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ORIGINAL ARTICLE

Determining the shape of the productivity function for mechanized felling and felling-processing

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Abstract Productivity studies in forest operations are often carried out on new equipment, or on equipment being used in new conditions. Understanding how stand and terrain parameters impact the productivity of harvesting machines is important for determining their optimum use. 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, we can expect the machine to start to struggle, resulting in a decrease in productivity. Four different data sets—two based in New Zealand and two in Italy—are presented that clearly show an "optimum" piece size for maximum productivity. On average, productivity tended to decrease gradually, not drop off suddenly beyond the optimum. Using more complex statistical functions, it was possible to correctly correlate piece size to productivity.

Keywords Economics · Harvester · Logging · Mechanized felling · Productivity functions

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Introduction

Productivity studies in forest operations often produce empirical models used for many purposes, including wood-flow planning and harvesting cost calculation (Holtzscher and Lanford 1997; Spinelli et al. 2002; Adebayo et al. 2007). At a more fundamental level, productivity studies also allow us to understand the behaviour of harvesting machines and/or systems under varying stand and terrain conditions (Visser and Stampfer 1998). That is particularly important when deploying mechanized felling-processing machinery, which is a specialized industrial technology (Chiorescu and Grönlund 2001), and is therefore much less flexible than traditional general purpose equipment (Spinelli and Magagnotti 2010a).

Mechanized felling is used whenever possible in New Zealand as it increases productivity and cost effectiveness (McConchie and Evanson 1995), and can also reduce the occurrence of stem breakage and increase personal safety (Bell 2002). For the same reason, a major technology shift is occurring in Italian forest operations, and has already occurred further north in recent years (Spinelli and Magagnotti 2010b). Despite the challenging working conditions presented by Italian forestry, modern forest technology has already made significant inroads, as witnessed by a small yet substantial harvester and processor fleet, already counting about 100 U (Spinelli et al. 2010).

A large number of variables can impact the productivity of felling-processing machines. One can attempt to group them as stand and terrain variables. Typical stand variables include piece size (e.g., Iwaoka et al. 1999; Wang and Haarla 2002; Visser and Stampfer 2003; Nurminen et al. 2006), stocking density and thinning intensity (Eliasson 1999), type of cut and total volume (Suadicani and Fjeld 2001). Other variables proven to affect the productivity of felling-processing machines are tree form (Evanson and McConchie 1996), branch size (Glöde 1999), and selection criteria of trees to harvest (Eliasson and Lageson 1999). Typical terrain variables include slope, trafficability, and terrain roughness (Stampfer 1999). Again, there are other parameters that interact with the harvest system, including the layout of skid trails and landings.

As for all work tasks, productivity is also affected by the human factor (Ovaskainen et al. 2004). 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). 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 higher than found in follow-up longer-term studies (Sirén and Aaltio 2003). Kuitto et al. (1994) suggested using coefficients from combined studies in order to convert short-term productivity estimates into long-term productivity estimates, and such coefficients are already available for specific time study elements, such as delays (Spinelli and Visser 2008).

Most studies establish that piece size has a dominant effect on overall felling-processing productivity (Nakagawa et al. 2010). A common concept known as the "piece-size law" is that productivity increases at a decreasing rate with increasing piece size (Fig. 1). Some papers use a linear (Sirén and Aaltio 2003; Nakagawa et al. 2007) or even a quadratic (Kärhä et al. 2004; Nurminen et al. 2006) 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 monodirectional nature of these functions, when used for productivity prediction, the "optimum" productivity is always at the maximum piece size limit.

