operator begins 'revving' chainsaw to post (bring a 'hung-up' tree to the ground in pieces, clean a stump etc. Stops when the operator begins walking to the next tree.

Delay time

a. Maintenance – Any time the operator must work on the chainsaw that does not include refuelling. Starts as soon as the observer can recognise this has started. Finishes once another activity starts.

b. Chainsaw jammed – When the chainsaw bar is within the stem and the chain stops moving. Starts as soon as the observer can recognise the chain has stopped. Finishes when chainsaw begins cutting again.

c. Person – Time spent communicating, adjusting personal gear, etc. Starts as soon as the observer can recognise it. Finishes as soon as another activity is undertaken by the operator.

d. Other delay – Any other delay. Starts and finishes by the judgement of the observer.

Times for refuelling and changing batteries are not included in this study. This is because the operators often use this time to have a small break and fix/sharpen gear, which is beyond the scope of this study.

Table 2: Chainsaws used in this study.

	Stihl MSA 220 C	**Stihl MS 462**	**Stihl MS 310**
Power Source	Battery (Stihl AP 300s)	Petrol	Petrol
Power Output	2.1 kW	4.4 kW	3.2 kW
Weight	3.6 kg	6.0 kg	5.9 kg
Battery/Fuel Weight	1.8 kg each	0.69 kg	0.42 kg
Bar Length	16 inch	16-18 inch	20 inch
Chain Used	Semi-chisel	Full-chisel	Semi-chisel

Work Sampling Time Study

Operators were observed one at a time, working as normal for two periods. One period with their own petrol chainsaw and then with the supplied battery chainsaw for the next. Work and delay times were recorded for both 30 or more measured stumps for each chainsaw type ensuring a range of diameters were felled by each. Observations were taken from either a two tree length distance or from a position where the operator identified the observer will be safe. The first operator was observed in the morning, and the second in the afternoon. The operator observed in the morning used their petrol chainsaw in the first observation period, and the battery chainsaw in the second period. The operator observed in the afternoon used the chainsaws in the opposite order to try to mitigate any effects order may have on the productivity data. Time taken to refuel/swap batteries and walk between trees was not recorded as operators often use this as a break time and this time was needed to measure stump diameters.

Observation Method One:

Process of observation: Period 1 – 30+ measured stumps

1. Stand in a safe area where the operator can be seen felling as clearly as possible.
2. Start stopwatch when operator starts 'revving' the chainsaw to begin felling the desired tree.
3. For larger trees record the time taken for the tree to be on the ground and the operator to be starting the process of selecting and approaching the next tree. Press lap at the start and end of each delay (if delay is less than five seconds note the type but do not concern about length as too much observer error will contribute to the delay time recording), record all these times along with the corresponding delay cause. For smaller trees that will take less than 10 seconds to fell, record the time it takes to fell multiple trees if possible and note how many were felled in that time. Again using lap to record delays.
4. Once stump(s) is/are safe to approach measure and record the diameter(s). Doing this will take time therefore a more continuous form of measurement is needed to supplement so that a trees per hour rate can be established.
5. Repeat 1-4 for 30+ stumps of a range of diameters. Maintenance and refuelling/battery change delays will be recorded during this observation period, but these delays will not count toward the time per tree value. These delays will instead be recorded to provide more data to better estimate averages of each delay type.

Observation Method Two:

1. Stand in a safe area where the operator can be filmed felling as clearly as possible.
2. Film groups of trees being felled.
3. Once the stumps are safe to approach record the diameter of the stumps with a measing tape.
4. Review footage and record times from the film using the same process as in method one.

Gross Time Study

For the remaining available time during the study, each operator used a different chainsaw type while thinning. The operators were given counters to click every time they felled a tree/leader (a double leader tree counts as two trees felled if felled above the fork). The time they started was recorded and the operators were asked to radio in when they had a major delay (i.e. refuelling, battery change, maintenance etc) and once they had resolved it. The start time of the delay and the resolve time were both recorded. Once an operator has used three or more batteries this time and the batteries used was recorded. This process was then repeated with the operators using the other chainsaw type.

Controlled Cutting Rate Study

To precisely gauge the cutting rate of the different chainsaws a similar technique to the study by Neri et al. (2022) was used. The wood used in this study was fresh *Pinus radiata* stems, collected from the tops of tree stems beyond the merchantable length from a harvesting operation. This gave a round wood piece of similar dimensions to that found in a typical New Zealand thinning environment. However, because the stems were taken from the tops of harvested trees, they may have had different wood properties due to the change in density and microfibril angle with age/placement on the tree. To better identify the wood properties, samples were tested for density and moisture content after being cut. Roundwood was chosen for three reasons over the square beams used in the study by Neri at al. (2022); to investigate how changing cutting length effects the cutting rate; the test pieces were easier and cheaper to source; as a point of difference to the study by Neri et al. (2022); and so that the cut profile was the same as in-forest thinning.

To be able to identify the effect cut length has on cutting rate the analysis of times was broken into two sections. Section one was the first and last 30% depth of the biscuit (2 cm wide round cut from log end) and section two was the centre 40%. This gave two sections of almost equal area for each biscuit cut with a different average length as shown in Figure 4.

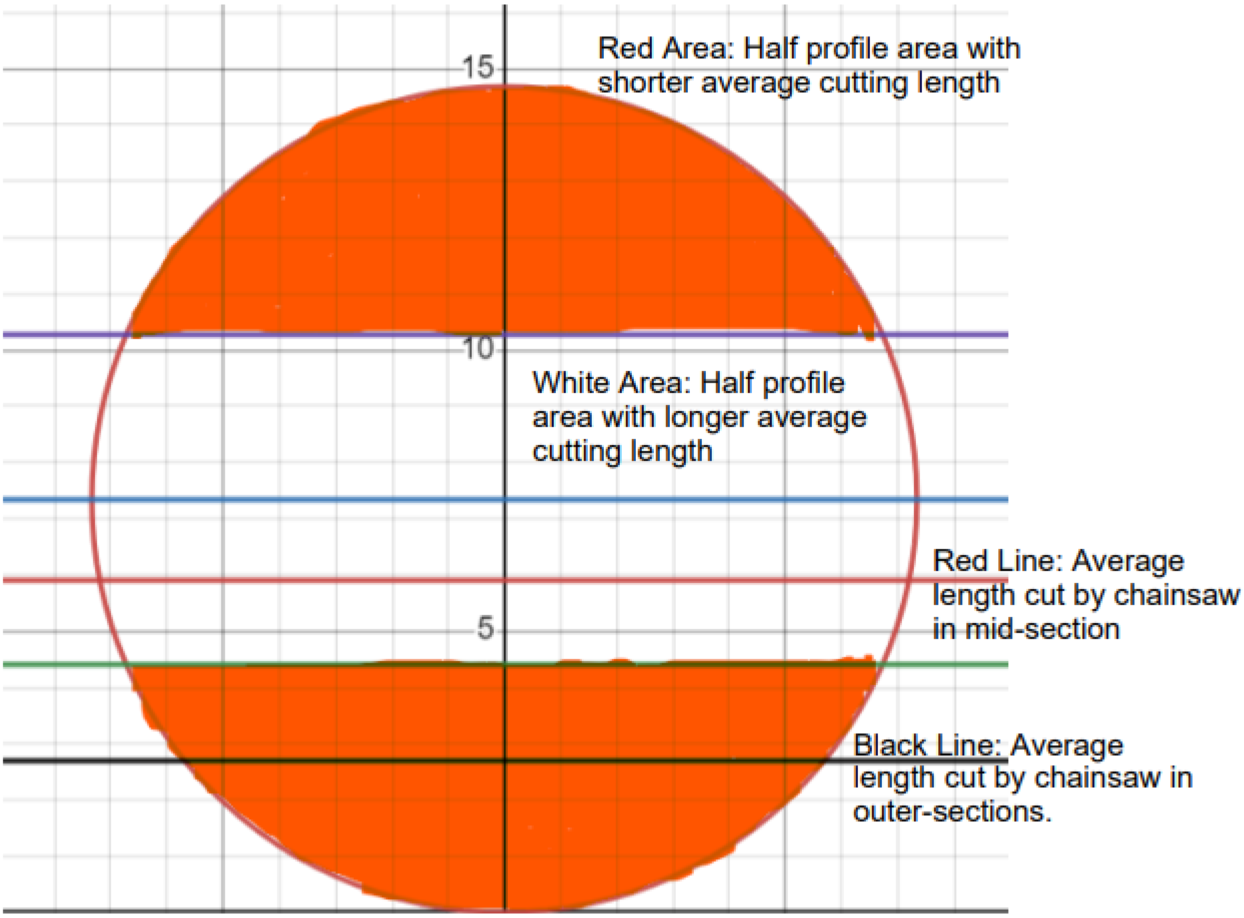

Figure 4: Diagram of biscuit sections for time measurement in the controlled cutting rate study.

Study process:

1. Acquire suitable *Pinus radiata* test pieces.
2. Securely attach one test piece to a solid frame with enough overhang such that the piece can be cut easily and safely.
3. Set up a high speed video camera to capture the cutting.
4. Set up a ruler next to the face being cut.
5. Cut a 2 cm biscuit off the piece by applying pressure which the operator feels is optimising the cutting rate.
6. Measure and record two orthogonal diameters of the biscuit cut.
7. Repeat steps 2, 5 and 6 alternating the chainsaw used every time.

Photo 2: Pinus radiata log in frame ready for cutting.

Survey

To understand the implications of different types of delays and reasons for higher or lower productivity the operators were asked a series of questions to give a human element to the data collected.

Questions asked:

1. Did either chainsaw cause you more delays than the other (give list of potential delays)?
2. Do you think the delays that occurred when using the electric chainsaw would decrease once you had a few months experience with it?
3. What caused each chainsaw to be more or less productive (trees per hour) than the other?
4. Any further comments?

