Productivity Measurements of Two Waratah 234 Hydraulic Tree Harvesters in Radiata Pine in New Zealand.

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ABSTRACT

Two Waratah 234 single-grip harvester heads were assessed for productivity and log-processing accuracy while working in radiata pine clearfell operations in New Zealand forests.

Estimated productivity, processing stockpiled trees into logs on a landing in a ground-based operation, was 77 m^3 per productive machine hour (PMH) in an average tree size of 1.63 m^3.

In a yarder-based trial, processing trees into logs on a landing, productivity was 77 m^3 / PMH in an average tree size of 3.1 m^3.

Length-measuring accuracy in a later trial was shown to be within ± 5 cm for 93% of logs.

In a second ground-based trial, estimated productivity for an average extracted tree size of 1.95m^3 was:

- 51 trees/PMH (100m^3) for felling, tree-length delimbing and bunching.
- 73 trees/PMH (143m^3) for tree-length delimbing (butt-first) and bunching of manually felled trees.

Keywords: *Waratah 234 HTH, Pierce HTH 26, mechanized logging, single-grip harvester, tree-length delimbing, processing, cut-to-length.*

INTRODUCTION

In New Zealand (NZ) plantation forests, the use of single-grip, cut-to-length harvesters in thinning operations, which produce pulp and short sawlogs, is not new. However, this type of equipment is now being used in clearfell operations. Major advantages of the use of mechanized logging equipment are worker safety, operational flexibility, and the potential for increased production.

The predominant system for the clearfell of radiata pine in New Zealand is the motor-manual/tree-length extraction method. Trees are felled by chainsaw, limbed, then extracted to a landing by a rubber-tyred winch skidder for manual processing. A log-maker marks the stem into log lengths, choosing from a set of up to 20 log types, each with its own specifications of length, small-end diameter, branch size and allowable defects. The stems are then cut into logs, at which time they may receive a final trim.

Value maximization and log quality are important for the New Zealand forest industry. Recent years have seen an increase in log prices both for export and domestic markets. Accompanying this trend has been the demand by customers for product quality commensurate with cost. Log attributes such as length, diameter, branch size, and allowable defects are specified in detail, as is the demand for timely delivery to reduce sapstain (Bluestain) degradation. In addition, many forestry companies have made significant investments in pruning, often to a height of 6 m. High value, pruned logs must be identified and cut with a minimum of loss. Mechanized processing systems have had to demonstrate that they can match or exceed the log-quality standards achieved by manual processing.

The radiata pine clearfell resource is physically demanding. Mean DBH (diameter at breast-height) can range from 45 cm (18 in.) to 54 cm (21 in.) at 25 to 30 years, depending on stand management and site. Mean total tree weights (at approximately 1 t/m^3) can range from 1.8 t to 2.9 t [13], [14]. Added barriers to processing are large branches and associated nodal swellings, and variable levels of malformation [5]. In stands that have been production-thinned, most malformed stems have been removed. However, there are many residual "unmanaged" stands in New Zealand due for clearfell, especially on yarder logging terrain.

One of the major advantages that mechanized logging in clearfell operations can offer, is increased personal safety (reducing the requirement for manual labour).

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For instance, in 1994, felling, limbing and landing-work accounted for 65% of Lost Time Accidents (LTA) in logging, and 81% of LTAs occurred in clearfell operations [12]. These figures can be expected to decrease with increased mechanization.

The Waratah 234

The Waratah 234 single-grip harvester head (sold under licence in the United States as a Pierce HTH 26) is designed and manufactured in New Zealand by Waratah Engineering Limited of Tokoroa. It is a derivative of the smaller Waratah HTH 230 commonly used for production-thinning operations in NZ. Designed specifically for radiata pine, the Waratah 234 (Figure 1) is capable of felling and/or delimbing trees of up to 70 cm butt diameter. It weighs approximately 4 t and requires a minimum 30 t base carrier and hydraulic capacity of 31000 kPa (300 l/min). Trees are driven through the delimbing knives by three hydraulically powered spiked drive rollers. Feed speed is approximately 3.2 m/s, and the theoretical feed power is 39 kN. The hydraulic felling/cutting chainsaw uses a 3/4 in. chain, with a 1 m (38 in.) bar. A topping saw is an optional extra.

