

# Finding the ‘Sweet-Spot’ of Mechanised Felling Machines.

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## Abstract

Understanding how stand and terrain parameters impact the productivity of harvesting machines is important for determining their optimum use. Productivity studies in forest operations are often carried out on new equipment, or on equipment being used in new conditions. Such information is normally presented as a productivity or efficiency function; that is, a regression equation that best represents the data. Most studies establish that piece size is the dominant predictor that impacts overall productivity. A common concept, known as the ‘piece-size law’, is that productivity increases at a decreasing rate with increasing piece size. What is not well understood is the upper limit to this piece-size law. That is, as the trees get ‘too’ large, the machine starts to struggle and we can expect a decrease in productivity. Four different mechanised felling machines were studied in New Zealand radiata pine plantations. Using more complex non-linear equations it was possible to identify an ‘optimum’ piece-size for maximum productivity, whereby this ‘sweet-spot’ piece size for all machines is considerably smaller than their maximum. Unexpectedly, productivity tended to decrease gradually, not drop off suddenly beyond the optimum. Using more complex statistical functions when correlating piece size to productivity will help identifying the ‘sweet-spot’.

## Introduction

In forestry, harvesting machine productivity is impacted by stand and terrain variables. Understanding these impacts is important for determining their optimum use. Therefore, productivity studies in forest operations are often carried out on new equipment, or on equipment being used in different conditions. The empirical models derived from such studies can be used for many purposes, including wood-flow planning, predicting machine or system productivity (Holtzschler and Langford 1997; Spinelli et al. 2009), and costing models (Adebayo et al, 2007; Bolding et al, 2007). However, at a more fundamental level it allows us to understand the behaviour of harvesting machines and/or systems under varying stand and terrain conditions.

A large number of variables can impact harvest machine productivity. We can attempt to group them as stand and terrain variables. Typical stand variables include piece size (e.g. Evanson and McConchie 1996; Wang and Haarla 2002; Visser and Stampfer 2003; Nurminen et al. 2006), stocking density and or thinning intensity (Eliasson 1999), type of cut and total volume (Suadicani and Fjeld 2001). However, for specific studies, variables such as tree form (Evanson and McConchie 1996), branch size (Glode 1999), pruned status, selection criteria of trees to harvest (Eliasson and Lageson 1999) and/or degree of wind-throw can also significantly influence productivity. There are also stand parameters that interact with the harvest system,

including the felling pattern and number of logs to extract. Typical terrain variables include slope, extraction distance, trafficability, and terrain roughness. Again, there are parameters that interact with the harvest system, include rutting, as well as the layout of skid trails and landings. Although slope can readily be measured either onsite or from maps, the impact of slope is very much dependant on the harvest system. While, in general, increasing slope decreases productivity for ground-based systems, a certain level of slope is desirable for cable yarding systems, but then again only if that slope is concave! While most parameters have a ratio scale, variables such as terrain roughness require a nominal scale using categories, or composite variables such as percent deflection for slope with cable yarding systems.

The impact of stand and terrain variables can also be significantly affected by the human operator. Operator performance can result in a 20-50% variation in machine productivity (Bergstrand 1987; Murphy and Vanderberg 2007). To overcome such variation, productivity models should be based on large samples (Nurminen et al. 2006). For operator variation alone, Bergstrand (1987) suggested that to achieve a confidence level of 95% approximately 400 operators would have to be included in the study. Machine productivity determined in short-term time studies is typically also higher than found in follow-up longer-term studies (Siren and Aaltio 2003). Kuitto (et al. 1994) suggested using common coefficients from combined studies, and such coefficients based on combined series of studies are already available for specific time study elements, such as delays (Spinelli and Visser 2008).

We often simplify the problem associated with the over-abundance of predictive variables in our harvesting studies by selecting the dominant factors to measure in the study, and then again when evaluating the data by assuming basic relationships to the response variable. For example, the impact of extraction distance on productivity is easily understood – and the relationship is mono-directional. That is, the longer the average extraction distance the lower the productivity. However, some variables are clearly not mono-directional.