Materials and Labour

- 2 x silvicultural workers, each with their regular chainsaw and equipment.
- Observer.
- 2 x Stihl MSA220-C chainsaws, each with:
    - 3 x fully charged batteries, mitt, spare chain, bar oil and sharpening tool.
- 1 x petrol-powered chainsaw with:
    - fuel mix, mitt, bar oil, spare chain and sharpening tool.
- Stopwatch.
- Spray paint or coloured tape.
- Go Pro and attachments or similar.
- Diameter tape.

- Measuring tape.
- 2x counters.
- Safety gear (helmet, high-vis, boots, warm layers, raincoat, hearing protection, first aid kit, PLB, chainsaw chaps etc).
- Stand to hold logs of below 30 centimetres in diameter securely.
- Pens.
- Clipboard.
- Preprepared log tables and survey questionnaire.
- Kestrel weather station.

Data Analysis

Data recorded during field trials was statistically analysed by finding the mean and standard deviation values, as well as R^2 values for any trends. The chainsaws were evaluated on their felling time (measured in cm^2 per second and across a range of tree stump diameters), delay time (as a percent of felling time) and total trees per hour rate (including all delays not influenced by the study taking place). This data was supplemented by using productivity data recorded in a similar way during the study by MacDonald, Harvey and Visser (2023).

To decide whether there was a significant difference in the data recorded for the two chainsaw types a Shapiro-Wilk test was carried out firstly to determine if data was normally distributed, then a double population t-test. This was all executed using Microsoft Excel. In addition to this relevant graphs and tables showing important data points and trends were made to aid with interpretation.

Results and Interpretation

The in-forest time studies in this report were done over two days in the Ashley Forest in North Canterbury, with two experienced silvicultural workers from Makerikeri Silviculture. Both men had over five years of experience thinning and were using their own Stihl MS 462 chainsaws when being observed with a petrol chainsaw. Data from the author’s previous study on battery-powered chainsaws was used to supplement the gross time study data collected during this study. The data from this previous study was collected from across Canterbury and the West Coast in Mt Thomas, Waimate, Mahinapua and Ashley Forests with operators from Central Forestry Services, Rees Contracting and Makerikeri Silviculture being observed.

On the two days which data was recorded during this study’s observations in the Ashley Forest the weather was cool, with the first day being drizzly. The weather data recorded by the Kestrel weather station shown in Figure 5 indicates that neither day is close to 26˚ C where the operators would start to be affected by heat stress (Kestrel Meters, 2014). Having a damp work environment on the first study day may have had some effect on productivity, however the under-canopy conditions were similar both days and did not worry the operators.

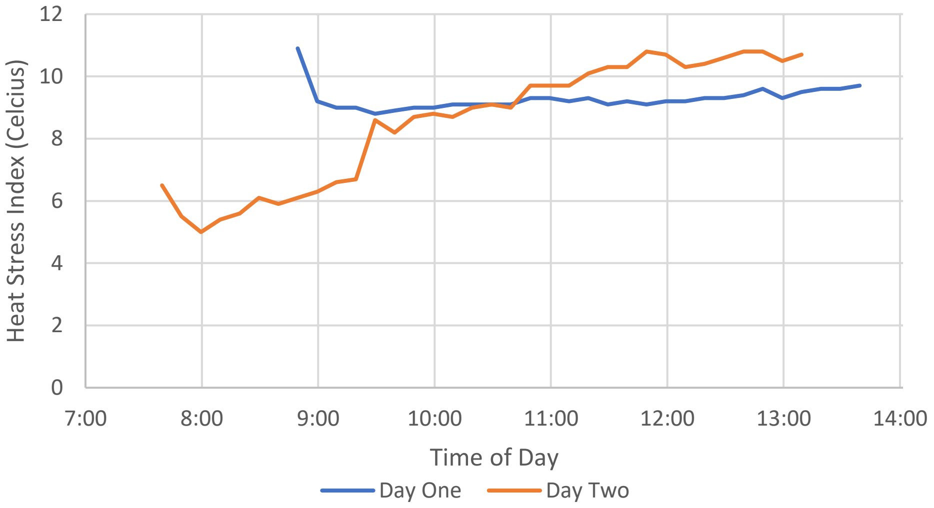

Figure 5: Heat stress index during time studies.

In total 128 trees were observed being felled during the work sampling time study, with 66 trees observed with the battery-powered chainsaw and 62 with the petrol-powered chainsaw. The first day's observations were done using method one outlined in the method above, while the second day used a combination of method one and two with the observer filming the felling from a safe distance and measuring the stumps after the thinning operator had moved on from that site. This change occurred due to difficulty recording data in a wet environment quickly, limiting the number trees able to be observed. To get the time of each action from the second day the video captured was analysed using Behavioural Observation Research Interactive Software (BORIS) (Friard & Gamba, 2016). This software allowed each activity to be recorded accurately down to 1/30 of a second and allowed a higher ratio of the trees felled by the operator to be recorded.

The stand being thinned in this study gave a good spread of tree sizes that would be typically encountered by a thinning crew in Canterbury and the West Coast (MacDonald, Harvey, & Visser, 2023) as shown in Figure 6. The terrain was typical of New Zealand forests with steep sections which caused movement to sometimes be difficult. Photo 3 shows that the forest had high hinderance due to blackberry and gorse undergrowth along with a high initial stocking, and no previous pruning. Comments from the operators suggested this level of undergrowth is found in many North Canterbury forests where they work.

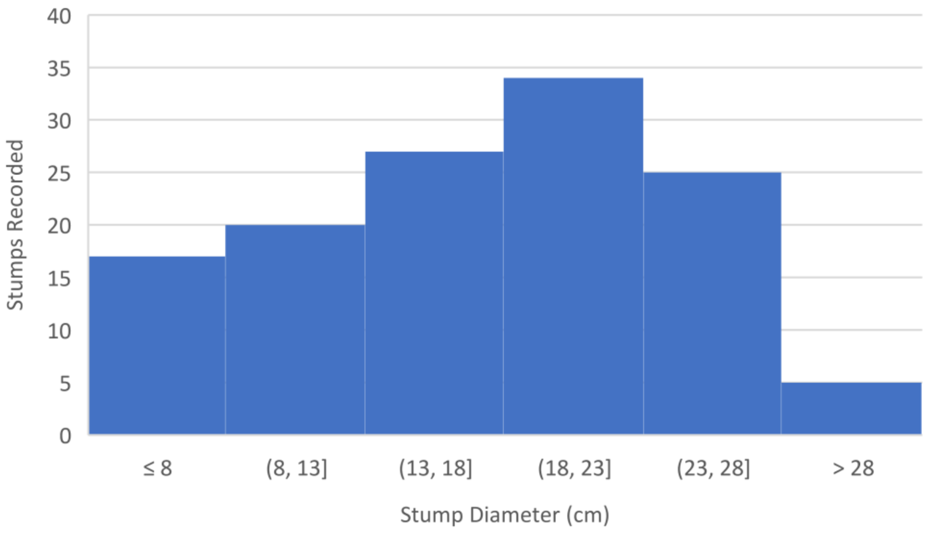

Figure 6: All stumps measured during in-forest study.

Photo 3: High hindrance area of undergrowth in the stand being studied.

Felling Comparison

Time

From observing thinning up close, the times to do each task stated in the method were able to be recorded for both chainsaw types. The task of the most interest to this study was the time to fell the tree being thinned. This time was taken from the moment the operator started engaging the throttle on the chainsaw prior to engaging with the tree, to when the tree hit the ground. This time did not include any delimbing or fell planning time, nor did it include any post fell clean-up such as posting (fixing hang-ups) or stump cleaning. Because this process was not always smooth, and delays were common in this process (predominantly hang ups and chainsaw jams) these times were subtracted from the felling times to account for difficulties specific to individual trees. However, these aspects are analysed later in this report.

Figure 7 shows how felling time related to the stump diameter of the trees felled in the study. From this figure it can be seen the battery-powered chainsaw was on average slower to fell trees than the petrol-powered chainsaw with an average felling time of 23.3 seconds versus 10.1 seconds. This gave a factor of difference of 2.3. By putting a linear line through the data it can be seen that the multiplier for the battery-powered chainsaw is 1.76 seconds per centimetre of diameter, while the petrol-powered chainsaw is only 0.59 seconds per centimetre of diameter. This is almost a difference factor of three, showing that the battery-powered chainsaw gets significantly slower when cutting larger diameter trees compared to the petrol. The linear representation is only a best-fit representation, as it would suggest cutting times could become negative. Below a stump diameter of 10 or 15 centimetres a polynomial relationship is more probable. These results are in contradiction with the authors previous study shown in Figure 8 below. From this result it would be expected that Figure 8 shows the opposite trend, with the chainsaw types converging at a smaller diameter tree and showing greater difference at larger diameters.

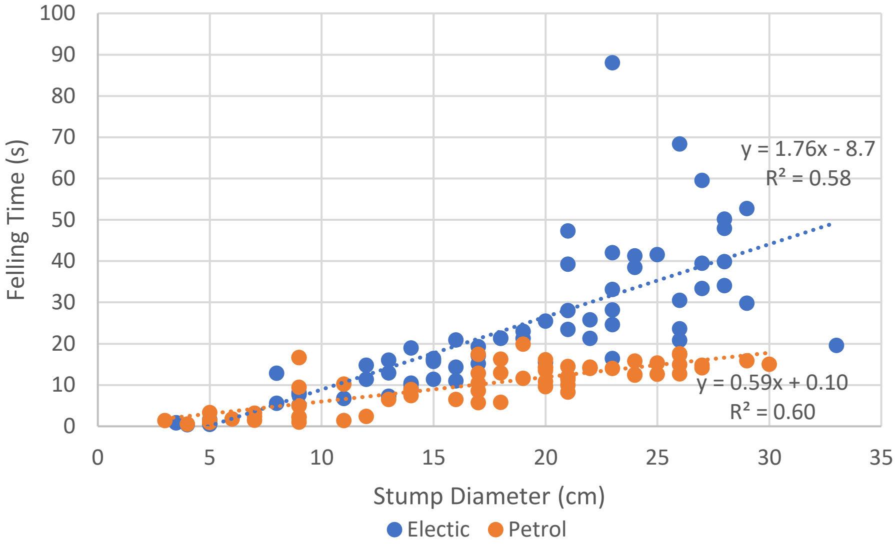

Figure 7: Felling time vs measured stump diameter.

