

A Comparative Study of the Influence that Motor-Manual Felling and Mechanised Felling has on Stem Breakage

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S. D. Andrews

**New Zealand School of Forestry
University of Canterbury
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Abstract

Motor-manual felling has been the predominate method of severing trees in the felling process of a forest harvesting operation. Yet this method has been coupled with numerous injuries and deaths, as trees can strike fallers during this task. An alternative felling method was developed in the form of mechanised tree felling, in an attempt to reduce the frequency of injuries. Subsequently, mechanised felling is poorly understood when compared to motor-manual felling upon the impact it has on stem breakage.

183 trees were assessed by measuring the frequency of breakage, height of the first break and the volume retention abilities of three felling treatments; motor-manual, mechanised felling out of the stand and mechanised felling into the stand. The effect that directional felling had upon the length to the first break was also investigated for motor-manual and mechanised felling out of the stand.

The percentage of stems that broke once felled was 73%, 76% and 94% for motor-manual, mechanised out of the stand and mechanised into the stand felling respectively. The height at which the first break occurred for the aforementioned felling treatments was 71%, 71% and 69% of the total tree height. Mechanised felling out of the stand had the greatest volume retention ability with 94.5% of the trees total volume being below the first break. Followed by 93.7% for motor-manual and 91.9% for mechanised felling into the stand, however these differences were statistically insignificant ($p=0.14$). Lastly the length to the first break for motor-manual and mechanised felling out of the stand failed to statistically change when a tree was felled through a range of directions from downhill to uphill.

The influence that motor-manual felling and mechanised felling out of the stand had on stem breakage is similar, yet mechanised felling into the stand had a much greater impact on the percentage of stems that broke. With further improvements in technology, it could be seen that the number of mechanised tree-felling operations over take motor-manual felling, as their impact on stem breakage is comparable.

Key words: Felling, stem breakage, motor-manual felling, mechanised felling, Pinus radiata, radiata pine, harvesting.

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3. Introduction

Tree felling is one of the first tasks required to harvest a forest. It can be performed either motor-manually with a chainsaw or mechanically with an excavator and a felling head. Furthermore, trees can be felled into the stand or felled out of the stand.

In the past 10 years there has been a significant increase in the number of mechanised harvesting operations and particularly mechanised tree felling (R. Visser, 2015). Worksafe have been a key driver behind the increasing number of mechanised tree felling operations, due to the improved safety benefits that it offers opposed to motor-manual felling (WorkSafeNZ, 2014). However given the sudden increase of mechanised tree felling, there is limited information regarding the effect that it has upon stem breakage.

A standing tree only has a potential value, which is realised once the stem has reached the landing and has been bucked into logs. Previous studies have suggested that the potential value of a tree can be reduced by 40% solely due to the impact that felling has upon stem breakage (Conway, 1976). Hence it is of great importance to understand the influence of different felling methods and the effect it has upon stem breakage and value recovery.

There have been numerous studies that have addressed the influence that motor-manual felling has upon the breakage of *Pinus radiata* stems in New Zealand. Yet there has been only one study that has looked at the effect of mechanised felling. However, there has not been a study that provides a comparison between the two alternatives and the impact that felling into the stand has compared to felling out of the stand.

There are multiple opinions amongst harvest crews and forest owners in regard to which felling method results in the greatest severity of stem breakage. This study will attempt to clarify which method has the greatest impact upon stem breakage and ultimately value recovery.

3.2. Problem Statement

The New Zealand forest industry is largely recognised as a dangerous industry, as the forestry sector has, on a per worker basis, the highest rate of fatalities of any industry over the last five years (Work Safe NZ, 2014). Throughout this period there have been 28 deaths; this is a 1:350 chance of death for people working in the forest and further a 1:20 chance of serious injury. The largest contributing factor associated with these deaths and injuries is motor-manual fallers being struck by an object during tree felling. This accounts for 52% of all fatalities and 35% of all serious harm. The concern for safety along with improving technology and innovation have led to the increase of mechanised tree felling operations in New Zealand.

Despite the increase in mechanised tree felling, there is limited information regarding the breakage characteristics that a tree exhibits when felled. The breakage characteristics of a tree during motor-manual felling have been sufficiently documented, as this was the most commonly employed felling method. However, there are currently no New Zealand specific studies that provide a comparison between the two aforementioned felling methods. Furthermore, mechanised tree felling provides the opportunity to fell trees both into and out of the stand, which often cannot be done via motor-manual felling due to safety issues.

3.3 Objectives

As such, the main objectives of this study:

1. Determine the percentage of trees that break through each felling treatment.
2. Determine the associated relative break height of a stem following either motor-manual, mechanised out of the stand or mechanised into the stand tree felling.
3. Develop a breakage function for each felling treatment where any differences are considered to be significant.
4. Determine the retention of volume below the first break that can be achieved by each treatment.

4. Review of Literature

The practice of motor-manual felling has been the mainstay method in New Zealand forestry for many decades (R. Visser, Raymond, K., Harrill, H., 2014). Subsequently, as the industry has developed and particularly through the late 1990's to early 2000's, there was a burst of activity, as contractors looked to move away from motor-manual methods and increase the mechanisation of logging operations (Riddle, 1995). The Health and Safety Act (1992) has been the main driver behind this increase, as mechanised tree felling provides an alternative to motor-manual felling and an opportunity to improve safety. Multiple studies have been conducted to provide a breakage function to predict the point at where a stem will break. This literature review will focus on these discoveries specific to *Pinus radiata*.

4.1 Breakage and Relative Break Heights

Several breakage function equations have been developed for *Pinus radiata* in different locations of New Zealand. The equations are used to predict the point at which a stem will break subject to specific stem characteristics, such as DBH tree height and felling method (Lambert, 1996). There is a lack of knowledge surrounding mechanised felling and this may be resulting in a loss of potential value. Conway (1976) stated that there is the possibility of up to 40% of the stands value being lost during felling. This suggestion may be slightly conservative, however the knowledge deficit still needs to be rectified to ensure maximum value is retained during tree felling.

Manley (1977) carried out a motor-manual breakage study across 20 compartments of an untended old-crop *Pinus radiata* stand in the Kaingaroa Forest area. It was found that 99.26% of the 541 stems felled during this study broke. Of those broken stems, the relative break height, which is a percentage of the length to the first break over the total tree height, was 67%.

Following on from Manley, Murphy and Gaskin (1982) studied the percentage of stems breaking and the relative break heights of a 41 year-old tended *Pinus radiata* stand in the Whakarewarewa State Forest. It was reported that less than

1% of the trees that were motor-manually felled did not break and the average relative break height was 70%.

Murphy (1984) carried out another motor-manual felling study in a Tairua State Forest. It was found that 73% of the 171 untended, 43-year-old *Pinus radiata* stems broke and the relative break height was 83%. This relative break height was significantly different from the relative break height indicated by Manley (1977) and Murphy and Gaskin (1982).

In 1987 Twaddle, reported by (Lambert, 1996), reviewed the piece size characteristics after motor-manual felling in both the Kaingaroa Forest and Kinleith Forest. The relative break height of a 31-year-old *Pinus radiata* stand was 66% and 65% for Kaingaroa and Kinleith respectively.

Lambert (1996) studied the breakage characteristics of *Pinus radiata* when mechanically felled by two different types of felling machines in the Kinleith Forest. For trees aged from 25 to 30, the percentage of stems that broke ranged from 84% to 100%. The relative break height across the two felling machines was on average was 76%.

Lastly, Fraser, Palmer, McConchie, and Evanson (1997), conducted a motor-manual breakage study across 20 sites in the North Island and South Island. Of the 1000 stems felled, 68.6% broke and the resulting relative break height of those 686 stems was 67%.

Table 1: Description of the percentage of broken stems and relative break heights of the previous studies conducted in New Zealand.

Author	Location	Breakage	Relative Break Height
<i>Manley (1977)</i>	<i>Kaingaroa Forest</i>	99.30%	67% (age unknown)
<i>Murphy & Gaskin (1982)</i>	<i>Whakarewarewa Forest</i>	99%	70% (age 41)
<i>Murphy (1984)</i>	<i>Tairua Forest</i>	73%	83% (age 43)
<i>Twaddle (1987)</i>	<i>Kaingaroa & Kinleith</i>	% unknown	66% (age 31)
<i>Lambert (1996)</i>	<i>Kinleith Forest</i>	84 – 100%	76% (age 25-30)
<i>Fraser et al, (1997)</i>	<i>New Zealand</i>	69%	67% (age 29)

The average percentage of stems that have broken across a range of sites throughout New Zealand is 86.46%. Additionally the average relative break height of these studies is 71%. There does appear to be a trend with increasing age resulting in an increase in the relative break height. However the same trend does not appear as obvious for tree age and the percentage of stems that break during felling. This may be a result of different study sites and variations in stem density (Murphy, 1984).

4.2 Relationships Developed

A major focus of previous research was to establish if there was an interaction between breakage and forest features such as tree characteristics and terrain. In most studies the concluding result was that relative break height multiplied by the total tree height is the most accurate method to predict the point at where a stem will break. Of the few studies that did develop a breakage equation, they are characterised by a poor ability to predict the break point due to the numerous influences that affect tree breakage, which cannot be accurately factored into one equation.

Lees (1969) conducted a study in the Golden Downs Forest looking specifically at breakage and the effect on sawlog yield. He found that when motor-manually felling *Pinus radiata*, the strongest breakage relationship existed between the diameter at the point of the break (DPB) and the diameter at breast height (DBH) of the tree. Lees suggested that the DPB is on average 50% of the DBH. Furthermore, the average volume of the stem below the first break ranged from 85% to 86.5% of the trees total volume for a range of DBH's from 25.4 cm to 60.9 cm. Suggesting that the most applicable method to estimate stem breakage and expected sawlog yield was to use the half DBH to DPB relationship in conjunction with the finding that 86% of a stem's volume will be below the first break.

Manley (1977) attempted to develop a breakage function for *Pinus radiata*, Douglas fir and Corsican pine. It was found that a breakage function to predict the height of the first break was difficult to develop. The most accurate predictor

of break height was to say that “relative break height for a species was approximately normally distributed with a certain mean and variance” (Manley, 1977). The main impairing factor restricting the ability of a breakage function to be derived was the numerous variables that influence breakage. Manley suggested that the greatest issue in developing an equation was due to the variations in the landing zone such as already felled stems, stumps and uneven ground. Manley stated that only slope and stocking were taken into account when categorising the landing zone. Yet the effect of slope and stocking upon stem breakage was considered insignificant in regard to predicting the height of the first break.

Following the work by Manley, Murphy (1982) carried out a directional felling study in a 34-year-old *Pinus radiata* stand in the Tauhara Forest. Murphy found that the DPB was approximately half the DBH. He also suggested that directional felling across slope rather than downhill increased the length to the first break by three to six metres. The higher valued log grades are towards the bottom of the stem and decrease in value further up the stem; thus a three to six metre increase in the length to the first break would result in increased financial benefits.

