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The effect of the number of log sorts on mechanized log processing productivity and value recovery

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New Zealand's forestry supply chain handles a wide range of log products to meet domestic and export market demands and to maximize returns to the forest grower. With a strong customer focus in diverse markets, one supply chain implication is the number of grades and sorts that a logging operation is expected to produce. A typical harvesting operation will produce 8–22 log sorts while harvesting one tree species (*Pinus radiata*). As New Zealand's log exports have grown strongly over the last 5 years, the prices for major export log grades have risen and converged with structural sawlog grades. This price convergence has reduced the incremental value gains from producing a wide range of log sorts. This paper details a production study at two harvesting operations whereby the mechanized processing component was studied in different market scenarios (5, 9, 12, and 15 log sorts) with respect to both product value and the operational impacts on log processing productivity. The study showed the market scenario with 15 log sorts to decrease processor productivity by around 10%. Cutting nine log sorts was estimated to be the optimum scenario in terms of the value produced per productive machine hour. Expanding on these findings to investigate other parts of the supply chain could result in significant value and productivity improvements through simplification.

Keywords: harvesting; processor; log grades; value recovery; *Pinus radiata*; New Zealand

Introduction

New Zealand's log supply chain handles a wide range of log products to meet domestic and export market demands and to maximize returns to the forest grower. The trend in the New Zealand forest industry has been to increase the number of log sorts to meet the specifications set by multiple log buyers and to obtain the maximum possible gross value from an extracted stem at the processing site (Murphy & Marshall 2003). Managing such a wide array of products through the supply chain requires intensive log processing, handling and logistics systems.

Individual log products are referred to as "log sorts," which is defined as a log grade of a given length. A single harvesting crew can produce around eight to 22 log sorts from a single species, which is radiata pine (Visser 2013). The number of log sorts produced by a harvesting operation affects the landing size (Visser et al. 2011), layout and processing requirements (Sinclair & Wellburn 1984) and also the subsequent log transport, port storage and shipping requirements. A thorough understanding of how the number of log sorts can affect productivity and costs through the supply chain could assist managers to make optimal decisions to improve efficiency and productivity.

Harvesting represents one of the most significant supply chain costs for forest managers and a logical starting point to consider the effect of the number of log sorts on the supply chain. This article focuses on the impact of the number of log sorts on mechanized log processing in landing-based harvesting operations. As the number and type of log sorts is a key driver of value that can be recovered from individual trees, the effect of the number of log sorts on value recovery is included in this article. An optimal cutting scenario was then derived by assessing the value outturn from mechanized log processing per productive machine hour.

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Log grades and sorts

A log grade is defined by a set of specifications as required by the customer relating to characteristics such as diameter, maximum branch size, maximum sweep and allowable defects. In New Zealand there are five major log types produced, which are pruned logs, structural, utility, industrial and pulp (Ministry of Primary Industries (MPI) 2010). Each log type contains multiple grades and sorts which are specified for domestic or export markets, or both (Table 1). Forest managers provide harvesting crews with a set of log grades and sorts, or cutting instructions, to produce to meet market demands. An important component of log processing operations is the ability of the operator to maximize value recovery (Cossens 1991) using the given cutting instruction.

There has historically been significant log price differentiation between domestic structural and export utility and industrial log grades. However, at-wharf-gate (AWG) and at-mill-gate (AMG) log prices for these grades have converged to a large degree since 2008 (Agrifax 2013). This has coincided with a rapid increase in total volume harvested and the log export volumes from New Zealand to China (MPI 2013). The convergence of log prices has an impact of reducing the incremental value gains from producing a large number of log sorts.

Mechanized production

Logs are typically processed and sorted on landings within the forest in New Zealand (Visser 2013). Mechanized log processing on landings has become increasingly common due to productivity and cost improvement goals, overcoming labor shortages and improving worker safety (Pasicott & Murphy 2013). Mechanized processors operating on cable yarder landings generally have multiple responsibilities in addition to the primary task of processing logs. Other responsibilities can include clearing the yarder chute as stems are extracted, managing processing waste to a designated part of the landing as part of environmental requirements and pre-sorting logs for the loader.

Landing-based mechanized processing productivity can be influenced by many factors. Tree size has been found to have a significant effect on productivity and the unit cost of production (Holtzscher & Lanford 1997), for as tree size increases, the unit cost of production decreases. Other influencing factors include, tree form (Evanson & McConchie 1996), landing layout, the number of products to be produced and sorted (Cass et al. 2009), and the

Table 1. Description of New Zealand log sorts and quality specifications (MPI 2010).