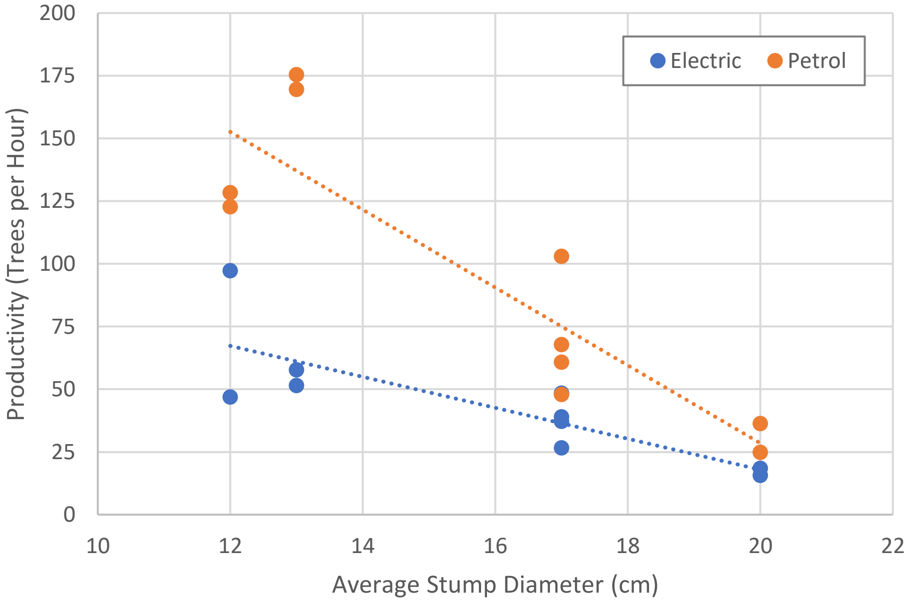

Figure 8: Average stump diameter vs productivity (MacDonald, Harvey, & Visser, 2023).

Photo 4: Stump and saw dust left after felling with the battery-powered Stihl MSA 220c.

Rate

As mentioned in the literature review, a good productivity measure to compare the two chainsaws is finding the cutting rate given by square centimetres cut per second (Neri, et al., 2022). To do this the stump diameters recorded were used to estimate the area of the stump assuming a circular profile, this area was then divided by the time taken to fell the tree. While the average stump diameter cut by the two chainsaw types was very similar (18.2 centimetres for battery-powered and 17.0 centimetres for petrol-powered), using the cutting rate accounts for any productivity difference caused by that difference in stump diameter. The two figures below (Figure 9 and 10) show the individual spread of stumps for each chainsaw type. These two figures show that the stumps recorded for each chainsaw type are similar but not exactly equal in distribution, with the battery-powered chainsaw having more large stumps recorded than the petrol-powered chainsaw, leading to the higher average stump diameter cut.

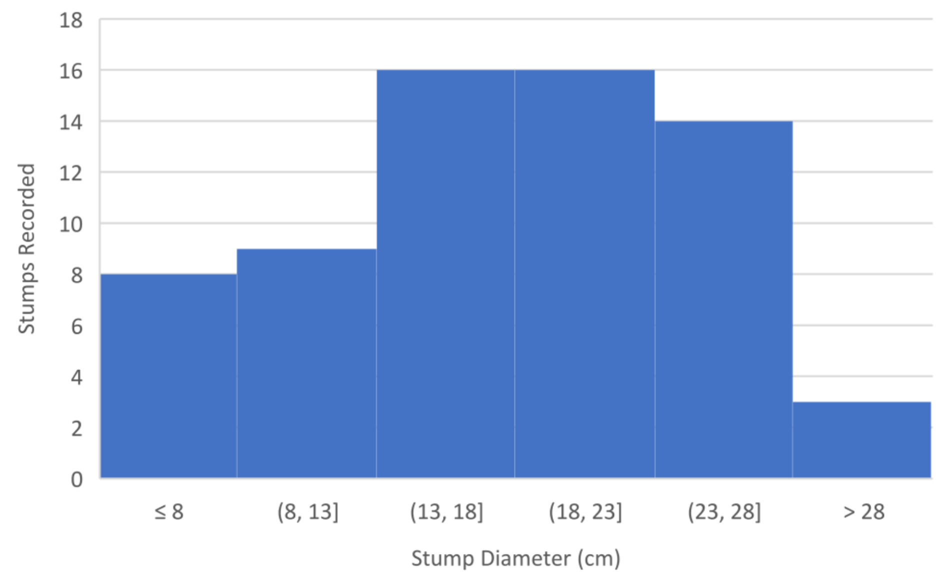

Figure 9: Stumps recorded for battery-powered chainsaw.

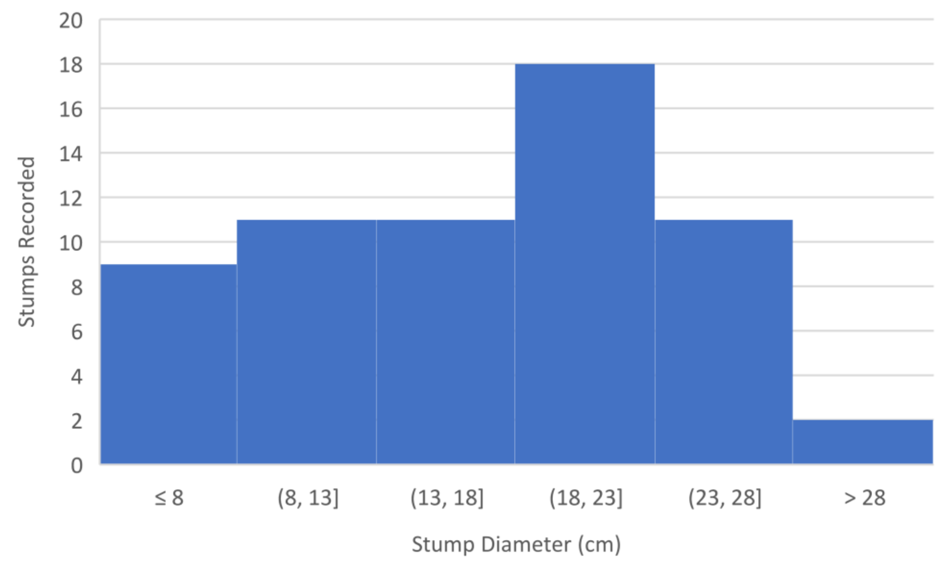

Figure 10: Stumps recorded for petrol-powered chainsaw.

The results from analysing the cutting rate show that the petrol-powered chainsaw is a factor of 1.8 faster at felling than the battery-powered chainsaw as shown in Table 3 below. This relates well to the previous study by this report's author where the difference in total productivity (trees per hour) showed petrol-powered chainsaws were a factor of 2.1 more productive than the electric chainsaws (MacDonald, Harvey, & Visser, 2023). When a two sided double population t test was done on the cutting rate data it returned that the rates were significantly different with over 99% confidence. The variance in rate recorded for both chainsaws is a similar percentage of the mean, shown by the similar COV (coefficient of variation). This shows that variance in cutting rate likely is not highly dependent on the chainsaw type, and rather is attributed to the operator and the forest environment, i.e. tree leaning awkwardly.

Having cutting rates significantly different is a key result, and shows the petrol-powered chainsaws are performing far better than the battery-powered at felling in forest conditions. However, this result has come from chainsaws that are different in power-output and equipped with different chains and bars. Also the rates shown above include time when the chainsaw is not in use while the tree falls, which is likely not correlated with chainsaw power. Therefore further analysis was undertaken do get better understanding.

Because the chainsaws used in this study are all of different sizes and power outputs the rates were further divided by the power output of the respective chainsaw. Table 3 shows that when adjusted for the power output of the chainsaw, the battery-powered chainsaw has the higher cutting rate per kilowatt of power output by a factor of 1.1. Having these values close is an interesting result, and shows that the power of the battery-powered chainsaws is likely a key factor in the lower productivity of these chainsaws in New Zealand thinning environments. This also shows that the battery-powered chainsaw may have advantages such as lower weight that are able to make it more efficient at cutting for its power output. This is also interesting as the petrol-powered chainsaws were equipped with full-chisel chains which cut more efficiently that the semi-chisel chainsaw on the battery-powered chainsaws (Husqvarna, 2023).

Table 3: Cutting rate statistics.

	Electric	**Petrol**
Average (cm^2/s)	15.0	27.0
Median (cm^2/s)	12.0	27.0
Std (cm^2/s)	8.0	13.1
COV	55%	49%
Average (cm^2/s/kW)	6.9	6.1

Figures 11 and 12 show the cutting rates recorded for each chainsaw type. While both histograms approximate a normal distribution there are differences. The battery-powered chainsaw is skewed to the left, with a long tail in the higher cutting rates. The fastest rates recorded with the battery-powered chainsaw were in stumps that were on the highest and lowest margins of recorded stump sizes, showing the rate is likely highly affected by the individual characteristic and challenges of a specific tree. The petrol-powered chainsaw has a more typical normal distribution, although it is flat in shape showing a large standard deviation. A Shapiro-Wilk test further confirmed that the two distributions of cutting rates were indeed not distributed normally with 95% confidence. Because of the unsymmetrical battery-powered chainsaw data the median is also showed in Table 3. Figure 11 shows that while it is possible for the battery-powered chainsaw to operate at a rate equal to the average rate of the petrol-powered chainsaw, this is uncommon.

