Evaluation of Alternative Cut-to-Length Harvesting Technology for Native Forest Thinning in Australia

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ABSTRACT

This research quantified the equipment productivity relationships between piece size and terrain conditions for mechanized harvesting operations in native forest re-growth thinning. In addition, the economic gains or losses of adding a feller buncher to a cut-to-length (CTL) harvesting system were quantified. Study results indicate that although the use of a feller buncher working in combination with two processors is more productive than the use of a harvester-processor (single-grip harvester) working alone the high cost per tonne of this harvesting system means that its use is not recommended in areas with moderately steep terrain and small tree diameter. The differential in costs obtained between the two harvesting systems (feller buncher and two processors vs. one harvester-processor) on moderately steep and gentle terrain was approximately AUD$5/tonne and AUD$2/tonne, respectively, for an average tree diameter of 19 cm. Regression models developed from the study showed that diameter at breast height accounted for more than 85 percent of the variance in productivity of the machines and, therefore, represented the main driver of productivity and cost per tonne of the harvesting systems in all of the scenarios studied.

Keywords: *cut-to-length harvesting systems, thinning operations, productivity, costs*

Introduction

The forest and wood products industry is an important resource and manufacturing sector in Australia. The total harvest per annum is 27 million cubic meters with 10 million cubic meters harvested from native forests and 17 million cubic meters from plantations (Australian Government, Dept. of Agriculture, Fisheries and Forestry 2007).

A significant portion of the wood supply from native forests in Australia is sourced by commercial thinning of stands originating from fire regeneration or earlier clear-felling operations. Past native forest re-growth thinning research in the states of New South Wales and Victoria have described thinning technologies and studied the effects of commercial thinning of native forests on flora and fauna, fire risk, eucalypt health, hydrology, and soil physical and hydrological properties (Roberts and McCormack 1991, Murphy 2005). There is, however, a need for additional re-growth harvesting productivity and cost information as forest managers consider moving operations into stands with smaller tree sizes and on steeper slopes. Overseas commercial thinning studies conducted in North America (Kellogg and Bettinger 1994, Hossain and Olsen 1998, Turner and Han 2003, Kellogg and Spong 2004) and Europe (Glode 1999, Hanell et al. 2000, Spinelli et al. 2002, Nurminen et al. 2006) are useful but they must be put into context with the native forest conditions found in Australia.

In Australian re-growth thinning operations, contractors typically use single-grip harvesters and forwarders (cut-to-length [CTL] system) with a major difference being the presence or absence of a feller buncher (Beveridge 1999). When a feller buncher is used to fell and bunch the trees, a processor (single-grip harvester) follows with processing the trees (delimbing, debarking, and crosscutting) prior to forwarding. The feller buncher represents a significant capital investment. Therefore, it is necessary to quantify the use of a feller buncher with regard to the productivity and cost of re-growth thinning across a range of slopes and tree sizes being harvested.

The objective of this study were to:

1. examine the impact of slope and tree size on harvesting costs and productivity for native forest re-growth thinning in New South Wales forests using a CTL system,
2. statistically analyze elemental times, productivity, and cost related to operational factors, and
3. develop predictive equations for feller buncher and harvester production and cost.

Our research hypothesis is that for smaller piece size and steep terrain the use of a feller buncher and two processors is more cost effective than the use of a harvester-processor. The information reported in this study focuses on identifying opportunities for potential harvesting improvements and cost reductions.

Material and Methods

Study Sites and Layout

A total of four sites located near the southeastern border of New South Wales, Australia (latitude/longitude: 37°29′01″S /

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149°56′24″E) were used for the study (**Table 1**). Two plots each (approximately 100 by 100 m) were laid out on sites 1 and 4, one for the first harvesting system consisting of a harvester-processor (single-grip harvester), and the other for the second harvesting system consisting of a feller buncher and two processors (single-grip harvesters). On sites 2 and 3, plots of the same dimensions as on sites 1 and 4 were laid out only for the second harvesting system. The study layout was limited by the availability of suitable sites within the designated harvesting compartment and by the necessity of not altering the normal operation of the logging crews. Pre-harvest inventory data collected by research collaborators were used for determining the location of the plots. The plot locations were selected to give a range of piece sizes (diameter) and operating conditions (slope). The terrain was uniform within each of the study plots. There were scattered old stems laying on the ground and minimal understory vegetation or unmerchantable trees. The predominant species on the sites was yellow stringybark (*Eucalyptus muelleriana* Howitt). The other two species present on the sites were silvertop-ash (*Eucalyptus sieberi* L.A.S. Johnson) and monkey gum (*Eucalyptus cypellocarpa* L.A.S. Johnson). The regrowth stands (28 yr of age) originated from a bush fire that occurred in the area in 1980.