Log type	Market(s)	Log grades	Lengths/sorts (m)	SED[a] (cm)	Max. branch size (cm)	Max. sweep
Pruned logs	Export	P30, P35	3.7, 3.9, 4.0, 6.0	≥30	0	SED/4
	Domestic	P35, P40	3.75, 4.0, 4.4, 5.0, 5.5, 6.1	≥35	0	SED/4
Structural	Domestic	S20, S30, S35	4.9, 5.5, 6.1	≥20	7	SED/4
Utility	Export	A, AO	3.7, 3.9, 4.0, 4.1, 5.1, 5.2, 5.4, 7.8, 8.0, 12.0	≥30	12	SED/4
	Export	K, KS, KM	3.7, 3.9, 4.0, 4.1, 5.1, 5.2, 5.4, 7.8, 8.0, 12.0	16–30	12	SED/4
	Domestic	L30, L40	4.1, 4.7, 5.0	≥30	14	SED/4
Industrial	Export	KI	2.7, 3.1, 3.7, 3.9, 4.0, 4.1	≥26	20	SED/3
Pulp logs	Export	Pulp	4.0, 6.0, 8.0	≥10	Unlimited	Unlimited
	Domestic	Pulp	3.0–8.0	≥10	Unlimited	Unlimited

Note: [a]SED: Small-end diameter of a log.

performance of the human operator (Murphy & Vanderburg 2007; Purfürst 2010).

The effect of the number of log grades and lengths on mechanized log processing productivity is not as well understood and there is limited available public information and research in this area in New Zealand. The increased time and machine capacity to undertake log sorting can add cost, which is partly due to the resulting decline in productivity (Cass et al. 2009). Murphy and Marshall (2003) suggested that producing and handling a larger number of log sorts could result in productivity decreases and cost increases, which can affect the economics of a harvesting operation.

Human operator factor

A key variable affecting mechanized harvesting productivity and processing accuracy is the performance of the human operator. In comparison to equipment, a human operator could be considered much more variable in terms of specifications, capabilities and limitations (Murphy & Vanderburg 2007). The physical, mental and emotional demands placed on a human operator could impact on productivity, safety and value recovery. Studies from other industries have shown the detection of defects to decline as an inspection task becomes more complex (Harris & Chaney 1969), which is directly applicable to manual or mechanized log processing. Frequent rests and job enrichment initiatives have been strongly recommended for log-makers to mitigate tediousness (Parker et al. 1993).

The operation of a harvester or processor is regarded as an intensive and complex work task which includes cyclic repetition of work activities. Gellerstedt (2002) study found operators having 3400–3700 inputs per hour in mechanized thinning operations in Sweden. Other studies on processor operators have shown mental and physical fatigue to increase over the work day (Kirk 1998) and that worker fatigue is a major driver of workplace accidents, particularly in forestry due to the physically and mentally demanding nature of the work.

The human operator factor must be taken into account when conducting harvesting production studies. Productivity estimates and models need to be based on large sample sizes to overcome the variation caused by operator performance, which can be as high as 20–50% (Murphy et al. 2005; Nurminen et al. 2006; Murphy & Vanderburg 2007; Visser & Spinelli 2011). Purfürst (2010) analyzed harvester production data in Germany from 16 new operators and defined a learning period of approximately 8 months before maximum productivity was achieved. In addition to collecting large sample sizes, production studies should be conducted in conditions reflecting normal operations to mitigate the "Hawthorne Effect," where productivity tends to increase during trials due to increased personnel interaction and supervision of work tasks (Karsten 2013).

Objectives

There is a limited amount of previous work which quantifies the impact of producing a large number of log sorts on the productivity of harvesting operations in the New Zealand forest industry. Recent trends in log prices further emphasize the need for research in this area, as a large number of log products of varying quality are selling for similar prices. This research aimed to answer the following questions:

(1) Does the number of log sorts affect mechanized log processing productivity in landing-based harvesting operations?
(2) Does the number of log sorts affect gross value recovery in landing-based mechanized log processing operations?
(3) How many log sorts should be produced to optimize processing value outturn in landing-based mechanized log processing operations?

Materials and methods

A field study was conducted in June 2013 to collect data on the implementation of a range of cutting instructions on mechanized processing operations. Two mechanized processing operations were observed with each using four different cutting instructions. The four cutting instructions were defined as "cutting scenarios" which differed in the type and number of log sorts. A log sort was defined as a log grade of a given length. The four cutting scenarios contained 5, 9, 12 and 15 log sorts. Two key types of data were collected from each cutting scenario to estimate productivity per productive machine hour and value recovery:

(1) Processed volume by stem, log and log grade; and
(2) Time and motion observations on the processor for each stem.

Site and stand characteristics

The field study was carried out in Onewhero forest, approximately 75 km South of Auckland in the North Island of New Zealand. This plantation was

Table 2. Estimated stand attributes of study sites.