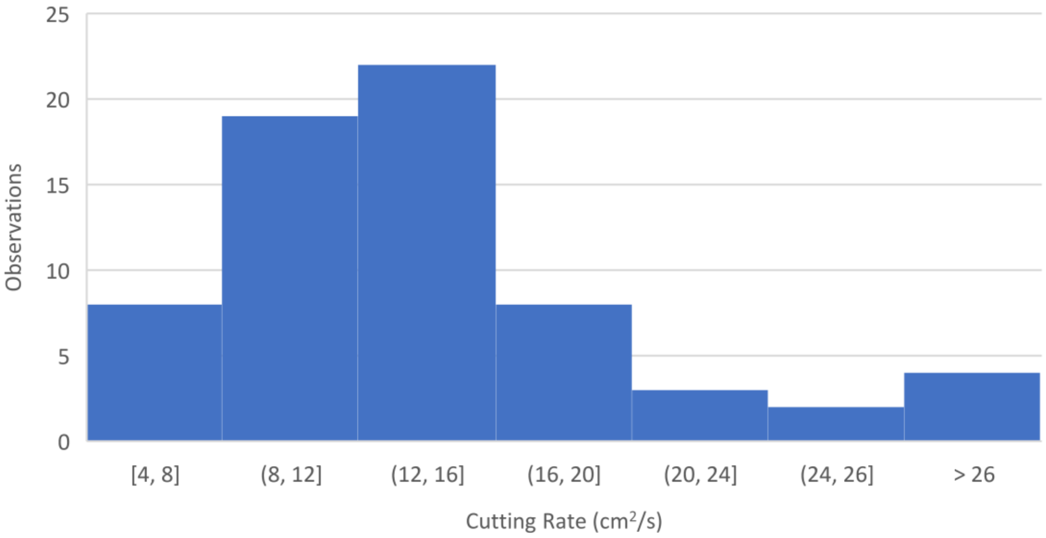

Figure 11: Histogram of the cutting rate of battery-powered chainsaw.

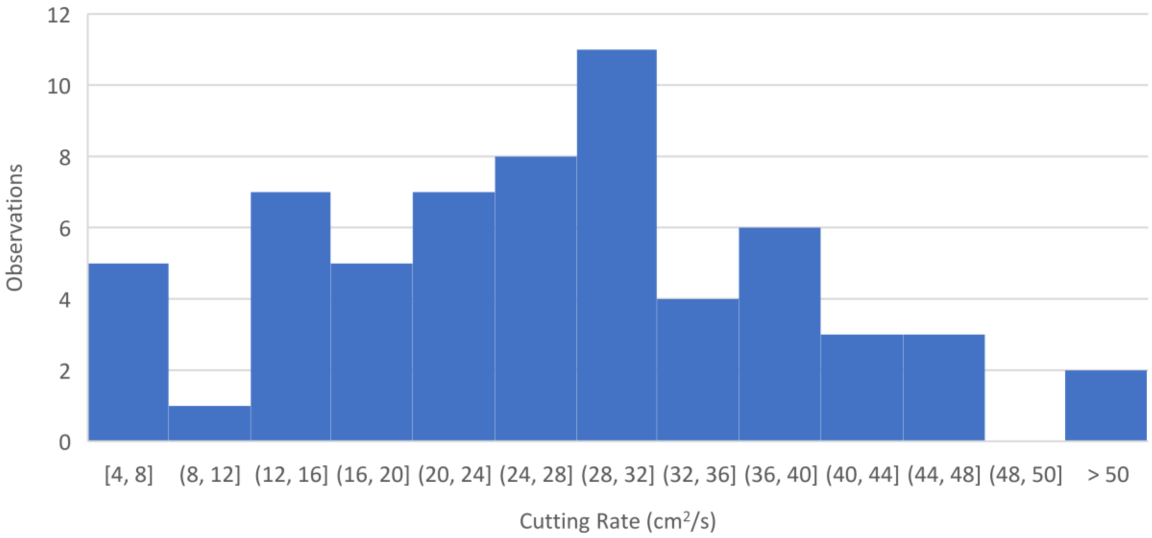

Figure 12: Histogram of the cutting rate of petrol-powered chainsaw.

To explain the deviation the distributions had from a normal distribution and to understand whether any measured variables were affecting the cutting rate, the cutting rate of the chainsaws was plotted against the recorded stump diameter in Figure 13. The result shows that the battery-powered chainsaws had no correlation between cutting rate and stump diameter with an R^2 value of less than 0.05. The petrol chainsaw does show a weak correlation between cutting rate and stump diameter with an R^2 value of 0.2. Below a stump diameter of 15 centimetres there appears to be very little to no correlation for the petrol, but above this there appears to be a significant positive correlation.

This correlation makes sense when comparing Figure 13 to Figure 8, where the petrol-powered chainsaws felling time did not increase as significantly as the battery-powered chainsaws did. This result then demands that a higher rate is achieved in the larger diameter stumps as shown in Figure 13. From this result it is unclear what gives the petrol-powered chainsaws the ability to cut at a faster rate in larger diameters, but it is likely a combination of factors including power output, bar length and a full-chisel chain rather than a semi-chisel chain.

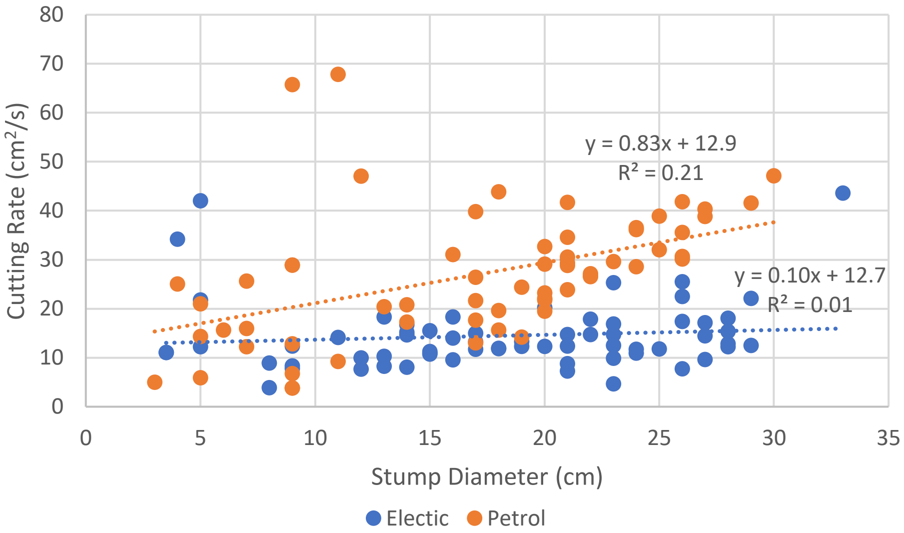

Figure 13: Cutting rate against stump diameter for both chainsaw types.

The in-forest felling time data collected in this study was only done so by observing two operators felling one stand. While this stand did give good variation in stumps and terrain, and the operators were experienced professionals, this does not mean the results shown are a good representation of all New Zealand thinning operations. Far more observations of other stands and operators would be needed to verify true average values for each chainsaw type. The times recorded may also be subject to the Hawthorne effect (Spencer & Mahtani, 2017) as the operators were very aware they were being observed; therefore their behaviour may have changed.

Photo 5: Felling a larger tree with the battery-powered Stihl MSA 220c.

Controlled Cutting Rate

To further understand the difference in cutting rate between the different chainsaw types an experiment in a controlled environment was undertaken over two days. This was done to better understand how the diameter being cut affected the cutting rate, as well as other factors that were harder to record in the forest such as how the cutting rate is affected by the length along the chainsaw bar and by defects in the wood. In this test the average diameter of biscuit cut was 15.1 centimetres, the average outer section length was 11.7 centimetres, and the average inner section length was 14.8 centimetres (refer to Figure 4). The average length used in this study was not the true average length but instead the length by which half of the specific area had been cut through. For analysis the times of both outer areas for each biscuit cut were added such that two equal areas could be compared on just average cutting length. Figure 14 shows the distribution of diameters of the biscuits cut in this trial and Table 4 shows the properties of the wood at the time.

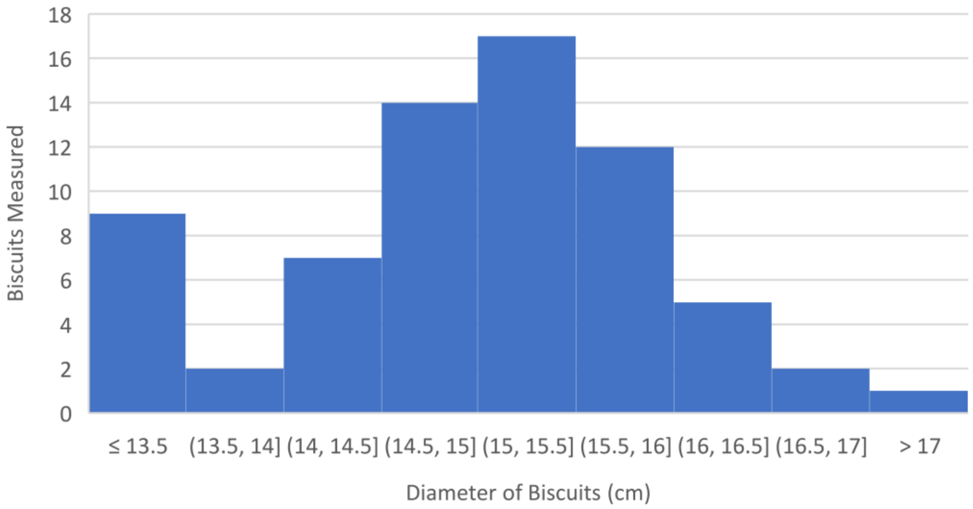

Figure 14: Distribution of diameter of biscuits cut in the controlled cutting rate trial.