The principal objective of the thinning operation was to grow high-quality sawlogs over a shorter rotation for future harvest. This was achieved with a "thinning from below" treatment, to reduce the number of smaller but competing stems in the stand and to concentrate growth potential onto the remaining final crop trees. In the compartment, thinning focused on a 40 to 50 percent retention in the standing basal area. Retained stems were primarily in the dominant and codominant classes with the greatest sawlog potential. In all of the plots, the equipment operators selected the trees for retention (Forests New South Wales 2007). The average diameter at breast height (DBH) of the trees harvested during the thinning operations was 19 cm.

Table 1. ~ *Pre-treatment description of the harvest units.*

	Site 1	Site 2	Site 3	Site 4
Area (ha)	1.80	0.83	0.79	1.55
Number of trees	1,290	592	563	781
Stocking (trees/ha)	717	713	713	504
Mean DBH (cm)	21.5	23.2	22.9	21.3
DBH range (cm)	12.0 to 65.0	12.0 to 51.0	12.0 to 61.0	14.0 to 62.0
Mean basal area (m^2/ha)	26.0	30.2	29.4	18.0
Ground slope (°)	15 to 20	15 to 20	10 to 15	0 to 10
Harvest system studied[a]	1 and 2	2	2	1 and 2

[a] Harvest system 1 is a harvester-processor and harvest system 2 is a feller buncher and two processors.

Table 2. ~ *Harvesting systems used in the study.*

Harvesting system 1:
Harvester-processor (**Fig. 1**): Timberjack 608S steel-tracked (21.3 tonnes and 245 HP) with a 7.6 m articulated boom. Equipped with a Waratah head of 56 cm (single-grip harvester).
Forwarder: John Deere 1710D, 18 tonne load capacity and 215 HP with a 8.5 m articulated boom.
Harvesting system 2:
Feller buncher (**Fig. 2**): Valmet 445 EXL steel-tracked (27.2 tonnes and 260 HP) with a 6.5 m articulated boom. Equipped with a Rosin CF750 head (chain saw) with a maximum opening of 1.1 m and 2.25 tonnes.
Processors: Two machines with the same characteristics of the harvester-processor used in harvesting system 1. Processing operation includes delimbing, debarking, and cut-to-length only (no felling).
Forwarder: same as the one used in harvesting system 1.

Harvesting Systems

A description of the two harvesting systems that were assessed and compared on moderately steep and gentle terrain (Sites 1 and 4) is presented in **Table 2**. In harvesting system 1, the harvester-processor (single-grip harvester) was used for tree felling, delimbing, debarking, and crosscutting, whereas in harvesting system 2, trees were felled with a feller buncher and two processors (single-grip harvester) were used for delimbing, debarking, and crosscutting. Only information on the felling and processing component of the thinning operation was collected because the short-wood forwarding methods were the same in both harvesting systems.

The broken terrain in the area dictated the road layout and hence the harvesting pattern. Roads were predominantly located along the ridges with the harvesting operation moving outwards in a perpendicular pattern from the roads, and up and down the slopes. Harvesting with the first harvesting system was conducted in parallel extraction tracks that were 15 m apart. The harvester-processor worked from the roadside downhill to the bottom of each track, felling and processing the trees from the tracks and to its right side. The processed logs were then piled in the previously thinned stand on the left side of the extraction track (as seen from the roadside). At the end of each track, the harvester turned around and travelled up slope to begin a new extraction track from road side. Trees were felled, processed, and cut to length (4 to 6 m logs), and then transported and loaded onto trucks directly by the forwarder or stockpiled for loading later.