	Site 1		Site 2	
Stand attributes	Average	Range	Average	Range
Piece size (m^3/stem)	2.1	1.4 – 2.6	2.4	1.9 – 3.3
Height (m)	36.6	34.1 – 38.5	35.5	33.5 – 37.9
Stocking (stems/ha)	276	171 – 440	239	142 – 369
TRV (m^3/ha)	587	349 – 805	565	337 – 746
Log type recovery				
Pruned %	13	2 – 31	12	0 – 27
Structural %	18	0 – 53	14	3 – 30
Utility/ Industrial %	49	32 – 64	54	38 – 76
Pulp %	20	7 – 43	20	7 – 48

chosen for the study as there were two harvesting crews located in close proximity to each other (site 1 and site 2) and both crews were operating the same mechanized processor and were able to use the same cutting instructions. Topography was predominantly rolling hill country with a series of steep valleys and long leading ridges which suited cable yarder harvesting operations. Cable yarding distances extended to a maximum of around 400 meters (m) in both harvest settings.

Stands in the harvest settings were *Pinus radiata* plantations established in 1987 and were 26 years of age at the time of harvest. Trees had been pruned to varying heights, with most stands being pruned up to 6 meters. Site 1 had an estimated average piece size of 2.1 m^3 per stem and site 2 2.4 m^3 per stem. Table 2 provides a summary of the averages and ranges of stand and log type recovery percentages for both sites.

Harvesting operations

The cable yarding operations comprised of a Madill 124 swing yarder operating a scab skyline system (site 1) and a Madill 171 tower yarder operating a live skyline shotgun system with a motorized carriage (site 2). The swing yarder at site 1 operated with a grapple where possible. Otherwise, two to three choker setters working with three chokers for extraction were used over the study period.

Processing was undertaken at both sites with Caterpillar 330DL excavators each fitted with a Waratah HTH626 processing head. Both crews averaged a daily production of around 240 tonnes of logs, which tended to vary on a daily basis according to the performance of the extraction phase of the operations. Each processor was fitted with an on-board computer to run Waratah TimberRite measuring and control system software. Stem files recorded by the processors followed the StanForD Nordic standard for collecting stem and log information from mechanized processing.

Processing areas were located adjacent to the cable yarders and processed logs were pre-sorted for fleeting. Site 2 was a two-stage operation where processed logs were transported to a second landing for fleeting and loading out. Each processor operator had over 5 years mechanized and 10 years log making experience. At each operation, the processor had multiple responsibilities which included:

- Clearing the hauler chute (whilst ensuring safety of breaker outs);
- Managing processing waste;
- Delimbing trees;
- Log processing; and
- Pre-sorting logs for the loader.

Both processors followed a similar work method, where the first work priority was to clear stems from the hauler chute (extraction phase) and then delimb the stems before placing them in a surge pile. During hauler cycles, the processor would move over to the surge pile and process delimbed stems into logs.

Processing scenarios

Log grades and sorts for the four processing scenarios were selected from the range of products in demand from domestic and export markets at the time of data collection. To prepare the four processing scenarios with 5, 9, 12 and 15 log sorts, longer length log sorts were retained as a priority and at least one sort for each log type (pruned, structural, industrial, utility and pulp) were retained if possible. Cutting instructions for each processing scenario were prepared using Silvia desktop software (.apt files) for subsequent uploading onto TimberRite on-board computer systems.

The processing scenario with the fewest log sorts (5) only included domestic pruned, two export K grades, export KI grade and a pulp grade (Table 3). To make this possible, the maximum small end diameter (SED) range of export K grade 3.9 m and 5.9 m lengths were expanded beyond the usual upper SED limit of 30–50 cm. This effectively combined A grade and S30 volume as K grade volume. Different P35 lengths were defined as one log sort to reflect how the lengths were fleeted on the landing and loaded out on trucks. The S30 structural grade lengths were divided into two log sorts to

Table 3. Log grades and sorts included in the study by processing scenario.

Cutting priority	Log type	Grade	Lengths/sorts (m)	Min. SED[a] (cm)	Max. branch size (cm)	Indicative price (US $/m³ AMG/AWG2[b])	Processing scenarios 15	12	9	5[c]
1	Pruned	P35	4.40/5.00/5.50	35	0	115	Y	Y	Y	Y
2	Pruned	P35	3.75	35	0	115	Y			
3	Structural	S30	6.10	30	7	88	Y	Y	Y	
4	Structural	S30	4.90/5.50	30	7	88	Y	Y	Y	
5	Utility	AO	3.90	45	10	87	Y			
6	Utility	A	5.90	30	10	87	Y	Y	Y	
7	Utility	A	3.90	30	10	87	Y	Y	Y	
8	Utility	K	5.90	22	10	83	Y	Y		Y[c]
9	Utility	K	3.90	22	10	83	Y	Y	Y	Y[c]
10	Utility	K	3.77	22	10	83	Y			
11	Utility	KM	3.95	16	8	81	Y	Y	Y	
12	Industrial	KI	3.90	26	20	73	Y	Y	Y	Y
13	Industrial	KI	3.15	26	20	73	Y	Y		
14	Pulp	Pulp (small)	3.00–8.00	10	Unlimited	38	Y	Y	Y	Y
15	Pulp	Pulp (large)	3.00–8.00	30	Unlimited	38	Y	Y		

Note: [a]Small-end diameter of a log.
[b]At mill gate/At wharf gate.
[c]In the 5 sort scenario, the SED was expanded for K grade 3.9 m and 5.9 m to combine A and K grade specifications.

also reflect the way these sorts were fleeted and loaded out.