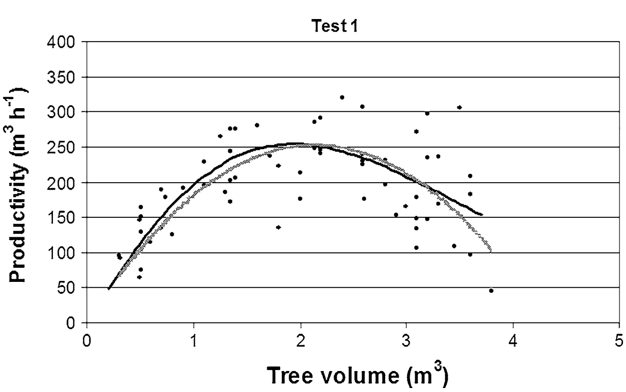

Fig. 1 Data points and compensation curves for test 1

Logically, this interpretation is simplistic, as we know that felling machines struggle with trees larger than they are designed to handle, and at some upper limit simply cannot cut them down. This leaves two important questions unanswered: (a) how should one determine optimum piece size, and (b) what happens after the optimum piece size has been reached. Most studies do not indicate what happens after the optimum piece size has been passed, and especially whether productivity rapidly drops to zero or declines more slowly. If there is a clear optimum, and the decline past the optimum is not identical to the increasing phase, then felling-processing productivity should be best described by nonlinear functions, which are somewhat more complex than the quadratic relationships already used by some authors. This would not only increase the accuracy of the model but also help us to define an optimum that is not necessarily at the maximum piece size.

The goal of this study was to improve the understanding of the piece size to productivity relationship, especially in the optimum and decreasing phases. For this reason, it is based on observing a number of felling-processing machines working in stands with large trees, including some considered at the limit of machine capability.

Materials and methods

Four mechanized felling-processing operations were chosen to study the effect of piece size on productivity. Two of the operations were located in New Zealand and two in Italy, in order to extend the study to very different work conditions and give its eventual findings a more general validity. All operations were selected, because the machines were working with a full range of tree sizes, including trees well above the rated capacity of the machines.

A general description of the studies is shown in Table 1, which reports both site characteristics and machine type. All of the time studies were set up and carried out by the same principal investigators and with the same methods. Productive time was separated from delay time (Björheden et al. 1995) and split into functional elements, which were expected to react to different variables (Bergstrand 1987). All time-motion data were recorded with Husky Hunter handheld field computers running Siwork3 time-study software (Kofman 1995).

The diameter at breast height (DBH) of each tree was also recorded and associated with the observation data. For this purpose, the DBHs of all trees to be felled were measured in advance, and the trees were identified by codes painted on the bark or flagged to the stem.

Units working in New Zealand performed felling and delimbing only, and produced full-length delimbed stems. The Italian units performed felling, delimbing, and

Table 1 Description of the four tests

Test #	1	2	3	4
Location	Bottle Lake	Lowmount	Seren	Intelvi
Country	New Zealand	New Zealand	Italy	Italy
Species	*Pinus radiata*	*Pinus radiata*	*Picea abies*	*Picea abies*
Base machine	Excavator	Excavator	Dedicated	Dedicated
Head	Waratah 622	Waratah 624	JD 758	JD 758
Max capacity (mm)	650	760	680	680
Work process	FD	FD	FDC	FDC
Mean DBH (cm)	39	45	29	40
Mean height (m)	29	32	19	24
Min. tree size (m^3)	0.3	0.3	0.1	0.1
Max. tree size (m^3)	3.8	5.2	4.4	4.4
Observations (*n*)	70	80	330	387

DBH diameter at breast height, *FD* felling and delimbing, *FDC* felling, delimbing, and crosscutting

crosscutting, and produced cut-to-length logs. In this case, target lengths varied between 2.4 and 5.2 m, depending on product type.

Approximately 20 trees were scaled at each test site by measuring the diameter at 5 m intervals along the stem, as well as a top length and DBH. A simple tapered cylindrical volume equation was used to calculate the volume of each segment. Segments were then summed to derive a close approximation of the real overbark volume of the tree. A simple exponential regression was used to correlate DBH to tree volume.

Productivity information (volume time^{-1}) was calculated based on the time it took the head to process different piece sizes. The purpose of this study warrants using productive machine hours (PMH) only, excluding nonproductive work time and delays. That also explains the very high productivity figures presented in this paper. In fact, such figures are only representative of net work productivity, which can be exceptionally high, especially in plantation forestry (tests 1 and 2). Combining all four studies, approximately 40% of the time was spent felling-delimbing or felling-delimbing and crosscutting; the remaining 60% was spent on bunching, clearing, moving, or delays.

Results

In all four studies, enough data were collected to clearly show the declining productivity phase. The tree samples ranged in piece size from 0.3 to 3.8 m^3 in test 1, whereas they ranged from 0.3 up to 5.2 m^3 in test 2. A very similar data set shape was also obtained from the Italian studies, where the piece sizes ranged from 0.1 to 4.4 m^3, and from 0.1 up to 4.4 m^3.

It would be unreasonable to attempt to fit either a linear or power function to these data sets because of the monodirectional properties of such functions. It may be more appropriate to apply a quadratic function to the data, as described below:

$$\text{Prod} = a \times \text{PS} + b \times \text{PS}^2, \tag{1}$$

where Prod = productivity (m^3 PMH^{-1}) and PS = piece size (m^3).