Murphy and Gaskin (1982) investigated the influence that felling direction had upon stem breakage. The effect of felling downhill (crossed), downhill (parallel), across slope and 45° uphill was examined. The relative break heights of downhill (crossed), downhill (parallel), across slope and 45° uphill were 68%, 71%, 69% and 71% respectively. A stem had the greatest probability (8%) of not breaking when being felling across slope and 45° uphill. Due to the relative break heights being so similar across a range of 135°, it was not the felling direction that was the greatest cause of breakage. Murphy & Gaskin believed that the three greatest contributors to breakage were changes in the slope where the tree lands, crossing over logs and malformed trees.

Murphy (1984) carried out a third study looking at breakage rather than directional felling. He found the major cause of breakage was due to trees crossing over other trees and variations in slope across the felling site. Murphy

suggested that slope steepness was not a significant contributor to the relative break height or the number of broken pieces within the stem. However, tree size was considered to have a significant effect on stem breakage. Murphy found that the smaller the tree, the lesser the probability of that stem breaking. Once a tree had a DBH greater than 50cm, the probability of the stem breaking was approximately 80%. While a stem with a DBH less than 25cm had a 50% chance of breaking. Murphy attempted to develop a linear model to predict the relative break height as a function of total tree height, however this model had a low predictive ability, ($r^2=0.08$). Lastly, Murphy stated that the Tairua Forest was considered as a forest with high-density wood, $> 475 \text{ kg/m}^3$. The normal basic density of *Pinus radiata* wood is 400-420 kg/m^3 (Radiata pine wood density, 2003). This allegedly denser and consequently stronger wood could have been a contributing factor reducing the occurrence of stem breakage and might explain the higher than normal, relative break height (83%).

Lambert (1996) conducted a study in the Kinleith Forest on the stem breakage of *Pinus radiata* as a result of mechanised felling using a Bell TF120 feller-buncher and a Timbco T445 hydro-buncher. Lambert's is the only study to date assessing the breakage during mechanised felling of *Pinus radiata* in New Zealand. Lambert found that crossing over or hitting already felled trees was the highest identifiable cause of breakage; followed by hitting a stump and changes in the slope of the felling site. Lambert developed a breakage equation, which found that the DPB and relative break height could be predicted by the height of the tree and the felling machine used. The two models developed had a moderate predictive ability ($r^2=0.54$ & 0.48). Lambert believed that the proportion of unexplained variability in the models was due to the effect of landing site and suggested that this was a significant contributor to stem breakage.

Fraser et al. (1997) investigated the breakage of *Pinus radiata* across 20 sites in New Zealand. This study determined that 27% of all breakage was due to changes in slope across the felling site, followed by 21% of the breakage being attributed to crossing stems. The results indicated that the greater the DBH of the tree, the greater the probability of the stem breaking. An equation was developed to predict the point of break, which used the variables tree height and site as the

predictors of the height at the first break. However, the point of break model had a low degree of accuracy ($r^2= 0.25$).

From the analysis of the studies that have been conducted to date, there is suggestion that relative break height is inconsistent throughout New Zealand (66%-83%). There was a reoccurring theme that landing zone had a substantial effect on the percentage and location of the break in the stem. Other variables such as tree characteristics (height, DBH, density) are also seen to impact stem breakage.

Research suggests that as technology and methods have improved, the likelihood of a stem breaking has decreased, with the exception of Lambert's 1996 study. Yet as mentioned by Twaddle (1987) in Lambert's (1996) paper, "other reasons for stem breakage, not yet fully understood, relate to the physical structure of *Pinus radiata* and the dynamics involved when a tree strikes the ground."

5. Methodology

5.1 Harvest Area & Study Site

This study was conducted in the Maramarua Forest, which is approximately 70 km Southeast of Auckland, New Zealand. This forest is managed by Rayonier Matariki Forests and comprises mainly *Pinus radiata*.



Figure 1: Location of study area

The trees measured in this study were 27 years of age and had been pruned. They were exposed to similar conditions such as soil type, annual rainfall, mean annual temperature and daylight hours. As such, characteristics were considered similar leaving felling method as the sole influence upon breakage. Basic stand data is presented in Table 2.

Table 2: Basic stand details of the Maramarua Forest Area.

<i>Age</i>	27
<i>Stocking (stems/ha)</i>	360
<i>Mean Top Height (m)</i>	38.0
<i>Mean Basal Area (m²/ha)</i>	51.9
<i>Total Recoverable Volume (m³/ha)</i>	527

A designated area was chosen for each felling treatment, which ensured that terrain features and slope were as similar as possible across all study sites. Site 1 was where the motor-manual felling component of this study was performed; a Southeast facing gully with a slope of 45% (Figure 2).



Figure 2: Site 1 was the area where all motor-manual felling was performed on a slope of 45%.

Site 2 was where the mechanised felling out of the stand component was carried out; it did not contain any undulating terrain features, was Northwest orientated and had a slope of 41% (Figure 3).



Figure 3: Site 2, the area where mechanised felling out of the stand was tasked on a slope of 41%.

Site 3 was where all mechanised felling into the stand was performed. This area had a mean slope of 38%, was Northwest facing and was located near the edge of a forest road (Figure 4)



Figure 4: Site 3, the area where all mechanised felling into the stand took place on a slope of 38%.

All sites were free of bluff features or terrain factors that may have created bias between sites. Unfortunately it was not feasible to perform this study in a single site, as the data collection required the assistance of two different crews whom were working in different settings under production constraints.

5.2 Motor-manual Felling

The person who performed all motor-manual felling was part of the Davis 91 crew and was considered as an experienced tree feller. This particular tree feller was the recipient of the NZ Logger Top Spot 1st place Tree felling award in 2014 and 4th place in 2013 (Ellegard, 2015). The motor-manual felling was completed with a Stihl MS 660 Magnum chainsaw. The bar used during the study was the standard 24-inch bar. In the situation when a tree needed extra directional assistance, wedges were used to provide a guiding force in the desired direction. All motor-manually felled trees were felled out of the stand; this is the common practice as it reduce the possibility of stem hang-ups and because it is difficult to motor-manually fell a tree in a direction that opposes its natural lean.

5.3 Mechanised Felling

When mechanised felling, one operator was used for both felling into and out of the stand in an effort to reduce bias by retaining consistency and accuracy. This machine operator was considered highly competent with eight years' experience in operating felling machines. The machine used was a Caterpillar 552 series 2 tracked felling machine with a Satco 630 directional felling head. It is designed to operate on steep slopes (up to 40%) (Competenz, 2005) with the help of a three cylinder hydraulic tilting system to enable self-levelling. The Caterpillar 552 is capable of being assisted via a tethered system to increase its ability to operate on steep slopes. However, the machine used in this study was not tethered.

5.4 Sampling Method

During motor-manual felling, one tree was felled, measured and then the next tree was felled and the process repeated. When mechanically felling, a line of trees, (15 to 20) were felled and laid parallel, allowing for adequate access to measure each tree. The mechanically felled trees were not shifted to achieve the optimum angle of lay for extraction. If this additional contact did occur, it may have resulted in further breakage and difficulties determining the number of broken pieces and the total tree height.

5.5 Measurements

A descriptive diagram of where measurements were taken can be found in the Appendix, Figure 2.

For every tree that was felled the following measurements were recorded:

- Diameter at Breast Height: Breast height measurement of the diameter of the tree outside of the bark using callipers was taken before the tree was felled. Two measurements were recorded at right angles and averaged to the nearest centimetre.
- Length to the first break: Measured from the back cut to the first break. The measurement was the distance from the back cut, to the point where

a flush crosscut was assumed with the focus of reducing the waste of merchantable timber and recorded to the nearest centimetre.

- Diameter at the start of the first break: Measured using callipers directly before the first break at the point where a flush crosscut was assumed. Two measurements were taken at right angles to each other, with the average diameter recorded to the nearest centimetre.
- Diameter at the end of the first break: Measured using callipers directly after the end of the first break at the point where a flush crosscut was assumed. Two measurements were taken at right angles to each other with the average diameter recorded to the nearest centimetre.
- Length to the second break: The measurement was the distance to the nearest centimetre from where a flush crosscut was assumed with the focus of reducing the waste of merchantable timber to the point where the next crosscut would occur as a result of the second break.
- Length to crown: Determined by measuring to the nearest 0.1 metre from the back cut, up to the first whorl where all the branches contained within that whorl had green foliage.
- Stem length: Determined by the distance from the back cut to the point where the stem diameter is 10cm. The distance was recorded to the nearest 0.1 metres.
- Tree length: Measured directly from the back cut to the apical shoot or apex of the crown. When treetops were broken, estimations were made as to the length of the unmeasurable piece and this value was added to the measured length and recorded to the nearest 0.1 metres.
- Angle of lay: The angle that the tree laid once felled. Angle was recorded via a compass to the nearest degree. The variation in angle of lay was then calculated via the difference in angle between directly downhill (0°) and the felled stem (Figure 5).

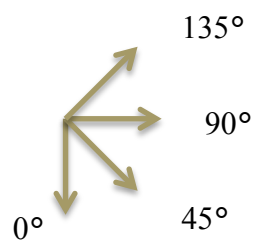


Figure 5: A description of the angle of lay (0° is directly downhill regardless of the compass heading of the felling slope). The angle of lay for each tree is the difference in the angle that the tree is laid on compared to directly downhill.

5.6 Study Design

The work routine for the motor-manual felling component was:

1. Select an area within the harvest site where the trees can be felled whilst ensuring a safe distance is maintained from the harvesting operation.
2. Measure the average slope of the felling site and note terrain features.
3. Manual tree feller will fell tree while the researcher is in a safe position during felling process. Once finished, the tree feller would give the researcher the OK signal to start the measurement process. The researcher was able to be within two tree lengths away from the falling tree, subject to the Approved Code of Practice for Safety and Health in Forest Operations, clause 11.4.3, (MBIE, 2012).
4. The researcher would then begin measurement process for the individual stem and record the details.
5. The researcher would then retreat back to a safe location before notifying tree feller to begin felling next tree and the process repeated.

The work routine for the mechanised felling component is as follows:

1. As per motor-manual felling work routine step 1.
2. Ensure the researcher has radio contact with the machine operator.
3. Measure average slope of felling site and note terrain features.
4. The researcher must retreat a minimum of two tree lengths away from the mechanised felling operation (MBIE, 2012).
5. Felling machine operator to fell a line of 15 – 20 trees and lay them in a parallel manner to allow for measurements to be taken.
6. Felling machine operator to signal or communicate to the researcher that it was OK to begin measuring the trees.
7. Researcher measures each individual stem and records the details.
8. The researcher would then retreat back to a safe location (minimum of two tree lengths away from felling machine) before notifying the machine operator to begin felling the next line of trees.