The order of cutting priorities in the processing scenarios reflects log prices at the time of the study. These log prices were applied to the processed volume data to estimate gross value recovery by cutting scenario. Gross value recovery is the AWG/AMG value of a processed stem, without taking any production, handling or transport costs into account. New Zealand dollar values were converted to United States dollars using the average currency exchange rate for June 2013 of NZD/USD $0.79. The study focussed on comparing actual value recovery and did not attempt to estimate potential optimum value recovery.

Work study

All activities associated with the operation of a mechanized processor on a cable yarding landing were considered for inclusion in the work study. Time study data was separated into three broad groups:

(1) Productive time – primary tasks
(2) Productive time – other tasks
(3) Non-productive time

Productive primary tasks were associated with processing logs (Table 4) while productive other tasks included tasks undertaken by the processor that contributed to normal landing operations. Scheduled breaks were not included in the time study. The study was conducted over a period of 2 weeks and data was collected on each processing scenario during two separate sessions at each operation. Sessions were scheduled randomly on different days to mitigate any effect of the day of the week on production. Sample units were defined as a stem or piece of a stem which was processed into at least one log.

Work study data was collected on an Android smartphone using SIWORK3 work study software developed by the Danish Institute of Forest Technology. Work activity definitions for the time study were pre-programmed into SIWORK3. Processing volume data was collected by downloading stem files (.stm) from the on-board computer at the conclusion of each data collection session. Time study data and volume data was aligned for each sample by matching up time study observations with the respective stem file data. Processing productivity was calculated by translating the processing time for a given piece size into the equivalent production volume per productive machine hour (PMH).

Statistical analysis

Analysis of covariance (ANCOVA) was applied to compare productivity across different processing scenarios using piece size as a covariate (as piece size was naturally different in each processing scenario). A series of iterations was undertaken using

Table 4. Work activity definitions for the time study.

Work element	Descriptions used for time studies
Primary tasks	
Positioning and pickup	Begins when the processor starts to move to the surge pile and ends once a stem has been picked up and is positioned by the feeder rollers for making the first cut.
Processing – cross-cutting	Starts when the first cut is made, continues while the stem is bucked into logs and ends when the last cut is made.
Other tasks	
Clear chute	Begins when the processor moves towards the yarder to collect extracted stems and finishes when the stems are placed in the surge pile or when the processor begins to delimb the stems prior to placing them in the surge pile.
Delimbing	Begins when the feeder rollers started moving the stem and finished when the delimbed stem was placed in the surge pile processing.
Waste management	Time spent picking up and moving logging debris into slash piles.
Log sorting	Time spent picking up and moving processed logs into sorting piles for the loader (pre-sorting).
Delays	
Operational delays	Time spent waiting while there are no stems to process or other operational interference that prevented productive work.
Other delays	Time when the processor was not operational due to breakdowns, maintenance and repairs.

R statistical software to determine if both piece size (continuous variable) and cutting scenario (categorical predictor) significantly influenced processing productivity (continuous response). Regressions were fitted to each of the four processing scenarios and then tested for statistically significant differences. The same approach was also applied to value recovery on a stem by stem basis to test if value recovery was significantly different by processing scenario.

Results

Production

The number of samples was similar at each site, with 288 observations at site 1 and 290 at site 2 (Table 5). There was a large range in piece size, which varied from 0.1 m^3 to 4.8 m^3. Field observations noted that the majority of stems had suffered some degree of breakage during extraction. A total of 578 stems and 1957 processed logs made from 2769 saw cuts were included in the sampling across both sites. An average of 4.8 saw cuts was required to process each stem to produce an average of 3.4 logs. The higher number of saw cuts reflects the extra cuts required for removing slovens, defects or other non-merchantable parts of a stem. Overall, 2769 saw cuts were required to produce 920 m^3 of logs, which equates to 3.0 saw cuts per cubic meter of logs.

Table 5. Log processing production data summary.