Most studies establish that piece size is the dominant variable that impacts overall productivity. A common concept, known as the ‘piece-size law’, is that productivity increases at a decreasing rate with increasing piece size (Figure 1). Some papers use a linear (Nakagawa et al. 2007, Sirén and Aaltio 2003), or even a quadratic (Nurminen et al. 2006, Karha et al 2004) relationship with piece size. Most common is a power function, whereby in a range of applied machine studies a power factor of approximately 0.6 describes the productivity to piece size relationship very well (e.g. Jirousek et al, 2007). Because of the mono-directional nature of these functions, when used for productivity prediction the ‘optimum’ productivity is always at the maximum piece size.

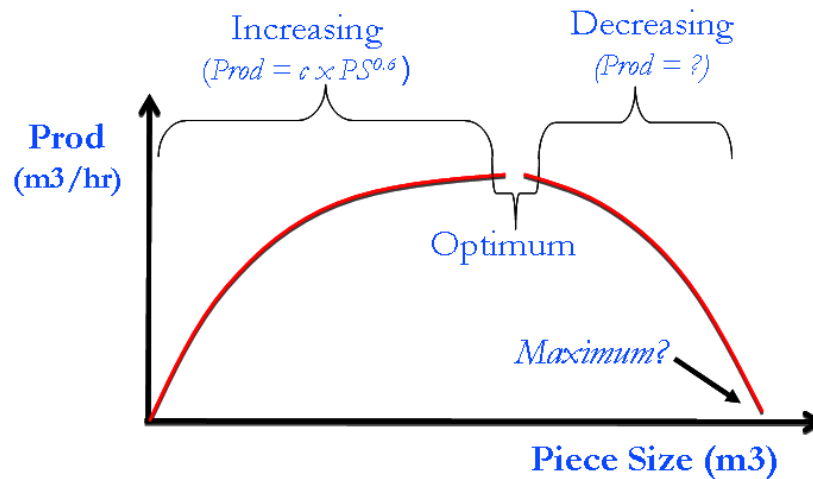


Figure 1: Graph showing the basic relationship between piece size and productivity. The graph has three phases: the 'increasing' phase reflecting the 'Piece-Size Law', the optimum or sweet-spot phase, and a decreasing phase beyond the optimum.

The raw data of some published studies exhibits a tendency to decrease at the upper limit. This simply means that the increase in time is greater than the increase in piece size. This effect is masked when assuming mono-directional relationships. If this is common, we should be using more complex non-linear functions to evaluate the effect of piece size in our productivity studies. This would not only increase the accuracy of the model, but it would also help us define an optimum that is not necessarily at the maximum piece size.

To improve our understanding of the piece size to productivity relationship, especially in the optimum and decreasing phases, this study focuses on studying a series of machines working with a relatively large piece size. For this purpose, we have chosen to focus on mechanised harvesters working in forest stands with above average-sized trees.

## Methodology

Four mechanized felling, and/or felling and processing, operations were chosen to study the effect of piece size on productivity. Mechanised felling is used where possible in New Zealand as it increases productivity and cost effectiveness, but can also reduce the occurrence of stem breakage and increase personal safety (McConchie and Evanson, 1995). The machines studied were all harvester heads attached to an excavator base.

All studies were conducted on clearfell operations in New Zealand radiata pine plantations. The study included operations using the following harvester heads on excavator bases:

1. Waratah 622 in Bottletlake Forest (Figure 2) – flat terrain with sandy soils
2. Waratah 624 in Lowmount Forest – rolling terrain with silty sandy soils
3. Satco 630 in Ashley Forest – rolling to steep terrain
4. Woodsman in Tarawera Forest – rolling terrain with volcanic ash soils

The first three study sites are in the Canterbury region of the South Island, the last is in the Bay of Plenty region of the North Island.



Figure 2: The Waratah 622 harvesting head in Bottlelake Forest.

A classic time and motion study was conducted at each site. The work tasks used for the study are shown in Table 1.

Table 1: Work task definitions for the mechanised harvester study

<b>Work task</b>	<b>Description</b>
Fell	Felling and bringing the tree to the ground
Delimb	Delimiting the whole tree
Bunch	Pre-bunching stems for extraction
Move	Repositioning between trees or rows
Clearing	Moving slash and or tops for either moving or felling
Delays	All operational and mechanical delays

In a suitable section of the stand, working ahead of the harvester, the DBH of each tree was measured and recorded, and the trees either flagged (Figure 3) with tape or painted. The Satco head is just a felling head and so did not complete the delimiting work task. The felling and delimiting work tasks were combined for the Waratah and Woodsman heads, as operator typically commences delimiting before the tree has hit the ground.