5.7 Data Analysis

The data set was screened and no outliers were found. Data was tabulated to provide a summary of means, standard deviations and the range of the data contained within each felling treatment. A linear regression was developed to predict total tree height. In the scenario where a tree broke post felling and the head or broken piece could not be identified, the total tree height could not be recorded. For the purpose of this study, total tree height was required; therefore, a predicted tree height was calculated. This was calculated through the relationship between the DBH and the tree height (Appendix, Figure 1). Every tree measurement in the data set contained a DBH; thus tree height was predicted from this variable.

An attempt was made to derive a breakage prediction equation. This equation utilised relative break height ($\frac{\text{break height}}{\text{total height}}$) rather than break height as the dependent variable; this increased the homogeneity and reduced the variability of the predictors in the equation.

The effect that DBH and felling direction had upon stem breakage during various felling treatments was explored. However, felling direction was only examinable for motor-manual and mechanised out of the stand felling. The effect that angle of lay had upon stem breakage was examined by assessing the length to the first break in relation to a deviation in the felling angle from directly downhill.

The volume of each broken piece above the first break was calculated assuming a three-dimensional formula for the volume of a coniferous log in New Zealand. The equation is as follows (Ellis, 1982).

$$V = \exp(1.944157 * \ln(L) + 0.029931 * d + 0.884711 * \ln((D-d)/L) - 0.038675) + 0.078540 * d^2 * L$$

Where V is the volume in the broken piece in cubic decimetres dm^3 ($1\text{m}^3 = 1000\text{dm}^3$). D is the large end diameter (LED) in cm, d is the small end

diameter (SED) in cm, L is the length in metres. Ln is the natural logarithm and exp is the exponential and the remaining numbers are coefficients.

The total volume of the stem was calculated via an equation associated with the volume under bark of a young crop (up to age 30) *Pinus radiata* stand in Kiangaroo (NZFRI, 1997).

$$V = (DBH^{b1}) * \left(\left(\frac{h^2}{h - 1.4} \right)^{b2} \right) * \exp(b3)$$

Where V is the volume of the stem in cubic metres (m^3), DBH is diameter at breast height (cm) and h is the height of the tree (m). The following variables are coefficients of the equation $b1 = 1.8264$, $b2 = 1.12869$, $b3 = -10.385$.

Lastly the volume retention of each stem was calculated by subtracting the stems total volume above the first break (irrespective of the number of breaks and size of the broken pieces) from the stems total volume. The total volume above the first break for each tree was calculated assuming a conical equation.

$$\frac{1}{3} \pi r^2 * length$$

Where r^2 is the radius of the diameter at the first break point and $length$ is the length from the first break point to the tip of the crown.

6. Results

6.1 Exploratory Data Analysis

The range of DBH and tree heights of the study are shown in Table 3. The minimum DBH was 23.9cm and the maximum was 65.1cm. The minimum recorded tree height was 22.7m, ranging to a maximum of 43.4m.

Table 3: The basic stand details of DBH and tree height for all trees measured for all felling treatments.

Characteristics of all trees (183)	Mean	Standard Deviation	Minimum	Maximum
DBH (cm)	42.6	8.3	23.9	65.1
Tree height (m)	33.9	3.4	22.7	43.4

DBH across the entirety of the data set is normally distributed (Figure 5) with a mean DBH of 42.6cm and a standard deviation of 8.3cm. Tree height exhibits a normal distribution albeit slightly skewed to the right (Figure 5). The mean tree height across all felling treatments was 33.9m with a standard deviation of 3.4m.

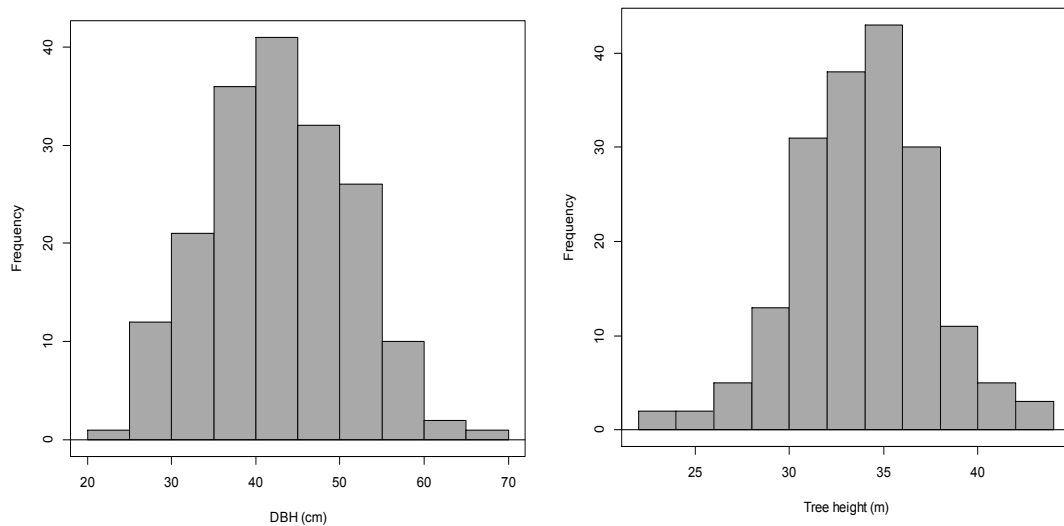


Figure 5: The frequency distribution of DBH (left graph) and tree height (right graph) of 183 trees for all felling treatments.

6.2 Percentage of Broken Stems

The stems that did not break during this study are characterised by the features shown in Table 4. The average DBH of the unbroken stems was smaller than the average for the entire data set as shown in Table 3 (a difference of 0.8cm). The average tree height was 0.4m greater in the unbroken stems than that of all the stems.

Table 4: The basic stand details of the DBH and tree heights of the trees that did not break for all felling treatments.

Characteristics of unbroken trees (34)	Mean	Standard Deviation	Minimum	Maximum
DBH (cm)	41.8	7.4	28.4	56.7
Tree height (m)	34.3	3.3	22.7	43.4

The percentage of stems that broke was considerably different between treatments and in particular the difference between felling out of the stand and felling into the stand. Motor-manual felling resulted in 73% of all stems breaking while mechanised felling out of the stand caused 76% of all the stems felled to break. Lastly mechanically felling into the stand broke 94% of all the stems felled.

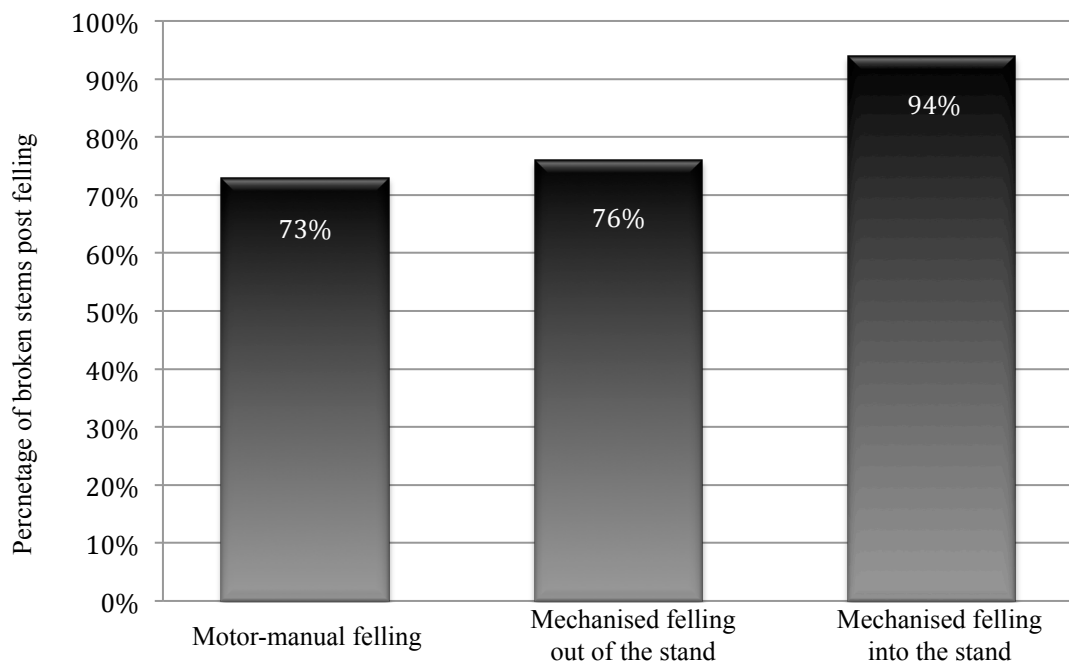


Figure 6: The percentage of broken stems as a result of each felling treatment.

A chi-squared test was performed to identify if the difference in percentage between each felling treatment was statistically different. There was a significant difference across all treatments ($p = 0.006$). The difference in stem breakage between motor-manual felling and mechanised felling out of the stand was insignificant ($p = 0.059$). The difference in percentage between mechanised felling out of the stand and mechanised felling into the stand can be attributed to the felling treatment ($p = 0.0071$).

6.2.1 Characteristics of the Material Above the Break

The characteristics of the material above the first break is shown in Table 5. Of all the stems that broke when motor-manually felled, the first broken piece (59% of broken stems) can be characterised by a LED of 21.2cm a length of 4.4m, an SED of 15cm and a volume of 0.079m^3 . 39% of the time, the material above first break, broke into two pieces. The second broken piece was characterised by a LED of 13cm, was 3.8m long, had a SED of 10cm and a volume of 0.044m^3 . When mechanically felling out of the stand, 52% of all broken stems had the first broken piece feature an average LED of 16.1cm, a length of 2.7m, a SED of 14.1cm and a volume of 0.049m^3 . When the stem had two broken pieces above the first break (33.3% of the time) the second piece had, a LED of 12.9cm, a length of 2.8m, a SED of 10cm and a volume of 0.032m^3 . Lastly, when mechanically felling into the stand, the features of the first broken piece were a LED of 18.1cm a length of 3.9m, a SED of 13.7cm and a volume of 0.080m^3 . The characteristics of the second broken piece above the first break when mechanically felling into the stand could not be determined, as the stem was pulled out of the stand and was separated from the material above the break. The characteristics of the third break are not included in Table 5 for each treatment as this occurred in only 11 stems out of 183 felled and was assumed valueless in regard to producing a log due to their small size.

Table 5: The large end diameter (LED), length, small end diameter (SED) and volume of the broken piece above the first break by felling treatment. The means are shown followed by the associated standard deviations in parenthesis.