Data type	Site 1	Site 2	Combined
Observations (*n*)	288	290	578
Total volume (m^3)	419	500	920
Avg. piece size (m^3)	1.5	1.7	1.6
Max. piece size (m^3)	4.8	4.6	4.8
Min. piece size (m^3)	0.1	0.1	0.1
Avg. base diameter (cm)	36.4	38.4	37.4
Avg. length (m)	14.8	15.9	15.4
Total saw cuts	1307	1462	2769
Avg. saw cuts per stem	4.5	5.0	4.8
Total logs	946	1,011	1,957
Avg. logs per stem	3.3	3.5	3.4

Machine utilization

A total of 26.1 hours of time study data was collected, with around 13.3 and 12.9 hours collected at site 1 and site 2, respectively (Table 6). Machine utilization by site shows each processor spent a similar proportion of time picking up and processing stems (47–50%). On average, the operator at site 2 processed stems 0.14 min, or 10%, faster than the operator at Site 1. This could be due to many factors such as less variable tree form and a larger working space at site 2 relative to site 1, or differences in operator performance.

Overall, machines were utilized for 84% of the time study, which included other productive tasks such as clearing the yarder chute (16%), delimbing (10%), waste management (5%) and log sorting (4%). For both sites 16% of total time was non-productive. Operational delays of 8% and 10% respectively tended to only occur due to long cable

Table 6. Breakdown of time and motion data by time element and site.

Work element	Site 1		Site 2	
	Avg. (min)	Proportion (%)	Avg. (min)	Proportion (%)
Positioning and pick up	0.33	12	0.25	10
Processing	1.06	38	1	38
Primary tasks	*1.39*	*50*	*1.25*	*47*
Delimbing	0.23	8	0.32	12
Clear chute	0.43	16	0.44	16
Waste management	0.1	4	0.17	6
Log sorting	0.17	6	0.04	2
Other tasks	*0.93*	*34*	*0.97*	*36*
Operational delays	0.23	8	0.28	10
Other delays	0.21	8	0.16	6
Delays	*0.44*	*16*	*0.44*	*16*
All work elements pooled	2.76	100	2.66	100

yarding distances or when the tailhold cable position was shifted.

Delimbing, which comprised 8–12% of total time, was carried out as stems were collected from the yarder chute. During periods of longer cable yarding distances, which often extended out to 300–400 m, the processor was able to spend most of its time on processing the surge pile. On occasions when the surge piles had been completely processed and hauler cycles were slow, operators used these opportunities to carry out other important tasks such as managing logging debris and slash (4–6%) or log sorting (2–4%).

Productivity

Processing productivity was shown to be strongly influenced by piece size ($p < 0.01$) and productivity tended to be more variable as piece size increased (Figure 1). Quadratic trend lines were used for productivity relationships in each processing scenario, as non-linear relationships appeared to provide a more appropriate representation of productivity trends. Quadratic functions have been considered an appropriate regression for mechanized productivity relationships, as power function regressions can be considered too aggressive and mono-directional (Visser & Spinelli 2011).

To test the representativeness of a non-linear relationship, second-degree polynomial regressions (quadratic regressions) were fit to normalized data (Figure 2). There was not enough evidence to suggest the four processing scenarios had different

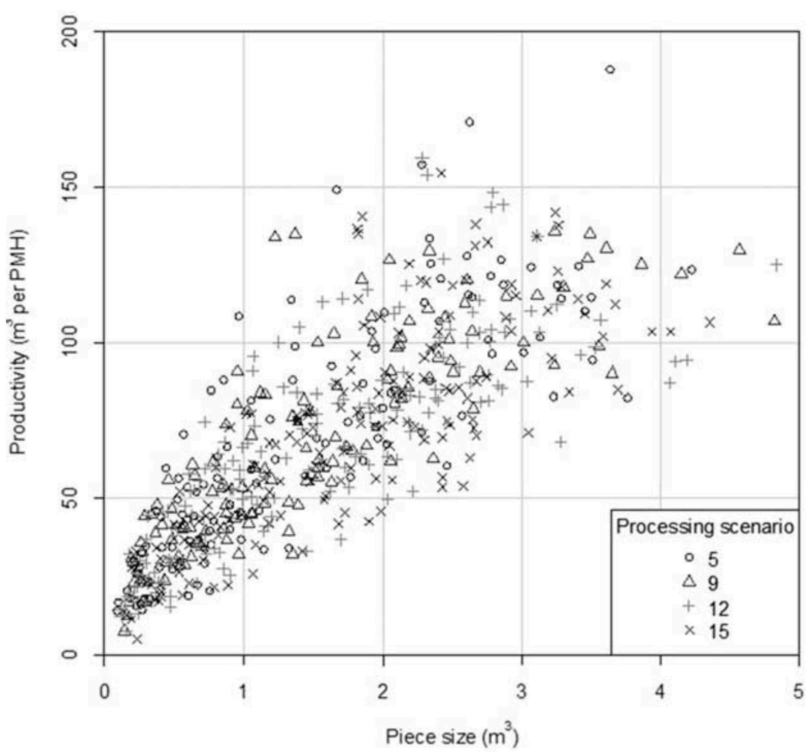

Figure 1. Productivity data points by processing scenario.