Table 4: Properties of Pinus radiata logs used in this test.

MC (%)	Density (kg/m^3)	Anhydrous Density (kg/m^3)
104%	861	521

Photo 6: Biscuit being cut during the controlled cutting rate test with the battery-powered Stihl MSA 220c.

Table 5 shows the cutting rates from the controlled cutting test where delay (time being jammed) times have been removed. As in the in-forest thinning trial the petrol-powered chainsaw (Stihl MS 310) proved to have a cutting rate of almost double the battery-powered chainsaw with a difference factor of 1.8. When dividing the biscuit cross-section cut into the inner and outer pieces the difference factor of 1.8 between the different chainsaws rates stays similar in the outer section where a longer bar length is engaged, and drops to 1.7 in the inner section where the length of bar engaged is shorter.

For both chainsaws the cutting rate decreases when cutting the outer section and increases when cutting the inner section. This suggests that both chainsaws are being limited in their cutting rate in the outer section due to having less teeth engaged with the wood. This result indicates that in the forest the chainsaws should both have higher cutting rates in the larger diameter trees. In Figure 13 this is shown to be true for the petrol-powered-chainsaw, but not the battery-powered chainsaw. This difference may be due to the battery-powered chainsaw becoming limited by power when it has more teeth engaged in the tree.

Table 5: Cutting rates from the controlled cutting rate trial.

		Average Rate (cm^2/s)			Average Rate (cm^2/s/kW)		
	n	**Total**	**Outer**	**Inner**	**Total**	**Outer**	**Inner**
Electric	35	43.5	39.1	57.4	20.7	18.6	27.3
Petrol	32	78.9	70.3	98.2	24.7	22.0	30.7
Difference Factor		1.8	1.8	1.7	1.2	1.2	1.1

The results of this test were consistent with the in-forest trial and showed that the battery-powered chainsaw has a slower cutting rate than a petrol-powered chainsaw. In this test the Stihl MS 310 was used as the petrol chainsaw rather than the MS 462 used in the forest trial. This chainsaw has a lower power output of 3.2 kW versus the 4.4 kW of the MS 462, closer to the MSA 220c battery-powered chainsaw's output of 2.1 kW. The difference in the total rate in this controlled trial was a factor of 1.8 which is lower than the difference obtained from the forest trial of 2.1. When adjusted for the power output of the chainsaws the result from the forest trial is reversed, with the petrol-powered chainsaw still having the faster rate, by a factor of 1.2. This is different to the forest trial where the difference factor was 1.1 in favour of the battery-powered chainsaw.

The difference in results from the forest and controlled trials can likely be linked to three key factors. The method of time recording, the change in petrol-powered chainsaw and the difference in cutting style. The method of time recording changed between the two trials as the controlled trial only recorded cutting time, while the in-forest trial included the cutting time and the time for the tree to fall which could range in time depending on the size and location of the tree. This extra time recorded in the in-forest trial is not dependent on the chainsaw used, and therefore is likely to be the same added time for both chainsaws on average. Because of this when the difference factor is taken in felling time rates it will make the chainsaws appear closer in the in-forest trial.

The different petrol-powered chainsaw used could affect the difference factor in total cutting rate due to its lower power output and because the MS 310 used in the controlled trial was equipped with a less efficient semi-chisel chain rather than the full chisel equipped on the MS 462 in the in-forest trial. Having a semi-chisel chain should result in the MS 310 cutting at a rate closer to the battery-powered chainsaw, especially when adjusted for the kilowatt output, as the difference in chain profile is no longer present.

Finally, the technique used when cutting was different between the two trials. In the forest trees judged by the operator to be over 10 centimetres in diameter would receive a front and back cut, and larger trees over 20 cm would be scarf and back cut (Compete NZ, 2015). Having multiple cuts takes into account more aspects of the chainsaws than just pure cutting rate. Having the lighter battery-powered chainsaw could likely be an advantage in manoeuvring between the different required cuts, resulting in a faster felling time. Ultimately the differences in per kilowatt cutting rate from both trials are small, and a far more in depth study would be needed to better analyse these differences.

Figures 15 and 16 show the cutting rates from the controlled trial plotted as a histogram. They show that again neither of the chainsaws produced a standard normal distribution as proved by a Shapiro-Wilk test. The battery-powered histogram is skewed to the right, opposite to the histogram for the in-forest trial. This could be due to most cuts being clear of defects creating the main distribution, and cuts with defects creating the tail of lower cutting rates. The petrol-powered histogram shows a similar distribution to the petrol-powered histogram from the in-forest trial, again showing significant variance on both sides. A tail of lower cutting rates can also be observed, although these low rates are significantly higher than the lower rates observed for the battery-powered chainsaw.

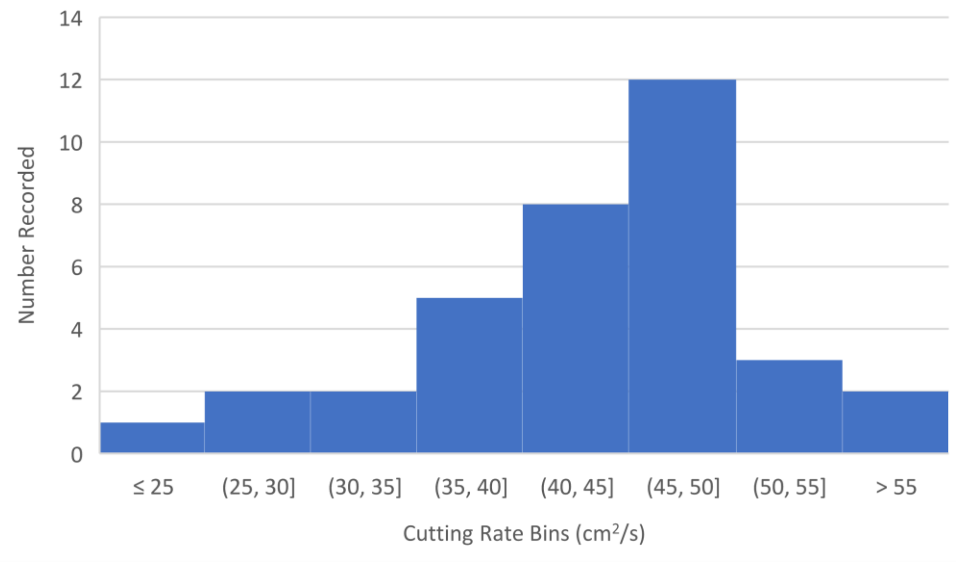

Figure 15: Histogram of battery-powered cutting rates from the controlled cutting rate trial.

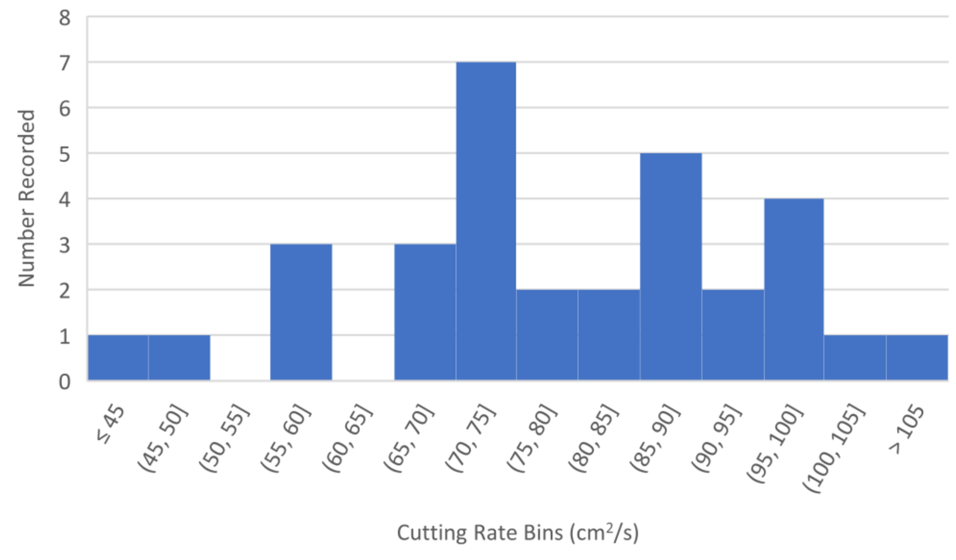

Figure 16: Histogram of petrol-powered cutting rates from the controlled cutting rate trial.

In Table 6 the effect wood defects had on the cutting rate and delays are shown. From this it can be seen that defects affect the two chainsaw types similarly in terms of percentage of their average cutting rate. It is interesting that the extra power of the petrol-powered chainsaw had no effect on this, although it did maintain a higher average cutting rate through the biscuits with defects, (64.9 cm^2/s versus 37 cm^2/s for battery-powered).

Table 6: Effect of defects on cutting rate.

	Average Cutting Rate Decrease from Defects (cm^2/s)	As Percentage of Total Mean Rate	Saw Jammed Events
Electric	6.5	15%	6 (17%)
Petrol	14.0	18%	5 (16%)

Table 7 shows where on the biscuit any jams occurred. This shows that the two chainsaws behaved rather differently in the limited observations where they became jammed. The battery-powered chainsaw did not become jammed due to defects in the wood, while the petrol-powered chainsaw became jammed in a defect biscuit three out of five times. The battery-powered chainsaw also became jammed when cutting biscuits of a smaller than average diameter more frequently than biscuits of larger than average diameter, while the petrol-powered chainsaw showed the opposite trend. Both chainsaws became jammed more frequently in the outer areas of the cut profile, with every occurrence of this being in the lower outer section. With such a small data size no significance should be drawn from this, but it is interesting to see how the battery-powered chainsaw typically became jammed in the smaller biscuits. This could potentially relate to the trend shown in Figure 8, with the chainsaw becoming jammed causing delays in smaller diameter stumps and therefore a lower trees per hour value compared to the petrol-powered chainsaw in stands with smaller average stump diameters.