*Figure 3: Waratah 622 with pine clearfell in Bottlelake Forest. Note that all trees are marked with unique colour-bands prior to felling.*

Post-felling, approximately 20 trees were scaled by measuring diameter at 5 meter intervals along the stem, as well as a top length and diameter. A simple tapered cylindrical volume equation was used to arrive at the volume of each segment, and summed to arrive at a close approximation of the volume of the tree. A simple exponential regression was used to correlate DBH to tree volume.

Productivity information ( $\text{m}^3/\text{PMH}$ ) was calculated based on the time it took the processing head to fell and process different piece sizes. Note that the productivity information shown in this study is for productive machine hours (PMH) only, and only includes the felling and delimiting phase. Combining all four studies, approximately 40% of the time was felling and delimiting, the remaining 60% with bunching, clearing, moving or in some type of a delay.

## **Results**

The Woodsman (piece size range  $0.7$  to  $3 \text{ m}^3$  – Figure 4) and the Satco head studied in Ashley Forest (piece size range  $1$  to  $5.3 \text{ m}^3$ ) are typical of many productivity studies, in that the sweet spot is not obvious. The data collection, through lack of large enough trees, did not extend far enough beyond the optimum.

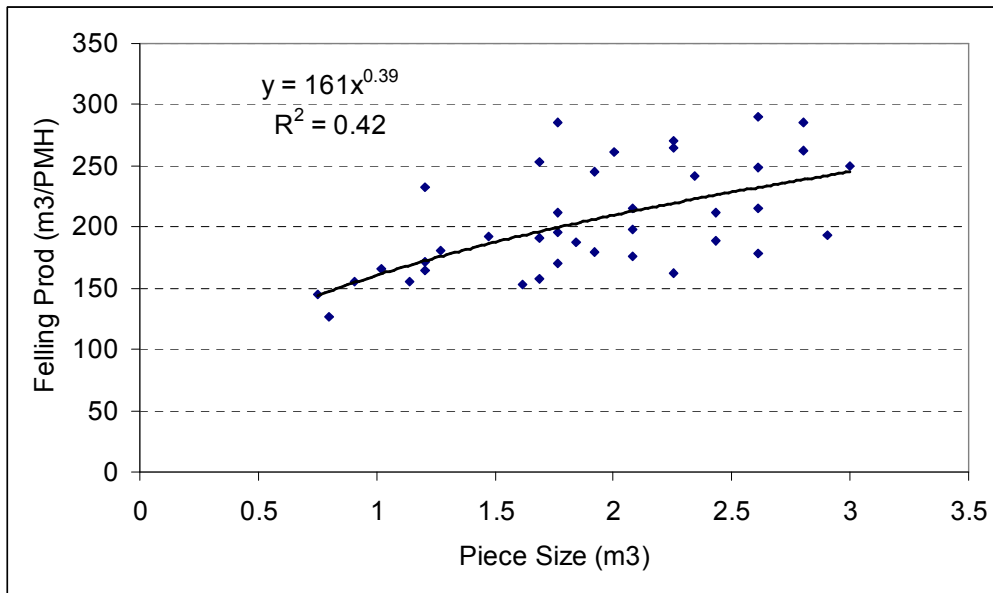


Figure 4: Woodman harvester head productivity (felling and delimiting only) and pieces size (m3)

The most common productivity type function to use for evaluating the effect of piece size appears to be a power function, in the form of

$$\text{Productivity (m3/hr)} = a \text{ PS}^b$$

Where PS is the piece size, and both a and b are coefficients determined by the regression analyses. For the above example (Figure 4) the regression yields:

$$\text{Prod} = 161 \times \text{PS}^{0.39} \quad (r^2 = 0.42)$$

It appears to provide an adequate relationship between Piece Size and Productivity – although only explaining only 42% of the variation. Note that it is also possible to work with efficiency as the response variable, whereby;

$$\text{Efficiency (min / m3)} = e^{-a \text{ PS}}$$

The problem of the mono-directional relationship remains the same.

In two of the studies we did succeed in collecting enough data to clearly show the declining productivity phase. For example, the Waratah 624 (felling and delimiting) data is shown in Figure 5.