Heads to be used as processors are equipped with a merchandising computer featuring 18 programmable lengths in eight different species. Length measurement is by a hydraulically damped, 1 m circumference, gear-cut tooth encoder wheel and two front-mounted "find-end" photo-cells. Measurement is also triggered by initiating saw travel. Diameter measurement is determined by a pulse encoder.

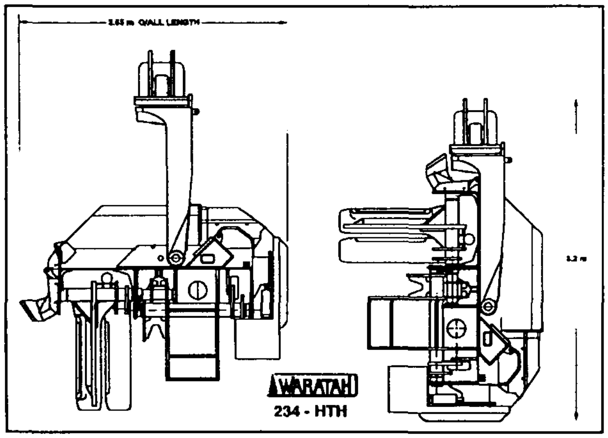

Figure 1. Waratah 234 Detail (processor version).

Several Waratah 234's are currently being used in clearfell operations in New Zealand forests: some as processors on landings in ground-based and yarder operations; others are being used as harvesters (felling and delimbing) and as tree-length delimbers. Some machines are also working in the US and Australia.

Little research information is available on the performance of harvesters or grapple processors in medium-to-large (30 to 50 cm plus) diameter trees of any species [10]. However, recent LIRO trials have provided the opportunity to assess the productivity of the Waratah 234 in a variety of applications, that is, as a processor [3], [4], as a "harvester" [11] and as a tree-length delimber/buncher [7], [11].

The objective of this paper is to report productivity and quality results from four evaluations, in four different applications, of the Waratah 234:

1. Landing-based processing in a ground-based operation.
2. Landing-based processing in a yarder-based operation.
3. Harvesting (felling and tree-length delimbing).
4. Cutover-based tree-length delimbing only.

The first study was carried out on a production operation, while studies 2, 3 and 4 were carried out during trials organized by forestry companies, with the aim of satisfying managers of the machine's suitability for specific tasks. The LIRO studies focused on potential productivity and quality, and effects of factors associated with these values, such as tree size and malformation.

METHODS

The three operations studied were located in three North Island forests, two on landings and one on a flat terrain cutblock (Table 1).

Evaluation 1. Processing: Ground-based

The Waratah 234 was operated as a processor, mounted on an excavator carrier, and was used on a single-shift basis, by one fully trained operator with more than 12 month's experience with this machine. The processing operation was a cold-deck, landing-based system. Trees were manually felled and the sloven (lilypad) cut. A Caterpillar 518 skidder, a Caterpillar D4 high-drive tractor and a

Table 1. Study conditions.

	Evaluation: 1 Processing: Ground-based	2 Processing: Yarder	3 and 4 Felling and Tree-Length Delimbing
Location	Kinleith Forest	Mohaka Forest	Tarawera Forest
Species	radiata pine	radiata pine	radiata pine
Age (yrs)	27	26	27
Stocking (sph)	approx. 500	284	376
Malformation (%)	3	10	11
Av. Diameter (cm)	-	52	45
Av. Height (m)	-	36.5	39
Recov. Vol/ha (m^3)	-	727	732
Av. Tree Size (m^3)	1.5	3.1	2.05
Terrain	landing	landing	flat
Soils	-	-	soft ash/scoria
Undergrowth	none	none	light, ferns
Weather	fine	fine	fine

Caterpillar D4 custom skidder extracted and stockpiled tree lengths beside landings. Trees were mostly butt-hauled, and piled so that butts were in line, just off the landing edge.