	LED (cm)	Length (m)	SED (cm)	Volume (m ³)
Motor-manually felled ~ First broken piece (59.2%)	21.2 (8.3)	4.4 (2.7)	15.0 (3.6)	0.079
Second broken piece (34.6%)	13.0 (4.3)	3.84 (4.4)	10 (0)	0.044
Mechanically felled out of the stand ~ First broken piece (52.3%)	16.1 (4.5)	2.7 (1.7)	14.1 (3.7)	0.049
Second broken piece (33.3%)	12.9 (4.2)	2.8 (1.1)	10 (0)	0.032
Mechanically felled into the stand ~ First broken piece	18.1 (4.55)	3.9 (2.5)	13.7 (3.2)	0.080

6.3 Relative Break Height

The features of the stems that broke when felled via different treatments are shown in Table 6. The DBH amongst the three treatments had an average difference of 2.4cm. While the average tree height experienced a variation of 1.3m. The associated relative break heights (RBH) when felled via different treatments is also shown in Table 6. Motor-manual felling has a RBH of 70.7% followed by mechanised felling out of the stand being 70.9% and mechanised felling into the stand being 68.8%.

Table 6: The features of the stems that broke post felling. The means are shown followed by the associated standard deviations in parenthesis.

	Motor-manual (45 broken out of 62 felled)	Mechanically felled out of stand trees (45 broken out of 59 felled)	Mechanically felled into the stand trees (45 broken out of 62 felled)
DBH (cm)	43 .8 (9.0)	41.4 (8.2)	43.0 (8.6)
Tree height (m)	34.3 (4.3)	35.0 (3.6)	33.7 (2.8)
First break height (m)	24.3 (4.0)	24.7 (3.5)	23.1 (4.9)
Relative break height %	71 (11)	71 (9)	69 (14)
Relative break diameter %	47 (13)	46 (7)	44 (14)

An analysis of variance test was performed to determine if the mean RBHs were significantly different between the three felling treatments (Figure 7). It was

found that the difference in means was not significant ($p = 0.58$). With felling types combined, (1=felling out of the stand, [both motor-manual and mechanised] and 2 = felling into the stand) again an analysis of variance was performed on the RBHs to determine a difference in means (Figure 7). The finding was that the difference was insignificant ($p = 0.30$).

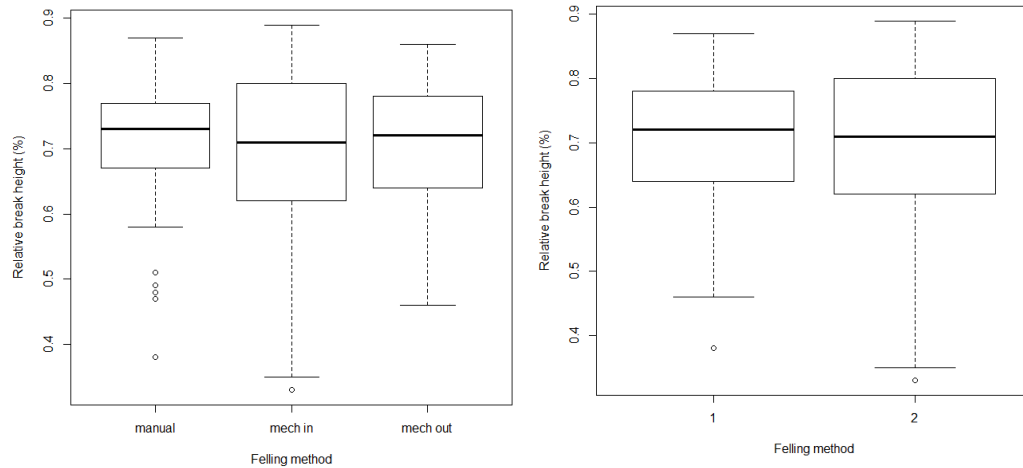


Figure 7: The relative break heights for each felling method (left figure) and the relative break heights for felling type (right figure) with 1= felling out of the stand and 2= felling into the stand.

A linear regression model was developed to predict RBH. The model used the variables felling type and tree height. The model had a low predictive ability ($r^2 = 0.051$) and felling type was considered an insignificant variable ($p = 0.133$). Tree height was the only factor deemed to have a significant impact upon predicting the RBH ($p = 0.003$). Therefore, the equation of the model has not been shown in the results due to the lack of significance within the variables and the low predictability of the model. The equation to predict RBH can be found in the Appendices, Relative break height.

6.4 DBH and the Effect on Stem Breakage

The effect that DBH had upon stem breakage was examined to determine if there was a trend. With the inclusion of all trees (183) from each felling treatment, all three trees in the 60 + cm DBH class broke and two out of 13 in the 20 – 29.9cm DBH class broke (Figure 8). The 40cm to 49.9cm DBH class had 83% of all stems break and 83% of the stems broke in the 50cm to 59.9cm DBH class. Lastly, 73% of all stems broke in the 30cm to 39.9cm DBH class.

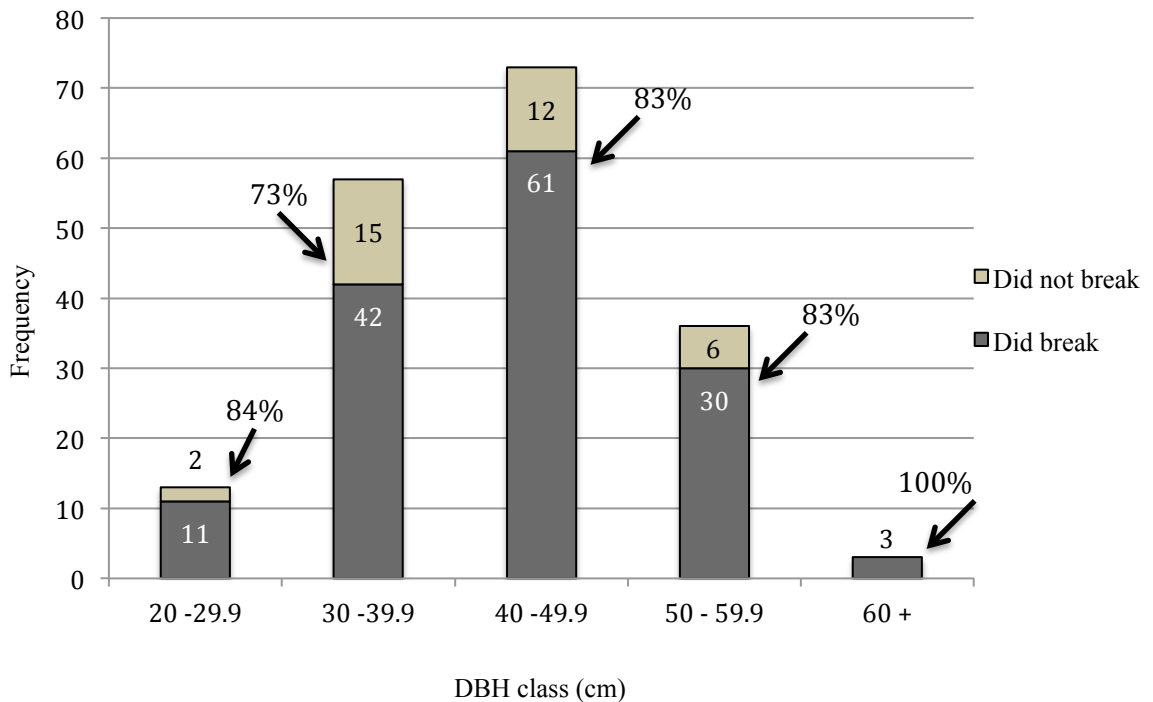


Figure 8: The distribution of broken and no broken stems by DBH size class.

There is no apparent trend with respect to DBH class and the percentage of stems that break within each size class. Yet it is seen that the 40cm to 49.9cm DBH class has the highest percentage of broken stems irrespective of felling method (with the exclusion of the 20cm - 29.9cm and the 60 + cm DBH class). A chi-squared test illustrated that the percentage change in breakage between DBH classes is not significant ($p = 0.52$).

6.4.1. DBH and Diameter at the Break

There is a relationship between the diameter at the point of the first break (DPB) and DBH, where DPB is approximately half the DBH (Figure 9). Mechanised felling out of the stand resulted in 84% of the broken stems having DPB between 10cm to 25cm. Motor-manual felling has the second closest relationship of half the DBH to DPB with 82% of the DPB's being between 10cm to 25cm. Lastly mechanised felling into the stand has a relationship between DBH and DPB nearing a third of the DBH rather than half despite 86% of the DPB's between 10cm to 25cm. This is because there are more stems that had a DPB greater than 25cm when mechanically felled into the stand compared to the two other treatments.

(Figure 9).

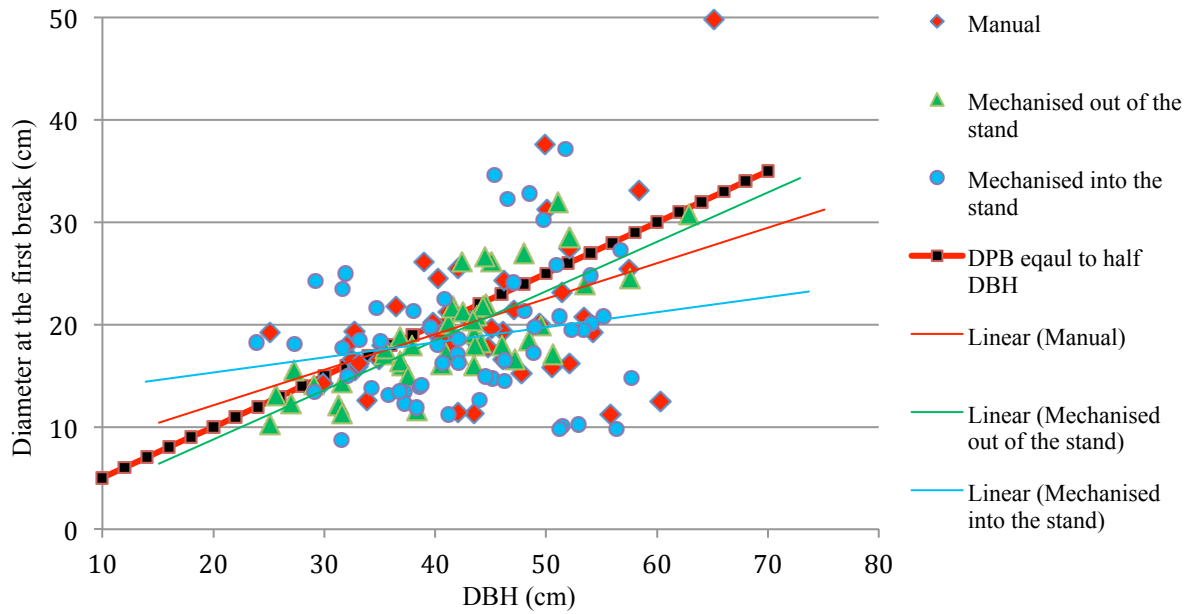


Figure 9: The diameter at the first break in relation to the diameter at breast height for each felling treatment.