However, 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 dealing with complex real-world phenomena. Few such phenomena can be truly represented by the perfectly symmetrical structure of a quadratic function, with its equally shaped increasing and decreasing segments. In the specific case of harvesters, it does not seem reasonable to assume that productivity drops below zero beyond a certain value of piece size. Furthermore, quadratic equations with an intercept have the additional conceptual defect of implying positive productivity in the absence of tree volume (i.e., piece size = 0), and we know that productivity without product is an essential contradiction. Of course, one can cut the curve at both tails and obtain a perfectly workable representation. However, our specific research is looking for a way to understand the phenomenon, not just to represent it. We are not just trying to fit a curve to the data, but rather to explain the phenomenon through the data. This is a subtle but important conceptual point, and the main innovative aspect of our paper.

A more complex nonlinear equation can also be used that provides an opportunity to identify an optimum, as well as to allow different shapes to fit the increasing and decreasing phases of the productivity relationship. In that case, the function would have the form described by the following equation (and the same notations as Eq. 1):

$$\text{Prod} = a \times \text{PS} \times e^{b \times \text{PS}}. \tag{2}$$

Table 2 Main parameters calculated for the alternative equation types

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

Maximum productivity is achieved at optimum size

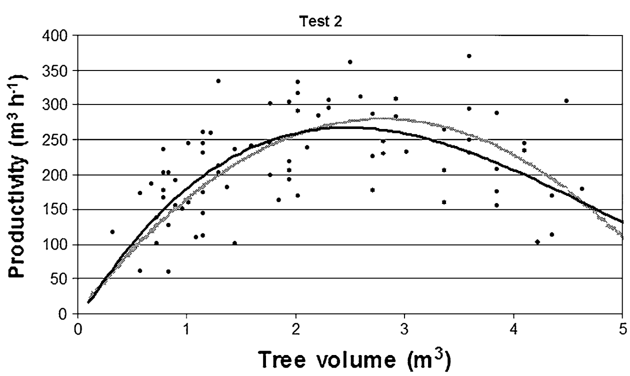

Fig. 2 Data points and compensation curves for test 2

Iterations run with the R statistical software suggested modifying Eq. 2 with an additional co-efficient, *c*, which leads to an improved version that provides a better fit:

$$\mathrm{Prod} = a \times \mathrm{PS} \times e^{b \times \mathrm{PS}^{\wedge} c} \tag{3}$$

Table 2 reports the main parameters and the main goodness-of-fit indicators obtained when Eqs. 1 (quadratic) and 3 (exponential, three coefficients) were applied to the four tests. Clear views of the data points, the quadratic compensation curve (gray), and the three-coefficient exponential compensation curve (black) are reported in Figs. 1, 2, 3, and 4, respectively, for tests 1–4. For all four case studies, the goodness of fit is improved by using the three coefficients: all of the exponential equations explain a larger proportion of the variability than the alternative quadratic equations. The average increase is about 10% of the original value obtained with the quadratic equation.