Prior to processing, the Waratah was positioned with the carrier's tracks at right angles to the stack. Trees were then slewed from right to left during processing into logs. Pulp logs were segregated into two fibre density grades and stacked close to the machine, while sawlogs were stacked further to the left.

Processed logs were stacked by Caterpillar 926E rubber-tired loader. Once the stockpiled wood had been processed, the Waratah 234 and loader would move to another landing and repeat the process. After processing, truck loading was carried out by a Caterpillar EL240B hydraulic loader equipped with a Prentice grapple.

Ten log grade and length combinations were cut, with a length tolerance of ± 5 cm. All logs were required to be flush limbed. Quality control procedures included periodic checking, by the operator, of some log grades determined to be more sensitive to length measuring inaccuracy (usually longer logs). Marked logs were subsequently reprocessed by the Waratah 234.

Evaluation 2. Processing: Yarder

The Waratah 234 (the same machine and operator used in the ground-based study) replaced one of two hydraulic loaders supporting a Madill 171 yarder for the trial period (one was used to clear the chute and lay out for processing, and one to sort, stack and load). The Waratah operator had not worked with yarders before.

Equipment used during the study comprised the Madill 171 yarder, the Waratah 234 (as a processor and for chute clearance) and a Caterpillar EL 300B 30 T loader. The yarder was rigged in a North Bend configuration and three chokers were used. As many as three choker setters were used during the study to maximize yarder production and test the Waratah 234. One worker was retained to unhook and carry out quality control on the processed logs. Eight log grades were cut, including pruned log grades. During the trial the required tolerance was +5, -2 cm from specified length. The loader operator controlled truck arrivals, and some loading out was carried out before and after the yarder operating shift.

Evaluations 3 and 4

The Waratah 234 used in these trials was a harvester model (not equipped with length-measuring equipment) of the same drive-roller configuration as most of the the units exported to the United States.

Evaluation 3. Harvesting (Felling and Tree-Length Delimbing)

The area to be felled comprised an "island" 100 m square, surrounded by an open cutblock. The Waratah operator worked a swathe along the stand edge, felling trees predominantly into the stand, forward of the machine. He preferred this technique as it crushed undergrowth and he believed it reduced tree breakage. The authors believe this to be an effective method, although some standing trees are sometimes broken, and tree crowns can become interlocked or caught on standing trees, hindering extrication of the tree prior to delimbing. However, problems can be avoided if a tree can be felled parallel to the delimbing direction.

Each tree was felled, delimbed on the left side of the machine (for better visibility), and ejected. Tree-lengths were accumulated in the form of a low continuous stack as the operation progressed. Sliding the logs along others enhanced delimbing.

Evaluation 4. Tree-Length Delimbing, Butt-First

The area planned to test this option comprised a road-edge strip approximately 400 m long by 25 m wide. Trees were manually felled parallel to the road. The Waratah operator approached from the butt-end, reaching and delimbing as many trees as possible from one location. Trees were delimbed and ejected onto low continuous stacks as above. Slovens or "lilypads" were cut prior to delimbing where necessary.

The owner/operator had been operating the Waratah 234 as a tree-length delimber for some six months prior to the trial, and had used it in harvester mode intermittently, for several weeks.

All Evaluations

Continuous time study using a "Husky Hunter" [9] field computer and "Siwork software" [1] was carried out on the Waratah 234 for defined elements of the work cycle. A description of time elements used is shown in Table 2.

Evaluations 1, 2. Ground and Yarder-Based Processing

Tree volume was estimated using a one dimensional volume table derived from trees scaled in the setting. All delays were measured, and changes in the method of operation noted. Samples of logs (629, and 551 respectively) were measured to assess length-measuring accuracy.