The difference in means between the diameters at the first break is not significant for any of the three treatments ($p = 0.53$), (Figure 10). A further investigation aimed to determine if the difference in diameter at the first break was significantly different when felling out of the stand (motor-manual and mechanised out of the stand) compared to mechanised felling into the stand (Figure 10). It was found that the difference between the two treatments was insignificant ($p = 0.26$).

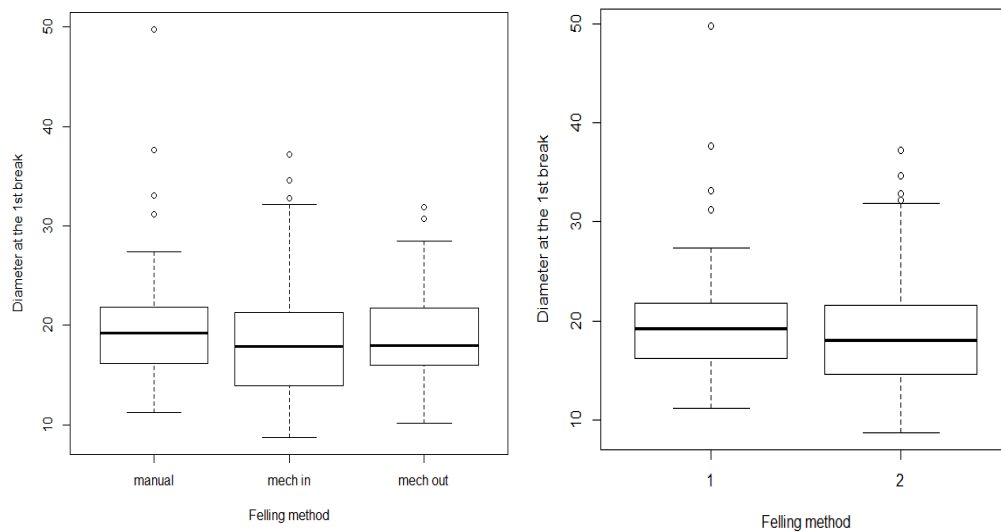


Figure 10: The diameter at the first break point for each felling method (left graph) and the diameter at the point of the first break by felling type (right graph) with 1= felling out of the stand and 2= felling into the stand.

6.5 Volume Retention

An analysis was performed to determine the volume of wood (m³) that was retained with each felling method (Figure 11). Of all the trees motor-manually felled, on average, 93.71% of the total volume was considered to be below the first break. Mechanised felling out of the stand resulted in an average of 94.49% of the stems volume being below the first break. Finally, mechanised felling into the stand had on average 91.85% of the stems volume being below the first break.

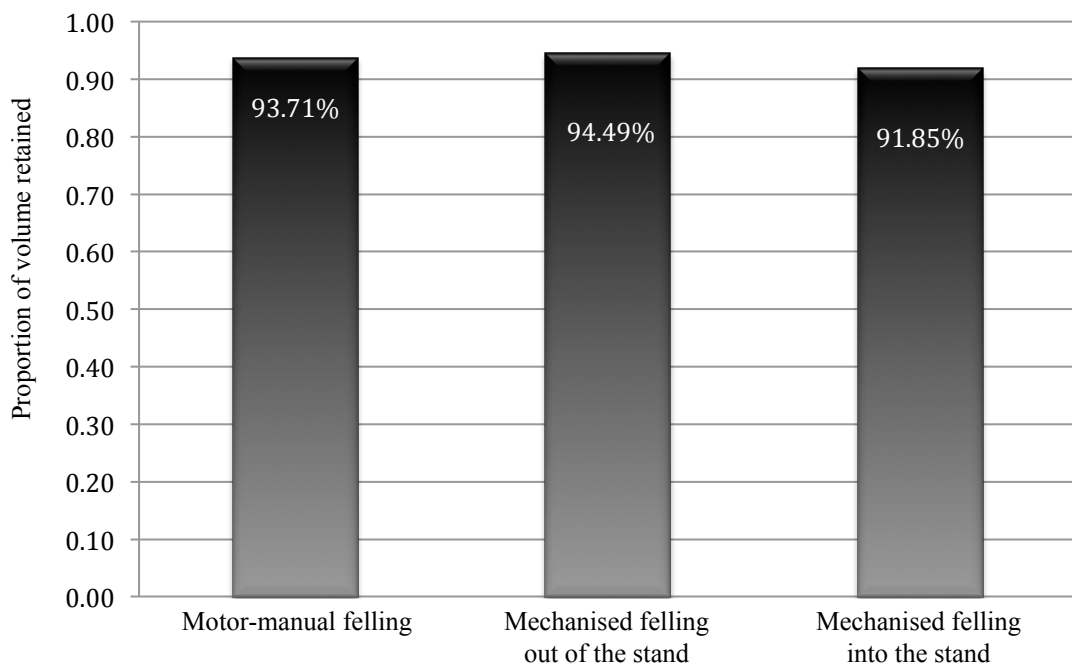


Figure 11: The average proportion of the trees total volume that was retained in a stem once felled by felling treatment.

It was found that there is no statistical difference between the percentages of volume retained by the three felling treatments ($p = 0.137$). Furthermore, the percentage difference in motor-manual felling and mechanised felling out of the stand combined was compared against mechanised felling into the stand and returned an insignificant result ($p = 0.12$).

6.6 Felling direction and length to the first break

The effect that felling direction has on stem breakage was examined to determine if felling downhill, across slope or uphill has an impact on the length to the first break. The effect that felling direction had on stem breakage was investigated for motor-manual felling and mechanised felling out of the stand. There are two distinct data sets seen in Figure 12 & 13, with the blue points representing felling approximately downhill and the red points represent stems felled on the same slope and site; however these stems were felled in an uphill direction to avoid undesirable terrain features.

Figure 12 shows the effect that a change in the motor-manual felling direction, be it downhill (observed deviation = 0°), across slope (observed deviation = 90°) or uphill (observed deviation greater than 90°) has upon the length to the first break. When a stem is motor-manually felled in a direction up to 50° away from directly downhill, there is no significant difference in the length to the first break. There is also no difference in the length to the first break between the two distinct data sets (i.e. felling up to 120° away from downhill).

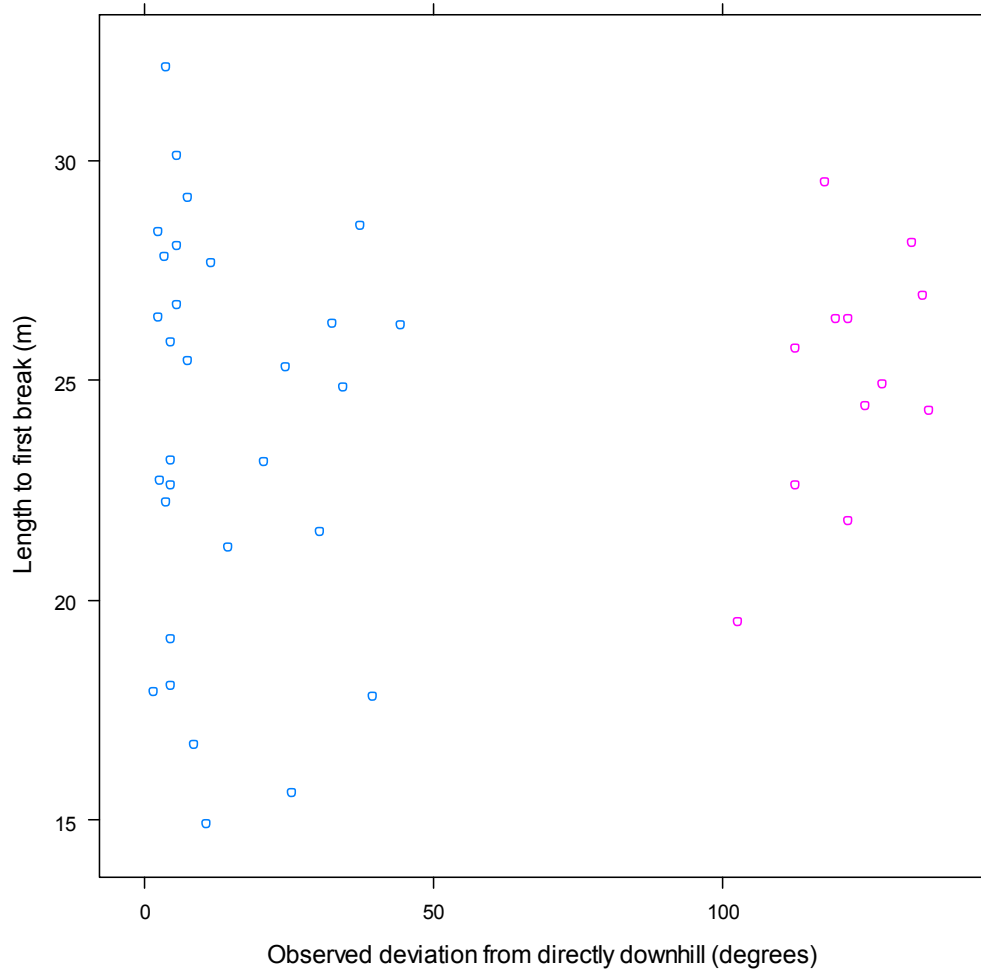


Figure 12: The effect that a change in the motor-manual felling direction from directly downhill had upon the length to the first break. Angles greater than 90° indicate trees were felled facing uphill.

The linear model (Table 7) indicates that there is no notable difference in the length to the first break when there is a change in the felling direction from directly downhill. Despite that some stems are felled predominately downhill and others have been felled up to 120° (30° uphill) from downhill, both observed deviation and the interaction between the groups returned insignificant p values (>0.05) (refer to Table 7)

Table 7: The coefficients of the relationship between motor-manual felling direction and length to the first break.

Variables	Estimate	Standard Error	P value
Length to first break (m)	24.20	1.105	$2 \cdot 10^{-16}$ ***
Observed deviation (degrees)	-0.02	0.059	0.66
Interaction between groups	0.16	0.141	0.26

The same analysis was performed on the felling direction for mechanised felling out of the stand (Figure 13). It was found that with two different distinct data sets (blue points and red points) that a change in the felling direction from directly downhill was not significant in respect to the length to the first break.