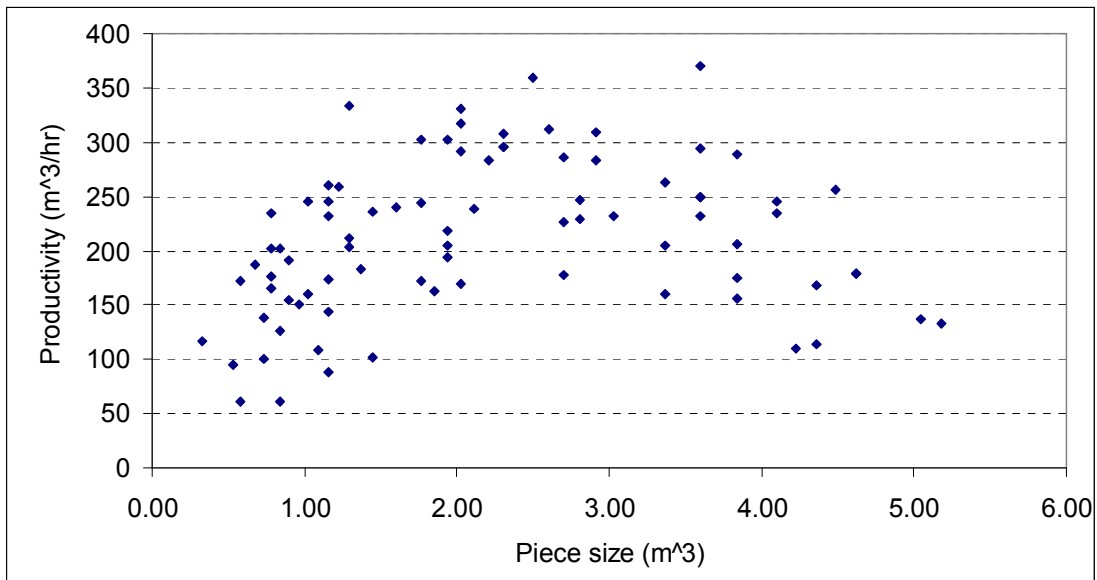


Figure 5: Productivity (felling and delimiting only) vs. Piece Size for Waratah 624 harvesting head in Lowmount Forest.

The declining phase can be attributed to a number of factors. While technically the bar is longer than the DBH, operator experience indicates that the bar is likely to pinch, or jam, with larger diameters. They therefore use a back-cut, move the head around the base of the tree, and then complete the cut. Extra time is also required for delimiting the larger branches, as well as for manipulating a heavy stem.

The shape of the data set for the smaller Waratah 622 study in Bottlelake forest was similar. The trees sampled ranged in piece size from 0.3 to 3.8 m<sup>3</sup>, whereas in the 624 study it ranged from 0.3 up to 5.2 m<sup>3</sup>. We note that it would be unreasonable to attempt to fit a mono-directional function to the Waratah data sets. It is possible to use a quadratic function to the data:

$$Pr od = a \times PS + b \times PS^2$$

A quadratic function assumes that the decreasing phase is identical to the increasing phase, and that the optimum is exactly in the middle. Quadratic functions are rarely preferred in statistics. For this data set it yields the equation:

$$Prod = 200 \times PS + 35.9 \times PS^2$$

The optimum (sweet-spot) for the Waratah 622 was 2.2 m<sup>3</sup>, whereas the Waratah 624 was 2.8 m<sup>3</sup>. The specification sheets for these two machines indicate a maximum delimiting diameter of 65 and 76 cm respectively. For these studies the sweet spot was with 48 and 55 cm DBH trees respectively. Figure 5 indicates that as the piece size approaches 6 m<sup>3</sup> the productivity will drop to zero, whereby this was just 4m<sup>3</sup> for the Waratah 622. This matches up well with the published maximum diameter as specified by the manufacturer.

The increasing phase of the productivity curve was almost identical for the two different Waratah head sizes. This is consistent with Iwaoka et al. (1999) and Ovaskainen et al. (2004) who suggest that lighter harvesters can operate at approximately the same productivity of

medium size machines. When considering the higher operating costs of larger harvester heads, then smaller harvester heads are more cost effective in smaller piece size (Jirousek et al, 2007).