A previous study of this machine, and other studies of some harvesters in New Zealand, mainly in thinning operations, have indicated that tree-processing time increases with severity of malformation. Difficulty with quantitative measures of malformation has led to a subjective approach [5]. Tree form was classified subjectively into either normal (straight trees with typically light or moderate branching) or malformed (trees that were forked, swept or kinked, or with heavy, excessive branching).

Grade recovery records for the crew (manual processing) were provided by the company, and the logs produced during the trial were kept separate in order to provide weight and grade recovery figures specific to the trial with Waratah 234.

Evaluations 3 and 4. Harvesting and Tree-Length Delimbing

Prior to felling, all trees involved in the study were measured for DBH and colour-coded at breast height (1.4 m) into seven diameter classes covering the range of diameters present. Diameter class and tree form (rated as "normal" or "malformed"), were recorded against the time to handle individual trees. Tree volumes were later estimated using MARVL [2], i.e., a mean extracted tree volume was derived from a DBH/Total Volume table for each of the seven diameter classes. All delays were measured.

RESULTS AND DISCUSSION

In all the evaluations, the time required to delimb or process malformed trees varied considerably and took longer than normal formed stems. A "malformation allowance" element was developed. Based on the sample of malformed trees, the average additional "Pick up" and "Process" time was calculated. The malformation allowance (min/cycle) was derived by multiplying the average additional time to handle the malformed tree by the percentage of malformation observed, expressed as a decimal.

Table 2. Description of elements used in the time studies.

Processor-time elements (butt and top pieces processed)

Pick up tree: begins when the last processed log of the previous tree is ejected from the processing head, ends when the next tree starts to feed through the head (Process phase) or the sloven (lilypad) is cut. It describes the acquisition of a tree from a prepared stack of tree-lengths.

Cut sloven: begins as the saw begins downward travel, ends as the saw is returned to its rest position.

Process: begins when the tree begins to feed through the processing head or after the sloven (lilypad) is cut, ends when the last processed log is ejected from the processing head. It describes the delimbing and cutting of the tree-length into processed logs.

Sort trees: untangle tree-lengths in the inventory stack to enable easier processing.

Clear chute: removing logs from the chute after unhooking and carriage or rigging outhaul, and either stacking or starting to process individual tree-lengths (includes some carrier movement).

Other work: quality control and reprocessing of out-of-specification logs, sorting of processed logs, movement between processing sites.

Tree-length delimb and harvesting-time elements

Move: travel between felling or delimbing positions.

Clear: "sweeping" ferns, shrubs, and vegetation from around the base of a tree prior to felling.

Fell and delimb: begins when the last tree-length is ejected from the processing head, ends when the next tree is ejected.

Delimb: begins when the last tree-length is ejected from the processing head, ends when the next tree is ejected.

Other work: delimb broken top pieces, reconnaissance, fell non-merchantable stems, stacking tree-lengths.

Note: Due to the short duration of these evaluations (two to three days each) Operational, Personal, and Mechanical delays have not been included with the results.

Evaluation 1. Ground-Based Processing

The operation was timed for approximately 26 hours (over three days). A total of 887 "normal trees", 39 "malformed trees" and 59 "broken top pieces" were extracted. Cycle time results are shown in Table 3.

"Other work" in this evaluation comprised:

- Moving or positioning on the landing, and moving to other processing sites.
- Travel between landings. Average travel speed was 2.3 km/hr over an average distance between processing sites of 390 m.
- Quality control checks of mostly longer log grades; and some sorting of processed logs. Logs were re-cut if found to be out of specification.

Tree volume was found to be a significant predicting variable ($P < 0.05$) for "total processing time" (pick up tree and process) Figure 2.

The following model was derived from the data using an unweighted, least squares, linear regression procedure:

"Pick Up and Process Time"

$= 0.362 + 0.341 * VOL (m^3)$

Where: VOL = tree volume in m^3

$r^2 = 0.40$

Table 3. Cycle time and productivity summary.