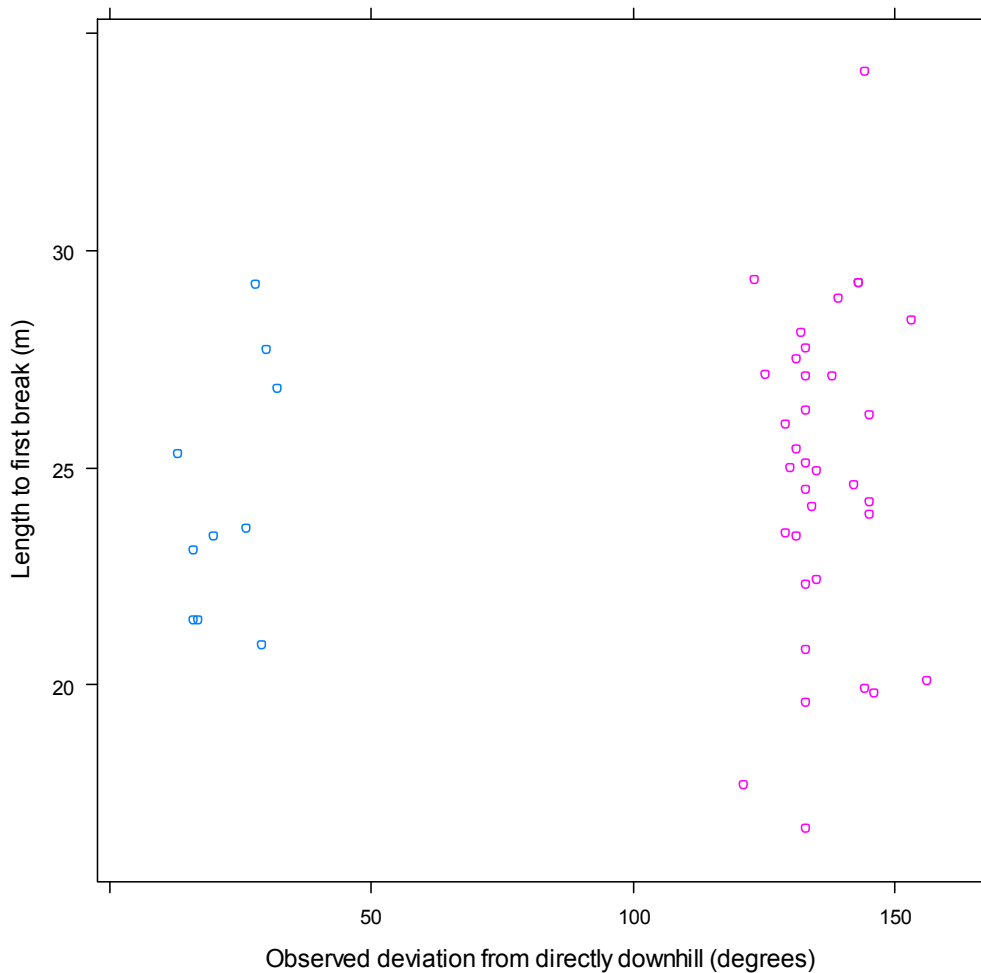


Figure 13: The effect that a change in felling direction of the mechanically felled out of the stand stems from directly downhill had upon the length to the first break. Angles greater than 90° indicate trees were felled facing uphill.

The length to the first break was found to be slightly less for mechanised felling out of the stand than motor-manual felling at 19.9m. Yet a change in the felling direction from directly downhill is predicted to increase the length to the first break, however this increase is considered statistically insignificant (Table 8). The interaction between the two mechanically felled data groups (red and blue points) is statistically insignificant ($p = 0.39$); which suggests that if trees are mechanically felled up to 150° away from directly downhill there is no substantial change in the length to the first break.

Table 8: The coefficients of the relationship between mechanised felling direction and length to the first break.

Variables	Estimate	Standard Error	P value
Length to first break	19.88	4.044	1.47×10^{-5}
Observed deviation	0.19	0.170	0.26
Interaction between groups	-0.16	0.187	0.39

7. Discussion

7.1 Percentage of Broken Stems

The difference in percentage of broken stems between motor-manual felling (73%) and mechanical felling out of the stand (76%) was insignificant. When motor-manual felling and mechanised felling out of the stand were combined and compared against the breakage percentage for mechanised felling into the stand (94%), the difference was significant. Thus, felling into the stand will result in a greater number of broken stems, as opposed to when felling out of the stand.

The increased number of stems that broke when mechanically felled into the stand is likely to be associated with the stem striking standing trees during the felling process. It is difficult for a machine operator to fell a stem through a gap between standing trees in a production forest with a stocking and spacing designed to achieve maximum volume per ha. Therefore the likelihood of a stem hitting a standing tree when being felled is high. However it is likely that the revenue from the maximum volume/ha outweighs the benefit of reducing the stocking and reducing the number of stems breaking.

In an attempt to reduce the percentage of stems breaking when mechanically felling into the stand, a fall and delimb head could be of merit, i.e. a Satco 424 fall and delimb head (Satco logging attachments). This would allow the stem to be felled as per the same as the felling head used in this study, however the fall and delimb head would pull the stem through the head via feed rollers and delimb it as it falls. This would reduce the exposure of the head of the stem, as a greater proportion of the stem would be below the felling head, potentially reducing the possibility of a break and reducing the number of stems that break when mechanically felling into the stand.

The percentage of broken stems when motor-manually felled out of the stand was similar to the 69% breakage rate proposed by Fraser et al. (1997) and the 73% by Murphy (1984). Additionally, the percentage of stems that broke when mechanically felled into the stand are within the 84% - 100% breakage range experienced in Lambert (1996) study. With the exclusion of Lambert (1996)

study which looked directly at mechanised felling into the stand, the percentage of stems that broke when mechanically felled out of the stand are similar to the percentages seen in earlier motor-manual breakage studies. Thus a conclusion could be drawn that felling out of the stand will result in a breakage rate similar to the 73% and 76% proposed in this study for motor-manual and mechanised felling out of the stand respectively.

7.2 Relative Break Height

The difference in relative break heights of each felling treatment is considered statistically insignificant. The difference between the RBHs of motor-manual and mechanised felling out of the stand combined and compared against mechanised felling into the stand is insignificant. The result indicates that regardless of felling method, and whether felling out of or into the stand, the length to the first break will be approximately 70% of the trees total height.

An attempt was made to develop a linear model that would predict the relative break height based on factors of a stem and the felling method used. This model (Appendices, Relative break height) had the greatest level of accuracy of all the models trailed, however it included insignificant predictor variables and had a low goodness of fit ($r^2 = 0.051$). The dynamic influences that affect a stem breaking is believed to be one of the reasons why the model was unable to accurately predict the relative break height. First the landing zone was not factored into this study; it is likely that this would have had an impact on a stem breaking but it was not accounted for in the model. Manley (1977) encountered the same issue when attempting to develop a breakage equation for Kaingaroa. The physical phenomenon of a stem breaking is clearly not limited to tree size, felling method and landing zone. Features such as wood density and environmental conditions are likely to affect stem breakage (Murphy, 1984). Based on the findings of this study the most accurate way to predict the relative break height is to multiply the mean tree height by the RBH, proposed in Table 6.

The three felling treatments returned effectively the same RBH's, it could be suggested that the type of felling method chosen for production clear-felling can be relaxed, as there is no difference in RBH. This could allow for greater mechanised felling to occur and reduce the use of motor-manual felling, as the value loss due to break height is the same. The implication of greater mechanised felling would minimise the risk surrounding tree felling and in particular, remove a man from the ground and potentially reduce the 52% of all fatalities that are currently attributed to tree felling (WorkSafeNZ, 2014).

7.3 DBH and Stem Breakage

Previous studies have developed relationships between the DBH of a tree and the diameter at the point of the break (DPB). Those studies (Lees, 1969), (Murphy, 1982), all suggested that the DPB is approximately 50% of the DBH. This study has found that the relationship between DPB and DBH is also approximately 50% with the exclusion of mechanised felling into the stand. These findings allow for a greater understanding of the SED of the stem that is likely to be extracted from the cut over. Before harvesting a stand, a forest owner conducts a pre harvest inspection (PHI) of the stand to determine the expected revenue once harvested. The PHI attempts to predict the expected number and volume of specific log grades. Given that the diameter at the point of the break, the RBH, the DBH, and volume of the expected stem once felled can be characterised relatively accurately; forest owners can increase the accuracy of forecasting the expected volume of log grades, as predictions on where the stem may break can be factored into the PHI. This will directly increase the accuracy of the PHI and the ability to determine the expected value from harvesting their forests.

7.4 Volume Retention

With the lack of literature describing the effect that different felling methods have upon stem breakage there are numerous opinions suggesting which felling method is superior in regard to minimising value loss. Contractors are at the front line and are exposed to the frequency and severity in stem breakage that occurs during different felling methods. The machine operator in this study believed that the greatest loss of volume occurred when mechanically felling into the stand.

While the crew foreman had opposing views with the belief that motor-manual felling resulted in the greatest volume loss. The finding of this study rejected these two opinions by disproving the theory that a difference exists amongst the volume retention abilities of the three felling methods.

The difference in the percentage of volume that is retained below the first break is statistically insignificant between the three felling treatments. Therefore, an average volume retention can be assumed; 93.35% of the stems volume is retained, leaving 6.65% of the stems volume above the break and potentially left in the cut over. However, this 6.65% does not necessarily relate to 6.65% of the value of the stem. On average the LED of the first broken piece for all felling treatments is 18.5cm. The average length of the first broken piece is 3.66m, the SED is 14.2cm and the volume is 0.08m³. The log that could be made from this material is a pulp grade log (SED ≥ 10cm, length ≥ 3.5m), (Rayonier, 2015). The value of a pulp log sold to the domestic market is \$50/m³ based on the 2015, 12-quarter average log prices (*Indicative New Zealand Radiata pine log prices*). Thus the value of a pulp log that can be made from first broken piece is \$3.95 (\$50 * 0.08m³). It has been found that when motor-manually felling, the second broken piece can be made into a pulp log and this has a value of \$2.20 (Table 5). When mechanically felling out of the stand the second broken piece is 2.8m long thus it fails to meet the length limit of 3.5m.

Based on the typical log out-turn in the Forest Owners Association, Facts and Figures (New Zealand Plantation Forestry Facts and Figures, 2012/2013), the average pruned *Pinus radiata* tree will produce 50% of the stems volume as pruned log, 43% of the volume will be attributed to sawlogs and 7% attributed to industrial grade logs. Based on the 2015 12-quarter average log prices and the average volume of the trees measured in this study (1.57 m³), the potential value of any stem in the Maramarua forest is \$167.30. Based on a motor-manual felling scenario, if two logs are worth \$3.95 and \$2.20 worth break away from the main stem during the felling process, this relates to a loss of 3.7% of the total value of the stem. This disproves suggestions by parties such as Conway (1976), whom believed that up to 40% of the stands value can be lost during felling, however it should be noted that this was in reference to old growth fir in the US.