With the second harvesting system, the trees were felled with the feller buncher in parallel extraction tracks similar to the harvester-processor in the first system. Unlike the harvester-processor, however, the feller buncher worked from the bottom of the slope to the top (roadside) of each track, felling some trees to its left side but mainly from the track and to its right side. The trees were bunched on the left side (as seen from the bottom of the extraction track) again in the previously thinned stand. At the end of each track, the feller buncher turned around and travelled back down the slope to begin a new extraction track. Trees were processed and cut to length (4 to 6 m logs) at the stump by two processors that worked behind the feller buncher. But, the two processors primarily worked in a mirror image pattern to the feller buncher, that is from the top of the slope to the bottom, commencing their activity where the feller buncher finished and piling the processed logs to the left of the extraction track (as seen from the roadside). Logs from

Figure 1. ~ *Single-grip harvester "Timberjack" 608S – (harvester-processor or processor only).*

Figure 2. ~ *Feller buncher "Valmet" 445 EXL.*

the processor operation were transported by the forwarder in the same fashion as outlined above for system 1. In both systems, logging slash, debris, and unmerchantable trees remained on the ground. The operator of the single-grip harvester used in system 1 (harvester-processor) had more experience (10 yr) driving that machine than the operator driving the single-grip harvester that was used in system 2 as a processor (2.5 yr).

Data Collection

Prior to data collection, all of the trees within each plot were identified with a painted color code according to their diameter class (2 cm each, ranging from 15 cm to 41+ cm). Sixteen combinations of colors and symbols were used for this purpose. Over a period of 2 weeks, the operation of each machine was recorded with the use of a camcorder. Complementary information, such as operating delays, painted color code, species, branchiness, and number of logs per stem, were recorded on data collection forms. In addition, operators were provided with shift level forms designed for recording long delays (> 15 min). The contractor was also asked to complete an additional form, which was used to verify hourly machine costs.

Table 3. ~ *Description of time elements by machine type.*

Harvester-processor (HPR)	Feller buncher (FB)	Processor (PR)
Moving	Moving	Moving
Clearing	Clearing	Clearing
Moving LBT	Moving LBT	Moving LBT
Positioning	Positioning	Positioning
Felling	Felling	Processing
Processing	Bunching	Travelling
Travelling	Travelling	

Moving (HPR, FB, PR): Begins when the harvester starts to move and ends when the machine stops moving to perform some other activity.

Clearing (HPR, FB, PR): Clearing undergrowth and processing unmerchantable trees.

Moving LBT (HPR, FB, PR): Removing logs, branches, and tops.

Positioning (HPR, FB, PR): Begins when the boom starts to swing toward a tree and ends when the machine head is resting on a tree and the felling cut begins.

Felling (FB, HPR): Begins when the felling cut starts and ends when the tree touches the ground (FB) or when the feeding rollers start to turn on the stem (HPR).

Processing (HPR, PR): Begins when the feeding rollers start to run and ends when the last bucking cut is made and the last log is dropped onto the pile.

Bunching (FB): Begins when the tree touches the ground and ends when the tree is dropped onto the pile.

Travelling (HPR, FB, PR): Travelling from one row (swath) to the next one.

The detailed time study was conducted in the office by reviewing field operations recorded by the camcorder. The software Timer Pro^{TM} (Applied Computer Services Inc. 2007) with a PDA (Dell^{TM} Axim x51) and a spreadsheet, were used for recording equipment cycle times. Cycle times[1] of the machines were divided into time elements that were considered typical of the harvesting process of each machine (**Table 3**).

Variables believed to have an impact on the productivity of each piece of equipment were recorded together with the time elements. For the harvester-processor and the processor these included: DBH, branchiness (coded into three categories for big [> 7.5 cm], medium [5 to 7.5 cm], and small branches [< 5 cm]), hang-ups during felling (coded as 1 for presence and 0 for absence), logs (number of logs per stem), and slope. The same variables were included in the analysis of the feller buncher, but with the addition of a variable describing the feller buncher operator's work method. Tree codes were used to indicate if the trees were picked up and felled from the right (1), front (2), or left (3) side of the machine. During the detailed time study, small delays (less than 15 min) were recorded and classified as mechanical, operational, or personal delays. Small delays and long delays (from the shift level records) were used to determine the utilization of the machines in each harvesting system.

[1] A cycle is the complete set of operations or tasks that is repeated (Stokes et al. 1989). In the present study, it corresponds to the tasks (time elements) carried out between the felling (feller buncher and harvester-processor) or processing (processor) of two consecutive trees.