Time Element[a]	Frequency	Av. Time/Cycle (min)	Proportion of Total Time (%)
Pick up tree	100%	0.23	18
Process	100%	0.67	53
Sort stems	15%	0.09	7
Pick up and process	6%	0.04	3
Broken top pieces			
Malformation	4%		
Malformation allowance		0.02	2
Other work	10.6%	0.22	17
Total		**1.27**	**100**
Av. vol/tree(m^3)	1.63		
Range	0.10-3.18		
Logs/tree	3.6		
Trees/PMH	47.2		
Vol (m^3)/PMH	76.6		

[a]Sample size - 926 trees (59 broken top pieces)

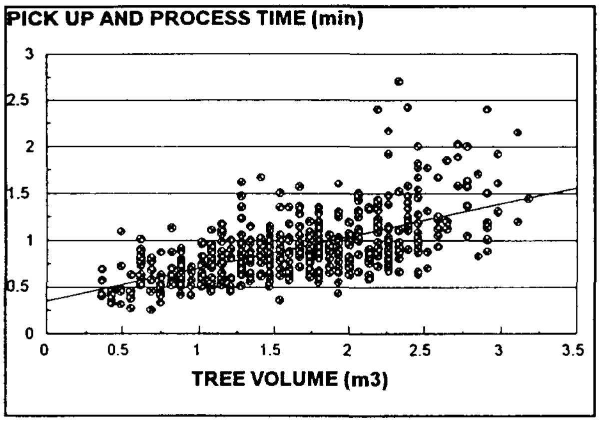

Figure 2. Effect of tree size on "Pick Up and Process" time.

A total of 629 logs were measured to assess the length-measurement accuracy. The percentage of logs in specification for different tolerances is shown in Table 4.

Longer logs (T and Q grades) were found to have more logs out of specification (at ± 5 cm) than shorter, F grade logs. However, two-sample t tests showed no significant relationship ($P < 0.05$) between difference from specification value and log grade, length or small end diameter.

Approximately 12 months later, as part of a project aimed at defining log quality from mechanized processing [6], logs from a Waratah 234 processor were assessed for length. Changes to the design of the length-measuring system had been initiated by the manufacturer. Results for 200 measured logs are shown in Table 5. A marked improvement in length-measurement accuracy is apparent.

Evaluation 2. Yarder-Based Processing

The operation was timed for approximately 22 hours (over three days). A total of 275 "normal trees", 53 "malformed trees" and 155 "broken top pieces" were extracted. Cycle time results are shown in Table 6. "Other work" in this evaluation comprised:
- moving and positioning,
- reprocessing after length measurement,
- sorting processed logs,
- assisting the yarder with rope shifts.

The effect of tree volume on processing time is illustrated in Figure 3. Another influential factor in determining processing time was whether or not the processing head was reversed to delimb a piece from the small end to the large end. Normally, most trees were delimbed and crosscut from the large to the small end. A head reversal was used to delimb (and sometimes reshape) a particularly rough tree or piece.

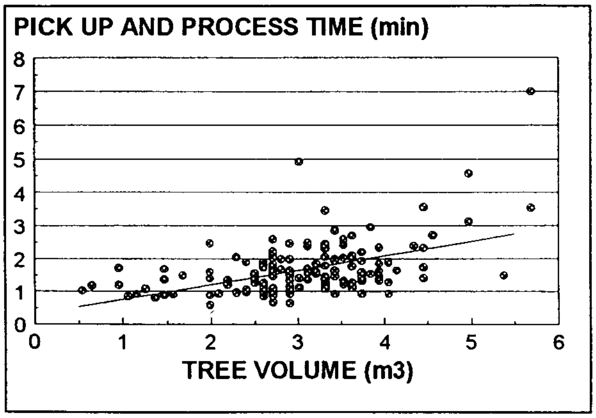

Figure 3. Effect of tree size on "Pick Up and Process" time.