Table 7: Attributes of where the chainsaws became jammed while performing a controlled cutting test.

	Defect	Outer Area	Inner Area	Larger than Average Biscuit	Smaller than Average Biscuit
Electric	0	4	2	1	5
Petrol	3	5	0	4	1

As with the in-forest cutting rate data, the controlled cutting rate data was plotted against the diameter of biscuit cut as shown in Figure 17. This shows that the data from the controlled test does not follow the same pattern as the data from the in-forest trial for the petrol-powered chainsaw. In this test the petrol-powered chainsaw has shown to decrease its cutting rate with the larger diameter sizes, with a linear line fitted with a negative correlation showing to have an R^2 value of 0.35 at two decimal places. This shows it is likely the time taken between the chainsaw stopping and the tree hitting the ground is that causes the consistent positive trend in Figure 13. This effect is likely caused by tree over a certain diameter taking a similar time to fall once cut. The decrease in rate shown in Figure 17 may be due the petrol-powered chainsaw not having ample power to cut through the larger diameters tested at its highest rate, as the chain speed is slowed by the added resistance. The battery-powered chainsaw showed a weak to zero correlation between cutting rate and stump diameter with an R^2 of 0.06. This could be due to the battery-powered chainsaw being limited by power, and therefore not allowing the higher number of teeth engaged to increase the cutting rate, while also having enough torque to maintain chain speed through larger diameter cuts.

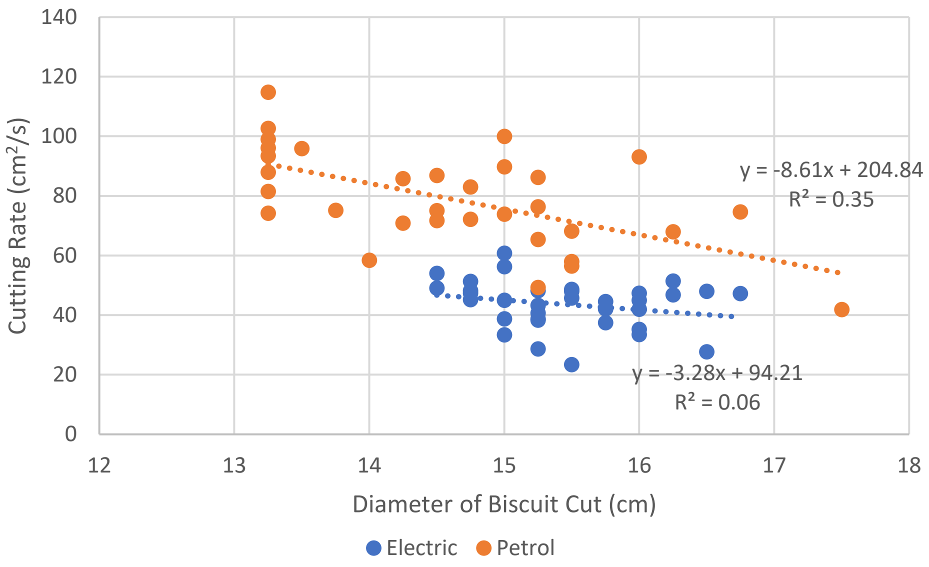

Figure 17: Cutting rate versus diameter of the biscuit cut.

Photo 7: High speed camera (circled) shown in relation to the log in the log in the stand. Also the beginnings of a large pile of saw dust created.

Pre and Post Felling Time

To understand the productivity of thinning more aspects than just the time spent felling the tree were observed. Pre and post felling time is the non-felling productive time spent at one location. For smaller trees or trees which are very easy for the thinning crew to fell this time was often zero, and any fell planning happened during their travel to the trees. For 63% of recorded trees pre felling time was needed to identify possible hazards, and challenges and develop a method to best manage these, and delimb the trunk such that the thinning operator had a clear space to cut into. For 30% of recorded trees post felling time was needed to do one or more of the following: fix hang ups, detach a tree from its stump after having fallen, and clean stumps of any sharp points. The average times for these actions are shown in Table 8 below.

Table 8: Average recorded and total average pre-felling and post-felling times. Electric pre-fell: n = 39, electric post-fell: n = 21. Petrol pre-fell: n = 41, petrol post-fell: n = 18.

	Electric			Petrol		
	Pre-fell	**Post-fell**	**Total**	**Pre-fell**	**Post-fell**	**Total**
Average (s) (recorded)	13.0	10.1	16.0	7.7	4.0	8.6
Average (s) (for total tree sample)	7.7	3.2	10.9	5.1	1.2	6.3

Table 8 shows that the trees recorded when the operators were using the petrol-powered chainsaws took an average of 7.7 seconds to pre-fell and 4.0 seconds to post-fell. For the battery-powered chainsaw these times were roughly doubled. When the time spent doing these activities on each tree was totalled the operators were a factor of 1.9 faster using the petrol-powered chainsaws. This is consistent with previous results showing the petrol-powered chainsaw is near a factor of two faster. Because not all trees require time spent on pre- and post-felling activities the total time recorded for pre and post felling was divided by the total number of trees observed felled by each chainsaw type. This gave an average value of time per tree as shown in the second row of Table 7. This row follows the same trends as the row above but shows the post felling time was less significant than the pre-felling time, and that both are less significant than the average felling times observed.

Figures 18 and 19 plot pre- and post-felling time against stump diameter. This shows that both chainsaw types have similar trends, with time for pre-felling increasing with stump diameter and time for post felling having a negative correlation. The R^2 value of the trends fitted are between 0.1 and 0.2 for both petrol-powered times and electric pre-felling time showed these correlations are not strong. Electric post-felling has an R^2 of 0.01 showed there is no correlation between the recorded times and stump diameter. The data collected for post-felling in this study did not reach the statistically significant number of 30 samples so the regression analysis results and trends shown may not be truly representative of thinning in similar stands.

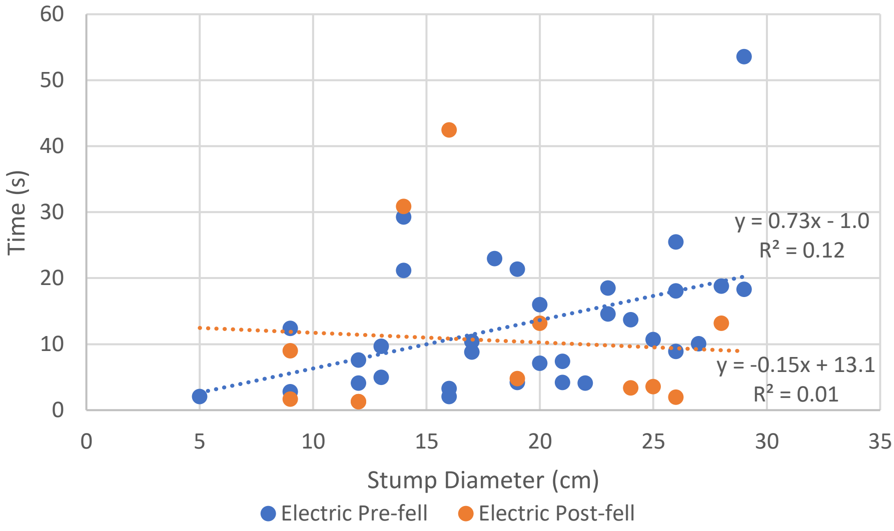

Figure 18: Battery-powered chainsaw pre- and post-felling time by stump size.

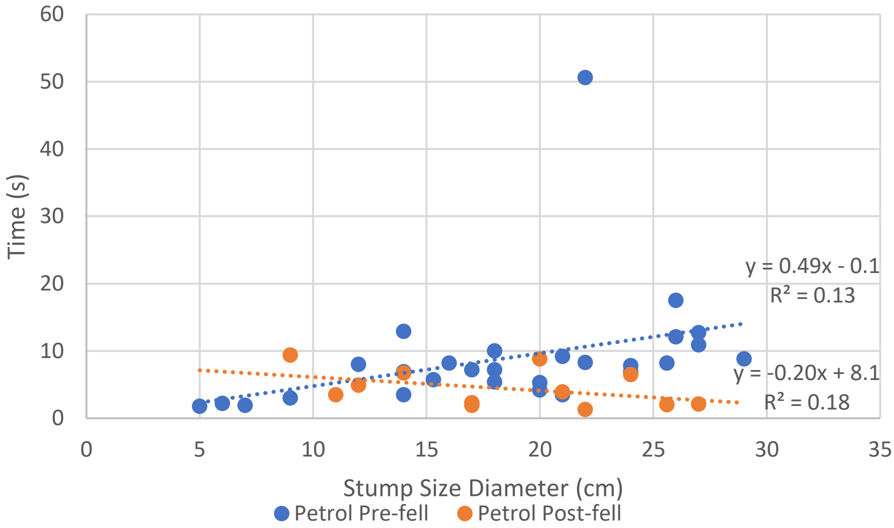

Figure 19: Petrol-powered chainsaw pre- and post-felling time by stump size.

Delay Time and Causes

During the in-forest trial delays were not common. In all 128 trees observed there were a total of 21 delay occurrences. Table 9 breaks this down further and shows that the battery-powered chainsaw caused the operators far more delays than their petrol-powered chainsaws. Mechanical delays for the battery-powered chainsaw all occurred due to the battery not sending power to the chainsaw, and the operator was made to either take the battery in and out repeatedly or try rolling the chain around manually on a tree stem to try 'help' the chainsaw to go. These mechanical delays often occurred in conjunction with jammed delays, having one delay cause the other (which delay was the cause of the other was unclear). Personal delays such as radio chatter were not linked to the chainsaw type, and only occurred during pre-felling time. Table 10 shows the average time of each delay. This shows that the mechanical delays caused the longest delay times, delay times when the chainsaw became jammed were short and personal delays were about ten seconds.