Table 4. ~ *Productivity and costs by harvesting system.*

	Harvesting system 1		Harvesting system 2							
	Site 1	Site 4	Site 1		Site 2		Site 3		Site 4	
Area (ha)	0.76	0.87	1.04		1.16		1.10		0.68	
Average DBH of harvested trees[a] (cm)	21.1	18.0	18.3		20.7		20.9		18.6	
Trees harvested	390	341	530		431		388		264	
Average number of logs	1.9	1.6	1.6		1.7		1.8		1.6	
Slope (°)	15 to 20	0 to 10	15 to 20		15 to 20		10 to 15		0 to 10	
Machine type[b]	HPR	HPR	FB	PR	FB	PR	FB	PR	FB	PR
Trees/PMH	62.0	68.0	169.0	158.0	155.0	140.0	168.0	166.0	185.0	180.0
Tonnes/PMH	10.5	8.2	21.9	20.5	24.8	22.4	28.5	28.2	24.0	23.4
Tonnes/SMH	8.5	6.6	18.6	16.2	21.1	17.7	24.2	22.3	20.4	18.5
$/SMH	168.0	168.0	171.0	164.0	171.0	164.0	171.0	164.0	171.0	164.0
$/tonne	19.80	24.90	9.40	20.90	7.90	18.80	7.20	15.00	8.40	16.40
Cost ($/tonne -system)	19.80	24.90	30.30		26.70		22.20		24.80	

[a] The range of harvested trees was 13 to 41 cm in all sites.
[b] HPR is harvester-processor; FB is feller buncher; and PR is two processors.

Statistical and Economic Analysis

Data collected with the time and motion study were used to determine harvesting system productivity and costs. The statistical analysis consisted of multilinear regression models for predicting cycle times and productivity and t-tests, which enabled the comparison of the two harvesting systems. Models were evaluated with the multiple R-squared, the error standard of the residuals, and the F-statistic. Cycle times and productivity were estimated based on DBH and ground slope. Productivity was calculated from the number of trees per hour and the tonnage per tree. The latter was calculated with a non-linear equation provided by SEFE[2] and included DBH and height of the dominant trees as independent variables.

Productivity is reported in both productive machine hours (PMH) and scheduled machine hours (SMH). The former considers only productive time (delay-free time), whereas the latter considers all of the time when a machine was engaged to do a specific task, including operating time and delays (Thompson 1988). Utilization was calculated as the ratio of PMH to SMH. For determining the cost per tonne, generic machine rates ($/SMH) were calculated with ALPACA[3], guided by information provided by the contractor. The analysis for determining productivity and cost, as well as the regression model development, followed standard methodologies used in harvesting work (Miyata and Steinhilb 1981, Thompson 1988, Olsen et al. 1998) and statistical analysis studies (Ramsey and Shafer 2002).

Results and Discussion

Productivity and Costs

Results of the time and motion study are summarized in **Table 4**. Although the number of trees felled and processed by the harvester-processor (harvesting system 1) on flat terrain (site 4) was larger than on moderately steep terrain (site 1), the machine was more productive on moderately steep terrain by approximately 2 tonnes per PMH. This is explained by the bigger trees (average tree diameter and tonnage per tree) that were harvested on site 1. The same pattern is observed with the feller buncher and the processors in harvesting system 2. In both cases, there was an increase in the number of trees harvested per PMH as the terrain slope decreased (from site 1 to 4). In spite of that, the productivity of the system was more dependent on the average diameter and tonnage of the trees harvested. Thus, the largest productivity (tonnes/PMH) with the second harvesting system was obtained on site 3, where the average tree diameter and tonnage per tree was larger than on the other sites.

Costs obtained with the first harvesting system (harvester-processor) ranged from $19.80/tonne[4] (site 1, steep terrain) to $24.90/tonne (site 4, gentle terrain). In the second harvesting system, the costs per tonne ranged from $22.20/tonne (site 3, mid-slope terrain) to $30.30/tonne (site 1, moderately steep terrain). These unit costs are explained by the productivity of each harvesting system, which in turn depends on the average diameter and piece size of the trees, and by the hourly cost and utilization percentage calculated for the machines.

In terms of the cost per tonne, the difference between both harvesting systems was more pronounced on moderately steep terrain (site 1), where the second harvesting system (feller buncher and processors) was approximately $10.50/tonne (53%) more expensive than the first harvesting system (harvester-processor). The same comparison in gentle terrain (site 4) gave a difference of just $0.10/tonne (0.4%) in favor of the second harvesting system.