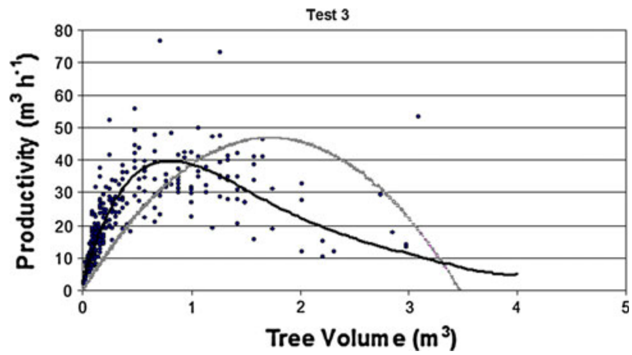

Fig. 3 Data points and compensation curves for test 3

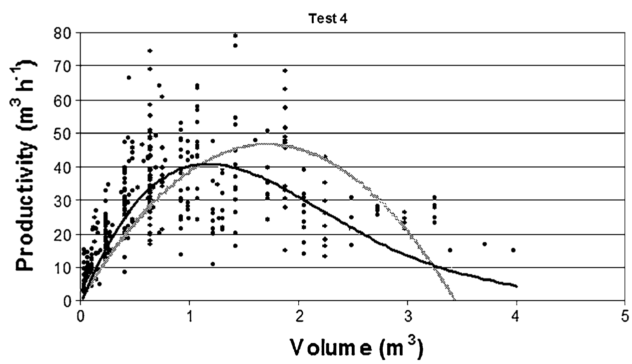

Fig. 4 Data points and compensation curves for test 4

Furthermore, exponential equations indicate a different optimum tree size and maximum productivity value compared to quadratic equations. In all four cases, the exponential equation peaks earlier and defines a lower maximum productivity level compared to the quadratic equation. In our study, shifting from a quadratic function to an exponential function entailed a reduction in the optimum tree size of between 10–50%, and a decrease in maximum productivity of between 4 and 17% (except for test 1). In short, the exponential equations offer a more conservative estimate than the quadratic equations, and may be more suited to long-term productivity forecasts.

It is worth noting that, in all cases, the exponential equation rises faster, peaks earlier and lower, and drops more slowly than the quadratic equation. Most importantly, the productivity values obtained with the exponential equation never drop below zero within the full range of explored tree volumes, whereas those obtained with the quadratic equation do drop below zero while still within the explored range, at least in tests 3 and 4. Of course, negative productivity values for observed tree volume figures are highly unrealistic. Hence, one of the main benefits of exponential equations is that they better represent the actual phenomenon and the shape of the raw data.

Discussion

Empirical models can be very useful for describing the relationship between machine performance and many different stand and terrain parameters. Mechanized felling machines are not frequently used to fell very large timber, and in many applications the use of a simple power function will be appropriate to represent their productivity. However, if one considers that such models may be used to predict performance, or even set logging rates, it is important that they behave in a rational manner. Upper and lower limits for the models are often not stated, or are ignored in such applications.

The declining phase of the function that describes the relationship between piece size and productivity can be attributed to a number of factors. For example, it is common practice to cut larger trees in two stages, performing a back-cut first and then moving the head around the base of the tree to complete the cut. This is done even when the bar is longer than the diameter to be cut, because operator experience indicates that when cutting trees at the limit of machine capacity, the bar is likely to pinch or jam. Extra time is also required to delimb the larger branches, as well as to manipulate a heavy stem.

Exponential equations can offer a better representation of the declining phase than quadratic functions. In this respect, readers must note that the data sets used for this study were heavily biased towards smaller piece sizes, which may have limited the increase in accuracy obtained by shifting to the exponential function. The study was based on commercial operations, where managers had deployed their machines in stands considered suitable for their use, so that oversized trees represented a minority. Had they been dominant, the managers would have deployed larger machines. This may explain the relatively small difference between the coefficients of determination for the exponential and the quadratic functions, despite the dramatically superior performance of the former in fitting the declining phase.

Furthermore, readers must remember that the productivity values reported in this study refer only to felling and processing, and represent theoretical figures. Actual work includes a number of other tasks, so that the actual productivity of a complete job is substantially lower than that indicated here. The dramatic difference between the New Zealand and the Italian datasets is explained by several factors: the larger sizes of the New Zealand machines and trees; the easier working conditions presented by the New Zealand plantations compared to the Italian natural stands; and finally the simpler job performed by the New Zealand units, which just felled and delimbed, whereas the Italian units felled, delimbed, measured, and crosscut. Pure felling work is logically much more productive than the combined tasks of felling and processing (Adebayo et al. 2007). Furthermore, pure felling work may be more sensitive than combined felling and processing to factors other than just tree volume, and possibly tree height and tree position. These factors were not recorded in the study, but their absence from our functions may explain the lower coefficients of determination of the regressions estimating pure felling productivity compared to those of the regressions calculated from combined felling and processing data.

While the more complex exponential function better represents the data, and especially the behavior beyond the optimum, there is the risk of overparameterization of the model. These models focus only on piece size; all other factors, such as travel time, are removed from the data sets. Using more parameters means that more data needs to be gathered to obtain model significance. The effects of branch size and tree form are also important, and have been included in other models (Spinelli et al. 2002).

Conclusions

Empirically based productivity functions are often used to describe the performance of forestry machinery as it relates to varying stand and terrain variables. Such models can be used to compare machinery, optimize work conditions, or formulate compensation rates. This study showed that piece size has a nonlinear effect on productivity, and that this effect should be considered when analyzing empirical data or developing productivity models. It also provides more conservative estimates than alternative quadratic models. The study is based on harvesting data sets collected in New Zealand and Italy, but its base findings are likely to be extended to other work environments.

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