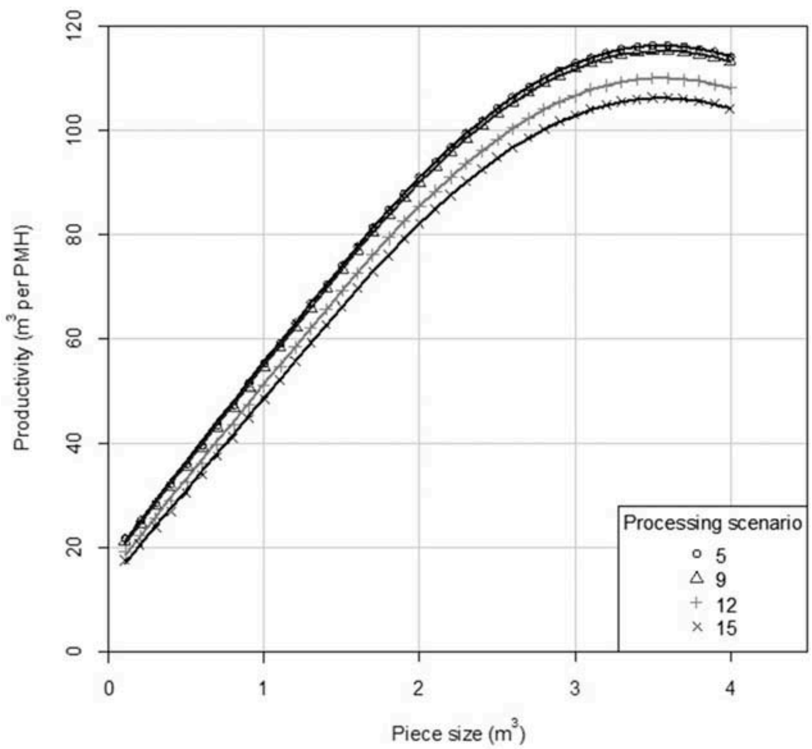

Figure 2. Productivity trend lines by processing scenario.

slopes, which indicated there was no significant relationship between piece size and processing scenarios.

ANCOVA used the five sort scenario as a base which showed an adjusted R-squared value of 0.73 and that the 12 and 15 sort processing scenarios were significantly different from the five sort scenario ($p = 0.03$ and <0.01, respectively). An F-statistic of 319 showed that the overall model was highly significant. There was not enough evidence to suggest any difference in productivity when processing five and nine sorts ($p = 0.73$).

As productivity data was normalized, the equation for the productivity curves includes a step to back transform the response variable by squaring the result of the transformed coefficients:

$$Y = (\beta_0 + \beta_1 x_1 + \beta_2 x_1^2)^2$$

where β_0 is the y intercept, β_1 is the linear slope, β_2 is the quadratic slope and x_1 is piece size. Coefficients for productivity functions are listed in Table 7.

Further ANCOVA showed no significant difference between 9 and 12 log sort processing scenarios (p-value 0.14) and a significant difference between the 9 and 15 log sort processing scenarios ($p < 0.01$). Predicted processing productivity across different piece size classes shows that at a piece size of 2.0 m^3, the model predicts processing productivity is 11% higher when producing five sorts compared to producing 15 sorts (Table 8). As piece size increases, the difference in productivity marginally diminishes.

Table 7. Coefficients for productivity functions.

Processing scenario (no. of log sorts)	y-intercept (β0)	Linear slope (β1)	Quadratic slope (β2)	p-value
5	4.29			(Base)
9	4.24			0.73
12	4.00	3.65	−0.51	0.03
15	3.81			< 0.01

Value recovery

Gross value recovery by processing scenario was as expected with average gross value recovery increasing with the number of log sorts (Table 9). Even so, increases in average gross value were marginal as the number of log sorts increased. Log grade outturn results showed the 15 log sort processing scenario recovering the highest pruned volume which was due to the option of cutting a shorter 3.75 m pruned log.

Table 8. Predicted productivity by processing scenario and piece size class.

Piece size class (m^3)	Productivity by processing scenario (no. of log sorts; m^3/PMH)				Relative difference between 5 and 15 log sorts (%)
	5 sorts	9 sorts	12 sorts	15 sorts	
1.0	55	54	51	48	14
1.5	74	73	69	66	12
2.0	91	90	86	82	11
2.5	104	103	98	95	10
3.0	113	112	107	103	10

Table 9. Proportion of volume by log grade and processing scenario.

Log type	Grades	Log grade outturn by processing scenario			
		5 sorts	9 sorts	12 sorts	15 sorts
Pruned logs (%)	P35	21	20	23	27
Structural (%)	S30	N/A	19	19	14
Utility (%)	A, AO	N/A	35	27	35
Utility (%)	K, KM	64	13	13	10
Industrial (%)	KI	5	5	13	9
Pulp (%)	Pulp	9	8	5	4
All pooled (%)		100	100	100	100
Avg. gross value (US$/$m^3$)		85	88	89	91

The outturn of the export KI grade was highest in the 12 and 15 log sort processing scenarios due to the option of cutting a 3.15 m KI log. These logs would have been graded as Pulp in the five and nine log sort processing scenarios.