Table 9: Delay occurrences by chainsaw type during the in-forest trial.

	Mechanical	**Jammed**	**Personal**	**Total**
Electric (s)	5	10	3	18
Petrol (s)	0	2	1	3

Table 10: Average time of delays during the in-forest trial.

	Mechanical	**Jammed**	**Personal**
Electric (s)	27.5	1.3	7.9
Petrol (s)	-	2.1	11.9

An interesting difference from the in-forest trial to the controlled cutting test was the occurrence of jammed delays. In the forest the battery-powered chainsaw caused the operators to have far more jammed delays than the petrol-powered chainsaw. This may be due to a combination of factors including the operator's difference in experience with the two chainsaws, the power output difference of the chainsaws, the different chain types fitted on the chainsaws, or the different cut types being made.

To understand how delays impacted the productivity of thinning the total delay times were divided by the number of trees observed to be felled by each chainsaw type as shown in Table 11. Personal delays were totalled across both chainsaw types as these delays were not affected by the chainsaw in use. The personal delays are shown as this information is not currently published anywhere else, although this studies data on this is very limited. Doing this shows that the petrol-powered chainsaw caused the operator to experience less delay time than the battery-powered chainsaw. At 2.3 seconds per tree on average the delay time of the battery-powered chainsaw is substantial compared to the felling and pre/post-felling times, whereas the petrol-powered chainsaws delays were less so.

Table 11: Delay times averaged by trees observed.

	Mechanical	**Jammed**	**Total Due to Chainsaw**	**Personal**	**Total**
Electric (s/tree)	2.1	0.2	2.3	0.3	2.6
Petrol (s/tree)	0.0	0.1	0.1	0.3	0.3

Overall Productivity

Putting all previously mentioned in-forest measurements together results in Table 12 and Table 13 summarizes key results shown so far. This shows that excluding the time walking between trees, changing batteries or refuelling, battery-powered chainsaws are a factor of 2.2 slower/less productive than the petrol-powered chainsaws. This table also shows that the battery-powered chainsaw has the largest difference from the petrol-powered chainsaw in felling and post-felling. These are the activities that require the larger diameter cross-sections to be cut. For a battery-powered chainsaw to compete with the productivity of a petrol-powered chainsaw the aspect most critical to focus on is the efficiency of felling and making larger cuts faster. Figures 20 and 21 show how each chainsaw type caused the operators to spend their time felling a tree on average using the numbers from Table 12. These show that delay times are not as important of an area for improvement, amounting to only 6% of the total average time to fell a tree using the battery-powered chainsaw.

Table 12: Average time per tree of each measured activity during in forest trial.

	Pre-fell	**Felling**	**Post-fell**	**Delays**	**Total**
Electric (s/tree)	7.7	23.3	10.1	2.6	43.7
Petrol (s/tree)	5.1	10.1	4.0	0.3	19.5

Table 13: Factors of time and rate difference described in this report.

	Time			**Felling Rate**		**Cutting Rate**	
	Felling	**Pre/post-fell**	**Delays**	**Unadjusted**	**Per kW**	**Unadjusted**	**Per kW**
Petrol	1	1	1	1	1	1	1
Battery	2.3	1.7	8.7	2.1	0.9	1.8	1.2

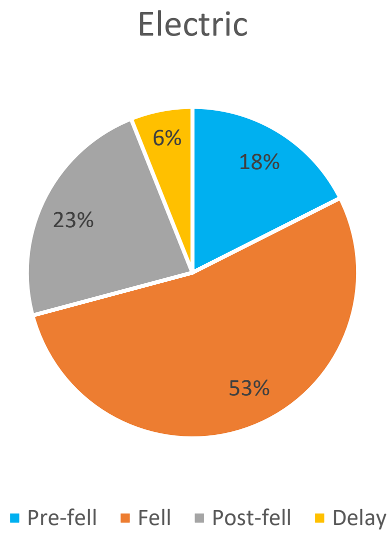

Figure 20: Average time spent per tree on each measured activity using a battery-powered chainsaw.

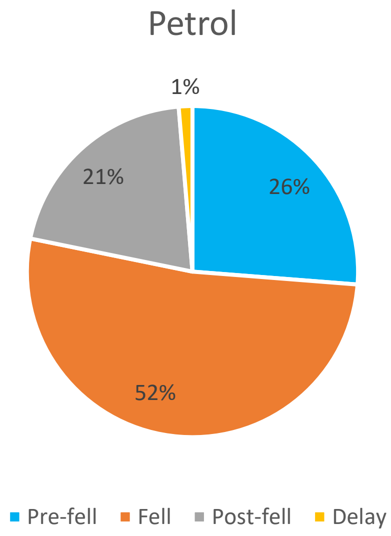

Figure 21: Average time spent per tree on each measured activity using a petrol-powered chainsaw.

The productivity recorded from the in-forest gross time study is shown in Table 14 along with results using the same measurement technique used in the earlier study by the author (MacDonald, Harvey and Visser, 2023). The data from the two studies were combined to show a total average. The result from the gross measurements taken in this study show the two chainsaw types performed very similarly, while in the forest trials in the previous study show the difference in productivity is greater than a factor of two. This is likely down to variations within the individual stands and operator performance. Figure 22 shows that there is significant overlap between the two chainsaw types when every period of productivity measured in the two studies is plotted. This shows the result from this study is possible due to the variance when using the chainsaws of the same/similar type. Performing a double population t test using the combined data from the two studies shows the petrol-powered chainsaw is significantly more productive with 97.5% confidence.

Table 14: Average trees per hour rate recorded during study by MacDonald, Harvey and Visser (2023) and during this study's in-forest trial.

	This Study		MacDonald et al. (2023)		Average	
	Petrol	**Electric**	**Petrol**	**Electric**	**Petrol**	**Electric**
Trees/hr	67.8	64.8	93.6	43.8	87.7	49.8
Std. Dev.	13.0	9.3	54.2	23.4	48.6	21.8
Average Stump	17.6	17.6	15.8	15.8	16	16

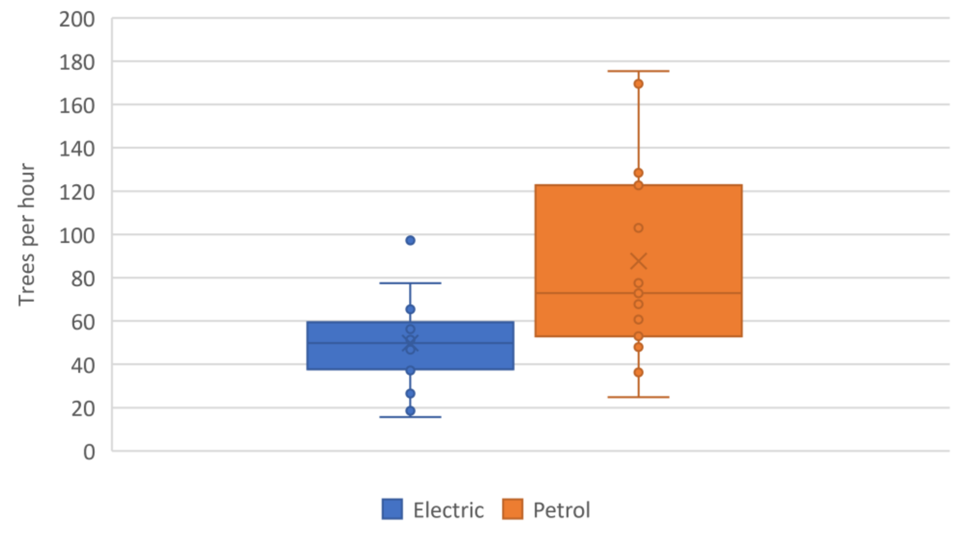

Figure 22: Box and whisker plot of trees per hour rates recorded in this study and the study by MacDonald, Harvey and Visser (2023).

The time taken by the operators to move between trees, and complete other actions that are not part of felling any individual tree when thinning were not directly observed in this study. However, these times can be estimated using the data which was recorded. By taking the average time to fell a tree from Table 12 the number of trees per hour can be calculated assuming there is no time taken between trees. This results in the trees per hour rate shown in Table 15. By then finding the difference in this theoretical trees per hour rate and the average measured trees per hour rate and multiplying this by the average felling time of an individual tree once again, the time per hour not spent felling can be calculated as shown in Table 15.

This value is calculated using the measured trees per hour rate from only this study's in-forest trial. This is done as without having a larger data set to average from, this calculated non-felling time only truly relates to the forest stand and operators within this study. However, it still gives insight into how thinning productivity changes due to chainsaw type. The values for non-felling time shown in Table 15 show that when using the petrol-powered chainsaw the operators are taking a considerably longer time between trees with almost 39 minutes per hour taken versus 10 minutes 36 seconds for the battery-powered chainsaw.

Table 15: Productivity calculated from average time of measured activities during thinning.

	Seconds/tree	Trees/hour	Non-felling time (mm:ss)/hour
Electric	43.7	82.4	10:36
Petrol	19.5	184.6	38:56

This difference could be due to the physical exertion threshold the operators want to maintain in order to be able to sustain a physically demanding job. By moving slowly between trees with the petrol-powered chainsaw they may be giving themselves a chance recover before felling the next tree. The lighter weight of the battery-powered chainsaw may also help in moving between trees faster.

Battery Performance

Using productivity data from this study and the authors previous study the average time for a battery to last during thinning and the average number of trees a battery could fell was able to be calculated. The result of this is shown in Table 16. At an average run time of 34 minutes, and assuming a thinner uses the chainsaw for five hours (not including breaks) a day in the forest they would require nine battery charges to get through the day. At 1.8 kg each, if the operator had to carry this many with them it would weigh 16.2 kg. With the addition of the rest of a standard thinning kit this would require the operator to carry over 20 kg worth of gear. In the trial run in this study and the authors previous study the operators have only ever carried three batteries or less. It is likely that increasing this weight by a factor of three would increase the physical requirement of thinning and possibly slow the operators down, decreasing productivity.