The current expectation of a logging crew is to harvest all the merchantable timber in the stand. This means that every piece of timber greater than 10cm in diameter is required to be extracted from the cut over. Logging crews generally extract all of the stems below the first break without issue. In some situations the broken pieces of timber are left in the cut over due to the loss of productivity that is encountered when extracting small volumes. This study has found that, the pieces that break away from the main stem are those that have a low economic value. Logging crews and forest owners may be losing money by implementing such a tight constraint of harvesting all the merchantable timber. McMahon, Evanson, Hall, and Baillie (1998) suggested that there is a greater cost of harvesting small pieces of timber due to the opportunity cost of moving the crew into a new setting. A new requirement could be developed where all timber greater than 20cm in diameter is required to be harvested; reducing the 'clean up' time for each crew. As suggested by McMahon et al. (1998), increasing the minimum piece size from 10cm to 20cm and reducing the harvest time, could result in a potential saving to the forest owner of \$1,134/ha and crews could increase their hauler productivity by 9%. At a small cost of disregarding small material less than 20cm in diameter, forest owners can attain increases in revenue by reducing their harvest cost and decrease their opportunity costs of moving the crew into a new stand. Additionally, crews can increase their productivity and harvest forests in less time. However, this is dependent on the number of pulp logs that can be made from the broken pieces. If a pulp log could be produced out of the material above the break for every tree in the stand (360 stems per ha) the return would be \$1422/ha ($360 * \3.95). However, this does not factor in the percentage of stems that break or the number of broken pieces that can actually produce a pulp log worth \$3.95. Therefore, if the percentage of broken stems is high and the number of pulp logs that can be produced from the broken material is low, it could be more economic to harvest to a minimum piece size of 20cm.

7.5. Felling direction

Directional felling has been a topic of interest for many years with multiple studies being carried out by Murphy investigated the effect that directional felling has upon stem breakage. In Murphy's 1982 study, he found that directional felling and specifically motor-manually felling across slope rather than downhill increased the length to the first break by three to six metres. He then supported his earlier study with another study in 1982 and found that felling uphill resulted in a RBH of 71% whereas felling downhill had a RBH of 68%. This study has found that the length to the first break was not statistically different with a change in the felling direction from directly downhill to uphill for either motor-manual felling or mechanised felling out of the stand.

The implications of these findings oppose those suggested by Murphy. However, given the findings of this study it could be suggested that tree fellers, being motor-manual or mechanised, can fell a tree in any direction and have confidence that it will not affect the length to the first break.

Multiple theories exist which suggest that felling direction does significantly impact stem breakage, hence why felling directly downhill was the mainstay method in the 1960's and 1970's. Felling downhill may have also been the mainstay method due to a lack of machines with the capability to fell trees and the difficulty associated with motor-manually felling a tree against its lean. Following Murphy's studies there was reason to believe that felling uphill would retain greater volume than felling downhill. However this study contradicts Murphy's findings, as it has been found that the felling direction has no effect on stem breakage. Directional felling and its impact on stem breakage is clearly not conclusive and it is an area of tree felling that requires further investigation. Subsequently it is important that a conclusive answer is found to understand that the effect that direction felling has on stem breakage so that maximum value is retained in the stem. It is also important that it is clarified to give confidence to tree fallers that the felling direction that they choose is not going to cause excessive damage to the stem.

7.8 Limitations

While the results of this study are consistent with others, these results are only valid to predict the break diameter, break height, and volume retention for a pruned *Pinus radiata* stand of a similar age, size and on slopes inclusive of 38% to 45%. The results are only applicable to equivalent machinery of which was employed in this study. Tree dimensions and age beyond the range of this study were not evaluated so it is possible that the results outlined will be different to those for another stand with a different ages, tree size and silviculture regimes.

The findings are limited to the Maramarua forest, as it would be advised against using these results for stands in different locations of New Zealand. The data in this study was collected over a two different times periods, 3 months apart from each other. This could have potentially introduced seasonal bias due to changes in the trees physiological state such as sap content, which may have affected breakage.

Felling was not carried out under the scenario of actual production pressure because of the requirement of measuring each tree. This may have potentially impacted the breakage of trees during felling and thus different breakage results may exist in actual production scenarios.

The final limitation of the study was that measurements were conducted in a difficult environment to accurately assess stem breakage. Often stems were felled and heads and broken pieces could not be found, as they were lost in the understory of the forest. In an attempt to improve the accuracy of factors such as tree height and the number of broken pieces per tree, the study would have required a controlled experimental where the landing zone was free of any debris or undergrowth, such as a clear paddock. This would ensure that broken pieces and heads were not lost and therefore increase the accuracy of the results.

7.9 Future research

Future research regarding stem breakage during felling needs to move away from assessing tree characteristics and felling methods and rather focus on the terrain features of where the stem lands once felled. Features of the landing zone such as soil type, number and size of boulders/rocks, stumps and soil mounds or significant undulations in the landing zone need to be categorised and given a rating of severity to determine their impact on stem breakage. Investigating the difference in ground moisture content and thus ground softness between winter and summer would also be of merit in regard to increasing the understanding of stem breakage.

Further studies of felling methods and their impact on stem breakage need to include a fell and trim assessment. Mechanically felling into the stand is deemed to have the greatest impact on stem breakage, however a fell and trim method may reduce the breakage that occurs when mechanically felling into the stand.

There needs to be further investigations into the required minimum harvest piece size. The number and frequency of pieces above the break that can be bucked into a pulp log needs to be investigated to confirm whether moving the minimum piece size to 20cm is more economic than the current 10cm requirement.

8. Conclusion

This study has provided evidence to illustrate the effect that different felling methods have upon stem breakage is relatively insignificant. There is no statistical difference in the location of the break point in a *Pinus radiata* stem when felled via motor-manual, mechanically out of the stand or mechanically into the stand. The RBH is best predicted by the finding that the break height will be approximately 69% to 71% of the total tree height. A regression equation to predict the height of the first break was unable to be developed due to the predictor variables tree height, DBH and felling method all returning insignificant predictability upon the RBH of a stem. Previous studies and this study have highlighted that the break point cannot be accurately predicted by tree height, DBH and felling method. Therefore, there are clearly more factors that affect stem breakage which need to be addressed in future studies.

The influence that motor-manual felling and mechanised felling both into and out of the stand has upon stem breakage is considered similar across the three methods. With the exclusion of the percentage of stems that break through each felling treatment, every other variable investigated in this study returned insignificant differences between the three treatments. Therefore when forest owners or crew foreman's are choosing between motor-manual felling or mechanised felling, it can be assumed that the chosen method will have a similar effect on stem breakage. This may encourage more mechanised felling and reduce motor-manual felling, as it is known that the result in stem breakage will be the same, whilst the risk associated during this activity will be reduced by removing a man from the ground.

The variables that influence the breakage of a *Pinus radiata* stem is not limited to tree height, DBH and felling method. There is a range of dynamic variables affecting stem breakage. The suggestion that a change in the minimum harvest piece size may result in greater revenue/ha due to the cost benefit of harvesting broken material illustrates the importance of appreciating stem breakage, thus the need for further research and a greater understanding of this activity.

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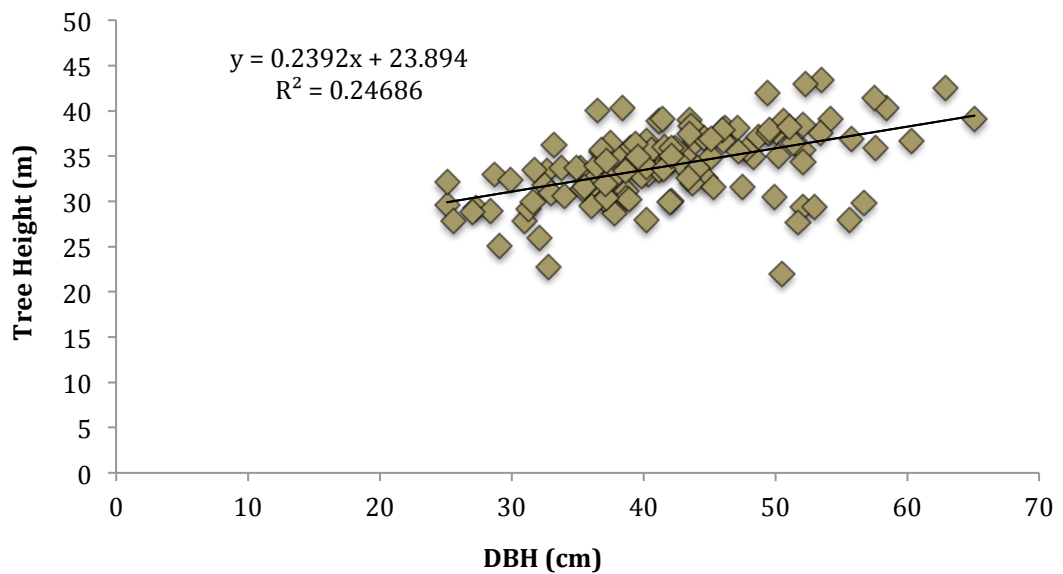
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Appendices

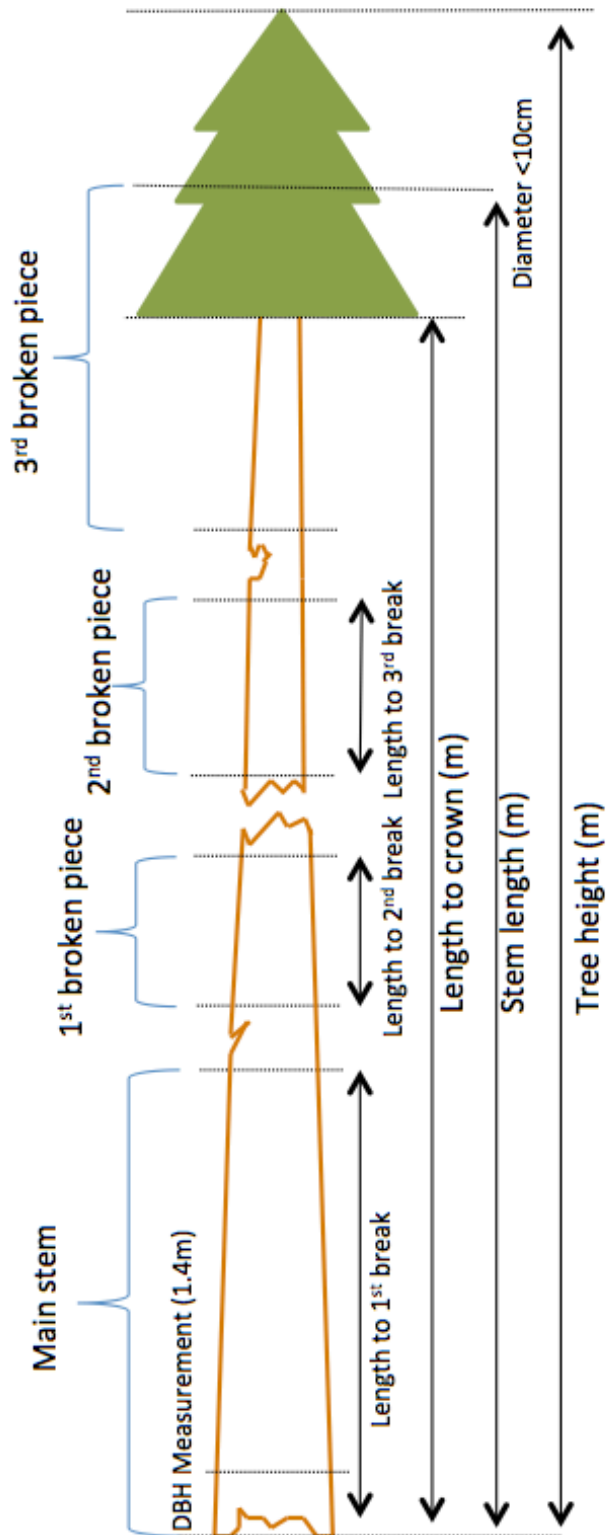
Predicted tree height

The below figure provides a graphical representation of the goodness of fit in the relationship between DBH and tree height. The equation: $y = 0.2392x + 23.894$ ($x = \text{DBH}$) was used to predict total tree height in the scenario where tree height was not recorded. It is seen that the r^2 is relatively low, however the linear fit is acceptable to use the equation as a predictor of tree height.