A more complex non-linear equation can be used that provides an opportunity to identify an optimum, as well as allowing different shapes for the increasing and decreasing phases of the productivity relationship. Two functions, each using just two coefficients, were preferred;

$$Pr od = \frac{PS}{a + b \times PS^2}$$

$$Pr od = a \times PS \times e^{b \times PS}$$

The behaviour of these two functions is very similar. Allowing the program R (software) to run an iterative optimising algorithm it yields:

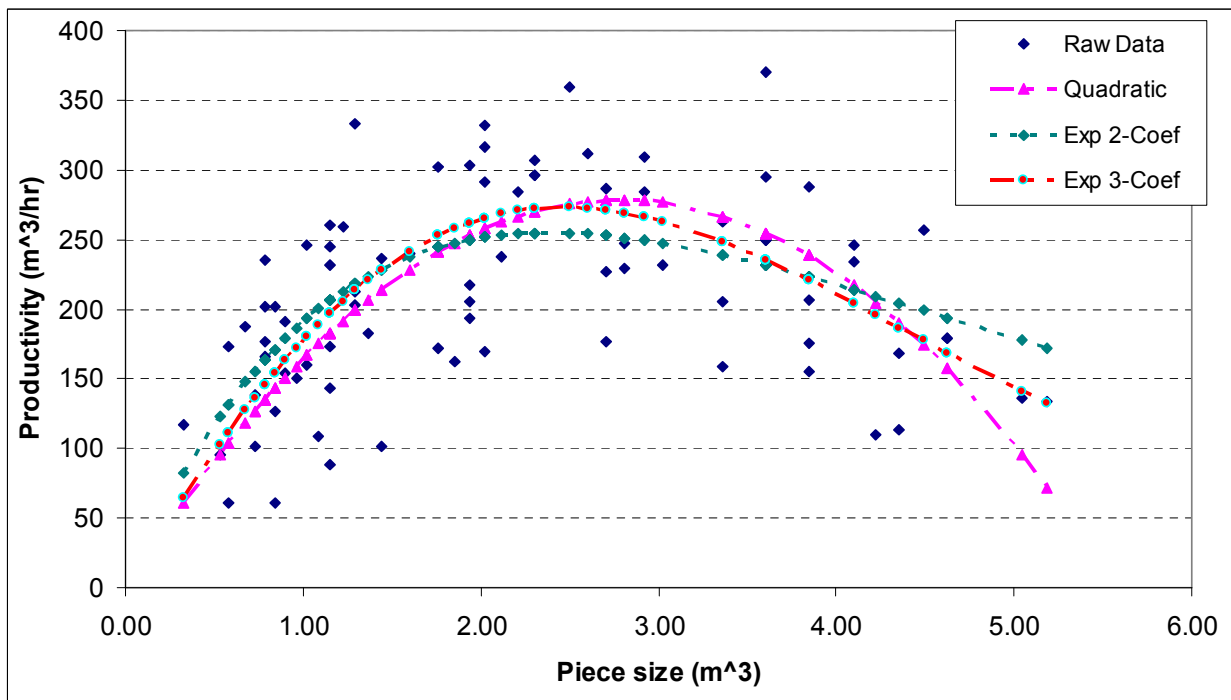
$$Pr od = \frac{PS}{0.0048 + 0.00058 \times PS^2}$$

$$Pr od = 289.6 \times PS \times e^{-0.418 \times PS}$$

These equations were adequate for re-evaluating the first two data sets, and it did find an optimum that was not the maximum piece size. It was noted that neither of these functions was able to bring the declining phase down quickly enough to match the data for the Waratahs. The latter equation was modified with an additional co-efficient, c.

$$Pr od = a \times PS \times e^{b \times PS^c}$$

Again using R, the iteration yielded a= 203.2, b=0.136 and c=1.655. Figure 6 plots the quadratic, as well as both the two and three coefficient exponential functions over the Waratah 624 data set. The 3-coefficient exponential function is the best fit with the lowest residual.





*Figure 6. Graph showing the Waratah 624 productivity data, as well as the quadratic and two exponential regression approximations.*

## **Conclusion**

Time studies are a great tool in forest engineering to understand the impacts the many stand and terrain variables can have on machine and harvest system productivity. While many variables exhibit a mono-directional relationship with productivity, this study has shown that piece size does not. Logically, there should be an optimum piece size where productivity is greatest that is not automatically the maximum piece size. For future studies consideration should be given to using a more complex function when relating piece size to productivity.

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