Most of the processor's operation delay could be attributed to yarder interference, where the heads of trees being processed ran afoul of the working ropes of the yarder. As the logging of the small setting progressed, the angle between the trees being processed and the ropes became more acute, and this type of interference became more pronounced. Ropeshifts were the next largest source of delay. Head-pulled trees took more time (86% longer) to clear from the chute than butt-pulled trees. This was because the tree had to be turned 180° before processing.

Evaluation 3. Harvesting

The machine was studied for approximately four hours during which 203 trees were felled. A summary of cycle element times is shown in Table 7. The effect of tree diameter on fell and delimb time is shown in Figure 4.

Table 4. Logs in specification (as percentages), for different tolerances, first assessment [3].

	DIFFERENCE FROM SPECIFIED LENGTH								
LOG TYPE (m)	± 1cm	± 2cm	± 3cm	± 4cm	± 5cm	± 6cm	± 7cm	± 10cm	± 15cm
Q9.8	22	40	60	74	80	83	87	95	98
T9.8	38	55	71	77	81	85	90	97	99
F6.1	23	44	72	81	88	92	93	98	98
F4.9	44	64	73	86	87	88	89	97	97
F4.1	43	61	72	79	87	92	92	97	97

Table 5. Logs in specification (as percentages), for different tolerances, second assessment [6], following changes to equipment.

	DIFFERENCE FROM SPECIFIED LENGTH								
LOG TYPE (m)	± 1cm	± 2cm	± 3cm	± 4cm	± 5cm	± 6cm	± 7cm	± 10cm	± 15cm
10.5	58	80	90	92	94	96	98	100	100
7.9	51	74	91	98	98	100	100	100	100
6.1	24	48	90	94	98	100	100	100	100
4.1	58	80	90	96	98	100	100	100	100

Table 6. Cycle time per tree, and productivity summary.

Time Element[a]	Frequency	Av. Time (min)	Proportion of Total Time (%)
Pick up tree	75%	0.21	8
Process	100%	1.28	53
Clear chute	74%	0.60	25
Pick up and Process broken top pieces	32%	0.21	8
Malformation	11%		
Malformation Allowance		0.04	2
Other Work	8%	0.09	4
TOTAL		2.43	100
Average Vol/Tree (m^3)	3.1		
Range	0.54-5.69		
Logs/tree	3.7		
Trees/PMH	24.7		
Vol (m^3) /PMH	76.6		

[a]Sample size = 328 trees (155 Broken top pieces)

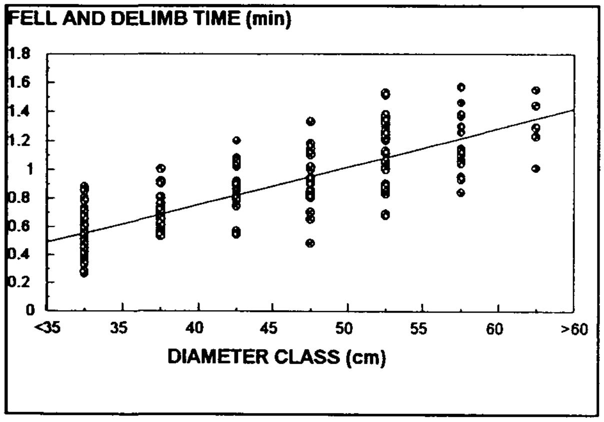

Figure 4. Effect of tree diameter on "Fell and Delimb" time.

An average of two trees were felled per "move" (ranging from one to five). Some limited movement was associated with getting the tree down through the stand during felling, or to aid delimbing or bunching. "Other work" included reconnaissance, felling non-merchantable stems, stacking or restacking for improved skidder extraction, and delimbing merchantable top pieces. Picking up and processing "top pieces" required 34% of "Other work" time shown in Table 7. Thirteen pieces took an average 0.46 min. to flush-cut one end and delimb. Fewer top pieces needed to be delimbed when harvesting than when tree-length delimbing following manual felling.

Evaluation 4. Tree-Length Delimbing Butt-First

The Waratah was studied for approximately three hours, during which 228 trees were delimbed. A summary of cycle element times is shown in Table 8. The effect of tree diameter on delimbing time is shown in Figure 5.