ANCOVA was undertaken to evaluate gross value recovery relationships in each processing using piece size as a covariate. Linear regressions (Figure 3) showed piece size and processing scenarios to be significant predictors of gross value recovery ($p < 0.01$). The model suggested each cutting scenario trend had a different slope ($p < 0.05$) which is expected as the number of log sorts has a strong influence on the value that can be recovered from a stem. The adjusted R-squared value for the linear gross value recovery model was 0.97.

Differences between processing scenarios were minor and ANCOVA showed mixed results. Gross value recovery was only significantly different between the five and nine and the nine and twelve log sort processing scenarios ($p < 0.05$). The linear function for predicting gross value recovery is described below (coefficients listed in Table 10):

$$Y = \beta_0 + \beta_1 x_1$$

where β_0 is the y intercept, β_1 is the linear slope and x_1 is piece size.

Optimal processing scenario

The optimal processing scenario was investigated by using the productivity and gross value recovery functions to estimate the value per PMH at a piece size of 2.0 m^3 for each processing scenario (Table 11). Estimates from the regression trends show an ordered decline in productivity and increase in gross value recovery as the number of log sorts increased.

The value per PMH indicated that the most optimal processing scenario was to produce nine log sorts, which reached the highest value per PMH at US$7928. Value per PMH declined to US$7677 and US$7417 when processing 12 and 15 sorts, respectively. This suggests predicted falls in processor productivity offset gains in gross value recovery when producing 12 and 15 sorts and that a cutting instruction including around nine sorts would achieve optimal value from processing.

Discussion

A key outcome of this study was determining if, after a certain point, gross value recovery gains from increasing the number of log sorts would be offset by losses in mechanized log processing productivity. The optimal number of log sorts was estimated at around nine, where processing productivity was

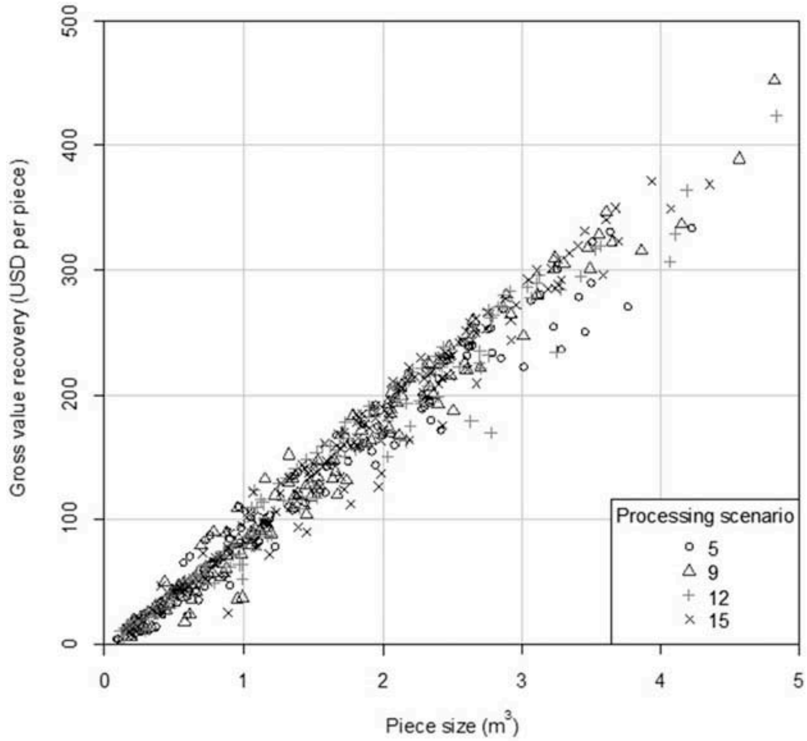

Figure 3. Value recovery observations by processing scenario.

Table 10. Coefficients for gross value recovery functions.

Processing scenario (no. of log sorts)	y-intercept (β0)	y-intercept *p*-value	Linear slope (β1)	Linear slope *p*-value
5	−1.97	(Base)	108.25	(Base)
9	−10.95	0.04	117.19	< 0.01
12	−3.03	0.79	114.47	< 0.01
15	−8.47	0.14	118.81	< 0.01

Table 11. Predicted productivity and gross value recovery by processing scenario.

Processing scenario (no. of log sorts)	Productivity (m^3/PMH)	Gross value recovery (US$/2.0 m^3)	Value per PMH (US$/PMH)
5	91	170	7728
9	90	176	7928
12	86	179	7677
15	82	181	7417

around 10% higher than productivity from producing 15 log sorts. Murphy and Marshall (2003) conceptualized that every harvesting operation has an optimal number of log sorts for balancing value recovery and costs. Beyond this optimum, marginal gross value recovery gains are offset by increases in log-maker errors and in processing and landing costs.