Appendix, Figure 1: The graphical output of the relationship between DBH and tree height.

Tree measurements



Appendix, Figure 2: A diagram of where each measurement was taken as described in section 5.5 measurements.

Relative break height

The relative break height equation that was developed is shown below:

$$RBH = 1.004492 - 0.008516 * (h) - \text{falling type}$$

Where h = tree height

Falling type ~ 1 (falling out of the stand) = 0

~ 2 (falling into the stand) = -0.029762

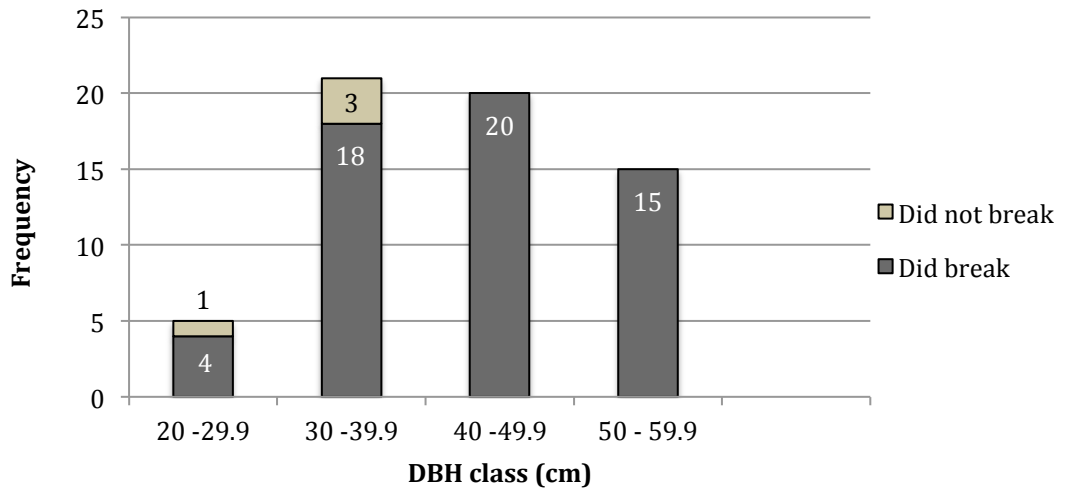
The model has a low predictability ($r^2 = 0.051$) despite tree height being a significant predictor variable ($p = 0.003$) and felling type being insignificant ($p = 0.133$). This model has a low predictability; hence it was considered to not accurately predict RBH. Given that tree height is the only significant variable explaining the RBH, it can be suggested that multiplying the total tree height by the associated RBH of the employed felling method, will be more accurate than the model shown above.

Stem breakage by DBH size class

The below figures provide an illustration of the number of stems that did break and did not break when either motor-manually felled, mechanically felled out of the stand and mechanically felled into the stand.

It is seen that when stems are motor-manually felled, the highest percentage of stem breakage occurs in the 40cm - 49.9cm DBH class with 78.2% of all stems breaking. The 50cm – 59.9cm DBH class had 71.4% of all stems in that size class breaking, followed by the 30cm – 39.9cm DBH class with a breakage percentage of 65%. The 60 + cm class had the greatest percentage of broken stems (100%) however this DBH class only accounted for 3% of all stems motor-manually felled.

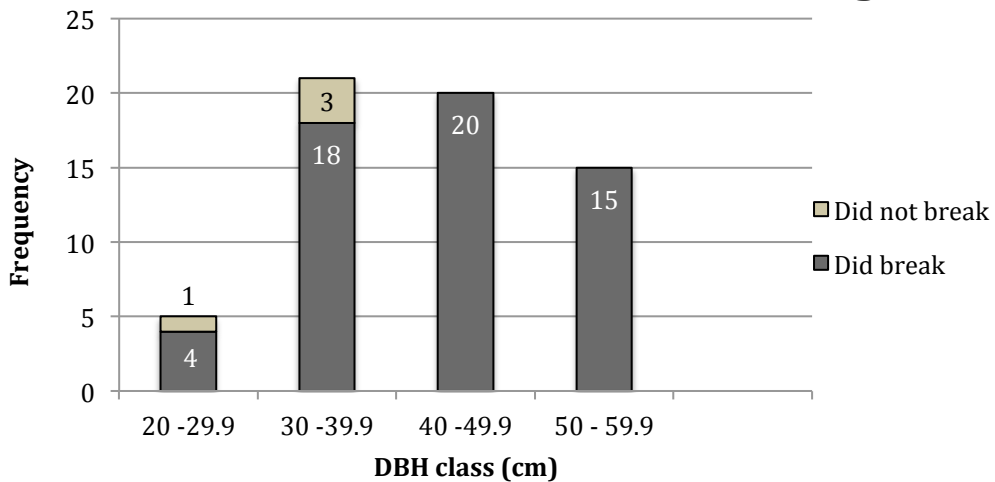
Motor-manual felling



Appendix, Figure 3: The distribution of broken stems by DBH size class when motor-manually felled.

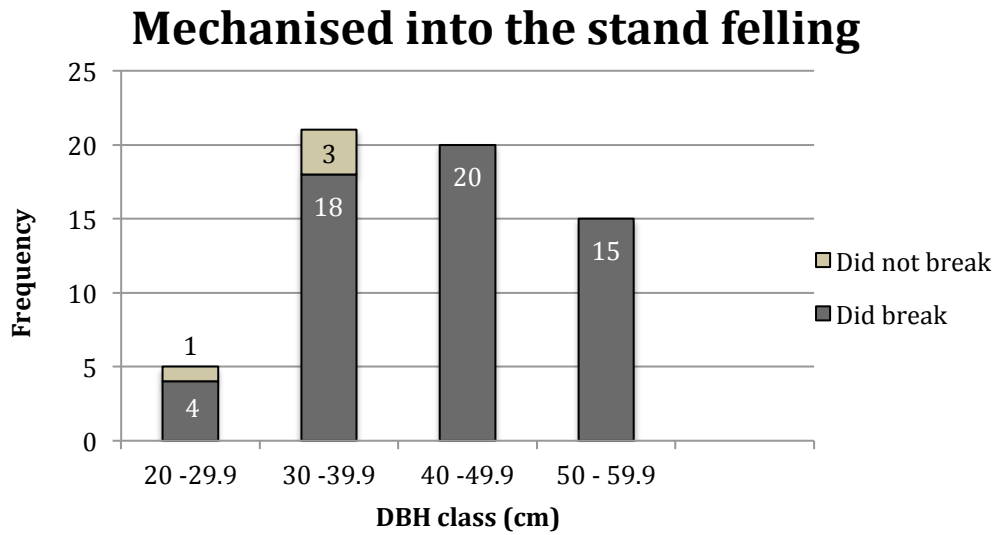
When stems have been mechanically felled out of the stand, it is seen the greatest percentage of stems breaking occurs in the 40 -49.9cm DBH class (85%) followed by 83% in the 20 – 29.9cm DBH class and 71% in the 50 – 59.9 cm DBH class.

Mechanised out of the stand felling



Appendix, Figure 4: The distribution of broken stems by DBH when mechanised out of stand felling.

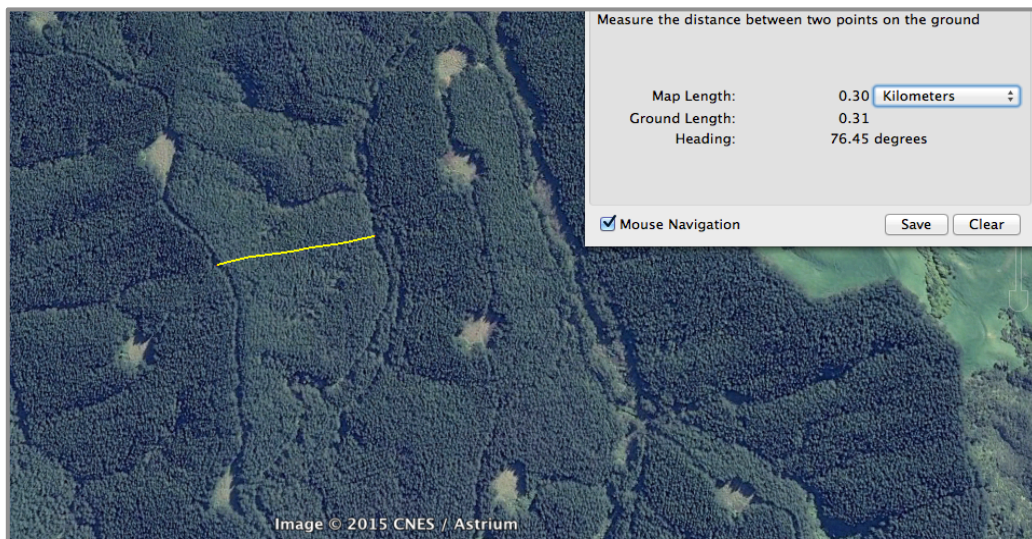
Lastly mechanised felling resulted in 100% of stems breaking in the 40cm - 49.9cm DBH class and 50cm – 59.9 cm DBH class. The 30cm – 39.9cm DBH class resulted in 85% of all stems breaking and 80% in the 20cm – 29.9cm DBH.



Appendix, Figure 5: The distribution of broken stems by DBH when mechanically felling into the stand.

Felling direction

The below figures provides an illustration of Site 1, the motor-manual felling area (Appendix, Site 1) and Site 2, the mechanised felling out of the stand (Appendix, Site 2). The heading of directly downhill is 76.45° for Site 1 and 249.23° for Site 2. The observed deviation is the difference in the felling direction of the tree, once on the ground in relation to directly downhill (76.45° or 249.23°).



Appendix, Site 1, the motor-manual felling site with a heading of 76.45 degrees being directly downhill (source: Google Earth).



Appendix, Site 2, the mechanised felling out of the stand site with a heading of 249.23 degrees being directly downhill (source: Google Earth).