On average 2.2 trees were delimbed per "move" (ranging from one to six). The "delimbing" time included; picking up the tree, removing the branches and bunching onto distinct, continuous low stacks. "Other work" time was dominated by time taken to handle broken top pieces. These equalled 13% of of butt logs (29 pieces), and took an average 0.4 min. to flush-cut one end and delimb. This made up 55% of all "other work" -- an increase over that recorded for harvesting, due to the increased breakage due to manual felling.

A small sample of 56 trees was delimbed tip-first. Productivity was similar to butt-first delimbing. Some limited breakage was observed.

Table 7. Cycle time per tree, and productivity summary.

Time Element[a]	Frequency	Av. Time (min)	Proportion of Total Time (%)
Move	49%	0.12	10
Clear	8%	0.02	2
Fell and Delimb	100%	0.84	74
Malformation	11.5%		
Malformation Allowance		0.07	6
Other Work	29%	0.09	8
TOTAL		**1.14**	**100**
Average Vol/Tree (m^3)	1.71	43 cm average DBH	
Range	0.45-4.38		
Trees/PMH	52.6		
Vol (m^3) /PMH	89.9		

[a]Sample size = 203 trees

Table 8. Cycle time per tree, and productivity summary.

Time Element[a]	Frequency	Av. Time (min)	Proportion of Total Time (%)
Move	46%	0.11	13
Delimb	100%	0.56	67
Malformation	11.5%		
Malformation Allowance		0.07	8
Other Work	28%	0.10	12
TOTAL		**0.84**	**100**
Average Vol/Tree (m^3)	2.21	47 cm DBH	
Range	0.45-4.38		
Trees/PMH	71.4		
Vol (m^3) /PMH	157.8		

[a]Sample size = 228 trees

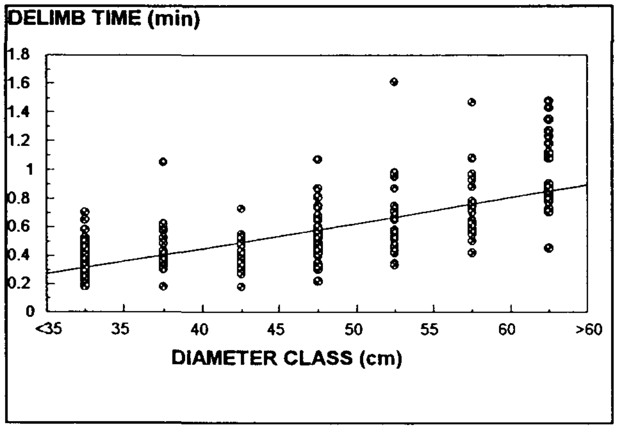

Figure 5. Effect of tree diameter on "delimb" time.

IN SUMMARY

These studies of different applications of the Waratah 234 have demonstrated its flexibility, i.e., its use both as a feller-tree-length delimber, and as a processor in both ground-based and yarder-based operations, in average tree sizes from 1.5 to 3.1 m^3.

The effect of operator skill on the productivity of harvesting or processing machines is well documented, with some research suggesting that operators may take up to two years to reach 100% of their potential productivity. The results in this paper were derived from only one operator per application, so these productivity results are indicative only.

Potential for increased daily production is evident. In the above tree sizes, daily production from a manual skidder crew could range from 220 to 310 t/day [8]. Based on recent results, a Waratah 234 felling and delimbing in 1.95 m^3 tree size might produce 300 t in three PMH.

Since these studies were undertaken, additional sales have been made of the Waratah 234 for these applications. Eighteen machines have now been sold in New Zealand, with eight sales in Australia, and six in the United States. The prototype model, reported on in Evaluation 1, has been reconditioned and fitted to a new carrier, and continues working as a processor.

Proven advantages over manual systems in terms of production and safety mean that mechanized clearfelling equipment is being employed by increasing numbers of New Zealand loggers.

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