Given that the number of log sorts can impact processor productivity, more research needs to be undertaken to quantify the effect on other parts of landing operations and subsequent parts of the supply chain. Visser et al. (2011) showed that the number of log sorts can impact on the size of a landing, which has a significant bearing on pre-harvest engineering costs. The next logical step would be to quantify the effect of the number of log sorts on loader utilization and quality control requirements.

The reduced productivity as the number of log sorts increased can be partly attributed to increasing complexity. It is understood that producing a high number of log sorts can contribute to more complex log-making which can impact on value recovery and productivity (Harris & Chaney 1969; Parker et al. 1995). Predictive log-making tools for mechanized processing intend to maximize value and simplify operator input. However, the operator is still required to visually assess every stem for quality features and make the key decision about accepting the proposed cut from the computer programme. As concluded by Gellerstedt (2002), further machine automation is required to reduce the intensive workload for mechanized harvester and processor operators.

Evaluating the performance of built-in predictive log-making functions was not part of this study. There is limited research on the performance, accuracy or use of these log-making functions in practice. A better understanding of how operators utilize these predictive functions for maximizing value recovery could help continually improve mechanized log-making. Further research to determine log prediction accuracy and the frequency that operators accept or reject predictions would assist in a broader understanding of the utilization of these log-making tools.

Production data from modern harvester and processor on-board computers provides a platform for collecting large datasets on machine and operator performance. The consistent StanForD format allows large amounts of data from multiple machines and locations to be consolidated. Machine software can also be configured to automatically collect time study and machine utilization data. Collecting and centralizing this data on a large scale has unprecedented potential for analyzing harvesting operations in New Zealand. Such large scale studies have been conducted in Russia to assess drivers of harvester productivity in varying stand and site conditions (Gerasimov et al. 2012).

The shape of estimated productivity functions showed productivity reaching a peak at a piece size of around 3.5–4.0 m^3. This was similar to quadratic productivity functions applied in other production studies in radiata pine plantations in New Zealand (Visser & Spinelli 2011). As there was limited data beyond around 4 m^3, the downward trend in the productivity curves represents a conservative estimate at very large piece sizes. These functions follow a logical interpretation of productivity trends where each processing head has an optimum operating piece size. Beyond this optimal operating piece size, which is relative to the size and capability of the machine, productivity results tended to be mixed as machines took longer to delimb, pick up and process exceptionally large trees.

This study did not take potential optimum value recovery into account. The New Zealand forest industry has established methods of monitoring gross value recovery and estimating potential optimum gross value recovery from harvesting operations. Optimum value recovery assessments tend to be derived from intermittent, small sample trials, and operator performance could potentially improve during such trials due to increased supervision and personnel interaction (Karsten 2013).

This study has demonstrated some potential for cutting instruction decisions to have flow-on effects on the economics of landing-based harvesting operations. Productivity and value recovery need to be viewed as interdependent to maximize the net value of an operation. Forest managers may look for opportunities to combine some log grades in order to reduce the number of log sorts while maintaining value recovery. This could be possible as some log grades only differ in SED range. Even so, changes to log grade specifications are only possible if there is an alignment with the requirements of customers.

Reducing the number of sorts could have efficiency benefits for the log supply chain. Wood availability in New Zealand is forecast to increase with the maturation of large areas of first rotation plantations established in the early- to mid-1990s. Much of the potential new harvest volume is planted on marginal, steep land in smaller woodlots. Fewer log sorts reduces not only the required landing size in steep terrain, but simplifies the management and logistics of harvesting and transporting logs from multiple locations. There would also be efficiency benefits for log storage areas at ports and ship-loading operations. Overall net gains from efficiency improvements in each part of the supply chain could improve stumpage returns to forest growers and enhance industry competitiveness on an international scale.

Conclusions

The number of log sorts was found to impact on mechanized processing productivity in landing-based cable yarding operations. Results of ANCOVA tests showed piece size and processing scenario to be significant variables for predicting log processing productivity. Processing scenarios with 12 and 15 log sorts were significantly different from the scenario producing five log sorts, while the scenario with nine sorts was also significantly different from the 15 sort scenario.

A linear regression model showed a strong relationship between gross value recovery, piece size and processing scenario. Gross value recovery was shown to increase with the number of log sorts. There were only small differences in gross value recovery between processing scenarios and only some of these differences were statistically significant. The processing scenarios with five and twelve sorts were shown to be significantly different from the cutting scenario with nine log sorts.

The value outturn per PMH indicated that the most optimal processing scenario was to produce nine log sorts. This suggests predicted falls in processor productivity, as the number of log sorts increased, offset gains in gross value recovery when producing twelve and fifteen sorts.

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