Table 16: Average run times and trees felled using a Stihl AP 300s battery in a Stihl MS 220c chainsaw.

Time (m)	**Trees**	**Average Stump Diameter (cm)**
34.0	27.1	16.0

If the batteries were able to be charged in the forest and the stand being thinned allowed the operators to access the battery charging station easily then this could allow less batteries to be carried and purchased per operator. Stihl (2023) has measured the charge time of the AP 300s batteries to be 80 minutes with the recommended charger and 45 minutes with their fast charger. With the 80 minute scenario this would allow an operator to bring three fully charged batteries with them and leave three more fully charged batteries at the charging station. They could then thin until their three batteries run out, return to the charging station, place all their used batteries on charge and swap them for the three fully charged ones. This would allow an operator to thin for as long as needed, so long as the charging station has sufficient amp hours to charge the batteries. With the 45 minute charging scenario the number of batteries the operator is required to carry drops to only two, therefore also requiring one fewer charger per operator.

This situation represents the ideal but thinning in New Zealand forests is often done where operators must travel by foot for a significant amount of time to reach where they are working, making a charging station not always a viable concept. Instead thinning operators may have to wait until battery technology becomes energy dense enough such that they can complete a day of thinning while carrying a reasonable weight and do not have to frequently return to their vehicle to swap batteries.

Financial Analysis

The battery-powered chainsaw was shown to be less productive the petrol-powered chainsaws currently in use. The petrol-powered chainsaw also appears to be the cheaper option. Table 17 shows the costs of each chainsaw type used in the in-forest trial of this study will incur over five years of use. This shows that while the battery-powered chainsaw is a cheaper up-front purchase, buying enough batteries for an operator to work productively makes the upfront cost of the battery-powered chainsaw $3010, $760 more than the petrol-powered chainsaw. However over the five years the petrol-powered chainsaw would use over $5000 worth of fuel and engine oil. Using these costs and the trees per hour rate from above the battery-powered chainsaw is $5.85 cheaper per 1000 trees felled. These results were made using the assumptions listed below.

- Five hours of chainsaw use per day for five days a week and 30 weeks a year.
- The MSA 220c is purchased with one battery and one charger.
- The MS 462 uses three tanks of petrol per day.
- Five additional batteries are purchased for the MSA 220c every five years. Assuming the batteries last 1000 charge cycles.
- One tank of fuel is $2.30 assuming a 50:1 petrol to oil ratio.
- No extra chargers, cost of charging/power or charging stations are factored in.
- All other costs are equal, and therefore excluded, including bar oil.
- No inflation or discount rate.
- Prices used are current prices as of September 2023 (Stihl, 2023).

Table 17: Costs and financial efficiency of Stihl MSA 220c and MS 462.

Costs	Chainsaw	Extra Batteries/Fuel for 5 years	Trees/5 years	$/1000 tree
Stihl MSA 220c	$1,245.00	$1,875.00	186,800	$16.70
Stihl MS 462	$2,240.00	$5,175.00	328,800	$22.55

The results shown above do not show a complete picture. While on a per tree basis the battery-powered chainsaw is more cost efficient, it will only get through 57% of the area. This will increase the cost of thinning for forest owners, and/or decrease revenue for the thinning contractors. These costs are also far lower than the labour costs associated with thinning. Therefore these results do not show that battery-powered chainsaws are more cost efficient, but rather if their productivity can be increased while their costs are kept to a similar level, they have the potential to be more cost efficient. A break-even analysis showed that if the battery-powered chainsaw were to have a productivity equal to the petrol-powered chainsaw, then it could have an initial chainsaw cost of ~$5,500 and be equally cost effective. This is due to no fuel usage. This is double the current MS 462 price, and if/when a battery-powered chainsaw is released with this productivity potential it likely will be cheaper, making it more cost effective (not considering charging costs).

Survey

After two days of using the chainsaw the operators were asked a short series of questions regarding their experience.

Q: Did you feel one chainsaw caused you more delays than the other?

A: Felt like waiting through the added cutting time of the battery-powered chainsaw was a delay; battery issues caused the chainsaw to sometimes become unresponsive; the battery-powered chainsaw died mid-cut in larger trees but performed just as good in the small trees.

Q: Do you think the number of delays would decrease if you had a few months experience with it?
A: Yes, but depends on the block, in larger trees maybe not.

Q: What caused each chainsaw to be more or less productive than the other?
A: Was not able to push the battery-powered chainsaw through the cut.

Q: Other comments.

A: The bar on the battery-powered chainsaw is flimsier, may be due to one bolt design rather than two on the petrol chainsaw, this makes it less effective as a walking pole on steep slippery ground.

A: Using the battery-powered chainsaw you get more of a rest while felling.

The answers given above show that the operators mostly agree with what the results of this study have found. Saying that they were not able to push the battery-powered chainsaw through relates to what was found in the controlled cutting rate test where the battery-powered chainsaw maintained a similar cutting rate through the inner and outer sections, likely prohibited by chain type and power output. The extra comments the operators gave were very insightful into their experience using the chainsaws. They both agreed that having a sturdy bar is advantageous as it allows them to use the chainsaw as a walking pole in the steepest sections, aiding their movement between trees. The MSA 220c has only one bolt attaching the bar to the main body, whereas the MS 462 model the operators normally use has two bolts to attach the bar.

Another good insight was the comment that when felling with the battery-powered chainsaws they felt like they got more of a rest. This relates well to the estimates of non-operating time per hour. Having more of a break while felling may make the operators better able to manoeuvre between tree at a better pace. The operators may also use the time between trees when using their petrol-powered chainsaws as a chance to catch their breath. This could be why the times for moving between trees for the petrol-powered chainsaw were much higher than for the petrol-powered chainsaw.

Conclusion

This report set out to compare and investigate the differences in thin-to-waste productivity between the commonly used petrol-powered chainsaws and the emerging technology that is battery-powered chainsaws. To analyse productivity this study broke thinning down into smaller components to understand where the differences in productivity between the chainsaw types originate. When looking at the time the chainsaws take to fell trees in the forest the petrol-powered chainsaw proved its superiority with an average felling time of 10.1 seconds, vs 23.3 seconds for the battery-powered chainsaw. When the time to prepare for felling and any post felling cuts were added to these times the petrol chainsaw remains well ahead of the battery-powered chainsaw with 19.5 seconds taken per tree on average versus 43.7 seconds for the battery-powered. This results in the petrol-powered chainsaw being a factor of 2.2 faster at felling trees than the battery-powered.

When analysing the rate of cutting it was found that in the forest the battery-powered chainsaw performed better per kilowatt of power output than the petrol-powered chainsaw on average. However, when looking at the trees felled with larger diameter stumps the petrol-powered chainsaw showed that it was able to increase its cutting rate while the battery-powered chainsaw did not. This led to the battery-powered chainsaw taking an increasingly greater amount of time the larger the stumps got compared to the petrol-powered chainsaw. This result was backed up by a similar result from the controlled cutting rate test carried out where the battery-powered chainsaw had a continuous cutting rate throughout a round profile, whereas the petrol-powered chainsaw had a higher rate in the centre of the profile. This shows that the petrol chainsaw has the power to make having more teeth in the cut make the cutting rate higher.

This is a promising result for the battery-powered chainsaw, as by felling at a higher cutting rate per kilowatt with a less efficient semi-chisel chain it has plenty of room for improvement. The felling time results from this study are in contradiction to the result from the authors previous study where in smaller diameter stands the petrol-powered chainsaws performed far better. Not enough chainsaws were tested in similar conditions in this study to gauge whether power output has a linear correlation with cutting rate. However, this study has shown that power output is the key factor in cutting rate, as in both the in-forest trial and controlled cutting rate test the rate per kilowatt of power output have been very similar with difference factors of 1.1 and 1.2 respectively.

Delays were found to be very uncommon and cause an insignificant amount of lost time when using the petrol-powered chainsaw, with only two chainsaw related delays recorded in total in-forest amounting to an average of only 0.1 seconds per tree. For the battery-powered chainsaws delays were more substantial, with 15 chainsaw related delays recorded in-forest amounting to 2.3 seconds per tree. Removing delays however would only improve felling time by 6%, therefore improvements that can address other areas of felling are likely more beneficial. In the controlled cutting rate test the chain become jammed a similar number of times for both chainsaws (six for battery-powered and five for petrol-powered). This test is not directly comparable with the in-forest trial results due to environmental and cutting technique differences, but was able to show where the chainsaw become more commonly jammed, both became jammed more frequently in the lower 30% of the cut profile where the entire width of the bar is within the cut. This shows that for both chainsaws having more friction with more teeth in the cut makes becoming jammed more likely.

The overall trees per hour rate found in this study and the author's previous study shows that petrol-powered chainsaws are still dominant in simply their trees per hour rate with the combined data showing that they on average achieve 87.7 trees per hour compared to 49.8 trees per hour for the battery-powered chainsaw. This difference of a factor of 1.8 is currently too great for the potentially cheaper cost of a battery-powered chainsaw. There may be potential that if this gap were to become closer that this lower productivity may be a worthwhile set back to take advantage of the health and environmental benefits of a battery-powered chainsaw.

From looking at all the results from this study battery-powered chainsaws such as the Stihl MSA 220c with power outputs of around 2.1 kW are not yet a viable replacement for the current chainsaws used in thinning which have power outputs above 4 kW. With more development and new chainsaws being produced like the recently available Stihl MSA 300 which outputs 3 kW, the productivity performance gap may be close to becoming narrow enough for adoption into the forestry industry. For complete adoption the battery weight for would have to decrease, and/or the battery run time increase. A safe in-forest charging solution could help adoption of battery power in forests before technology gets to a sufficient battery energy density.

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Photo 8: Makerikeri Silviculture in Ashley Forest holding the Stihl MSA 220c.

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