Variation of Cycle Time Elements

Results of the duration of the different time elements by machine type are presented in **Figure 3**. Longest cycle times were obtained with the harvester-processor on both moderately steep (15° to 20°) and gentle (< 10°) terrain and with the pro-

[2] South East Fibre Exports Pty Ltd.
[3] ALPACA: Australian Logging and Cost Appraisal Model; CRC Forestry Programme 3.
[4] The currency is expressed in Australian dollars (AUD$) throughout the text.

cessor on moderately steep terrain (15° to 20°), with over 50 seconds per tree. The processors took at least 40 seconds per tree on all ground slope conditions. A large percentage of the cycle time of these machines is explained by the magnitude of their processing times, which in turn are associated with tree diameter, piece size, and operator experience. This confirms the results obtained in other studies (Spinelli et al. 2002), where processing time, and specifically delimbing, were the most time-consuming elements of the working cycle. The mean processing time was estimated to be 6.6 seconds per tree greater with the processor than the harvester-processor on moderately steep terrain (95% confidence interval from 4.3 to 8.8) and 5.1 seconds per tree on gentle terrain (95% confidence interval from 3.1 to 7.1). Processing time for the processor machine is a function of size, number, and characteristics of the trees comprising the pile. Given the loose bark of the Eucalyptus species, as well as the size and weight of some of the trees in the pile, the processor operator took extra time to pick up the trees from the pile prior to their processing. This resulted in longer positioning and processing times than processing trees immediately following felling. The situation was accentuated when the pile consisted of a large number of trees (more than 15) with heavy branches. This situation did not occur during the operation of the harvester-processor as the trees were immediately processed after felling, and the operator did not have to pick them up from a pile. A t-test revealed statistically significant differences between the two machines working on the two slope classes (two-sided p-value = 0).

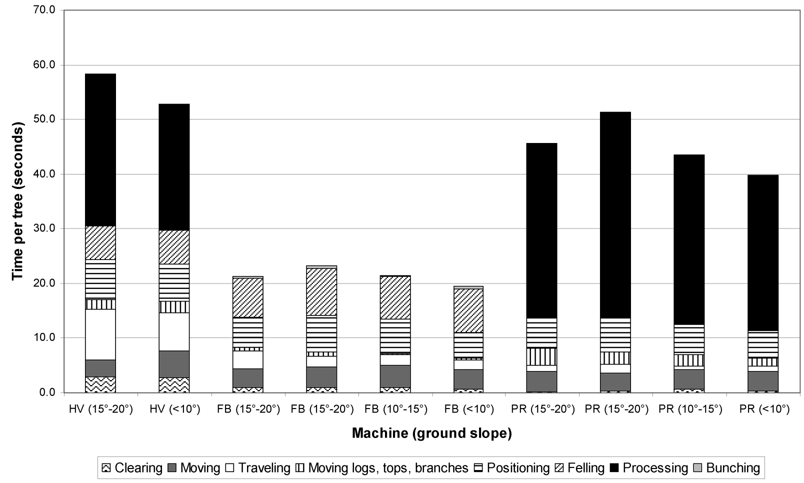

Figure 3. ~ *Contribution of time elements to cycle time by machine type and ground slope.*

Another factor that increased the processing time (processor) was the delimbing of heavily branched trees as well as the debarking and processing of small trees. As shown in **Figure 4**, the first two diameter classes had about one-third of the trees harvested by the two harvesting systems. During the processing of small trees, the breakage of the stems by the processor operator was 4 percent (range 2.5% to 6%) more intensive than by the harvester-processor operator. These broken trees accounted for no logs; however, they lengthened the processing times of the processor.

The time spent by the processor and the harvester-processor on time elements other than felling and processing (i.e., moving, clearing, moving logs, travelling) accounted for about 30 percent and 40 percent of their cycle times, respectively. Apart from the time spent on positioning and processing the stems, the processor spent a considerable proportion of its time moving between piles, located about 15 to 20 m apart, and removing the huge amount of debris (branches, bark, logs, tops) that resulted from the processing of the stems. This is a characteristic of the native forest thinning forest operations in Australia which commonly results in substantial impacts on productivity. In addition, the harvester-processor had longer travelling times due to the technique used by the operator to cut successive tree rows. Harvesting was conducted downhill in parallel

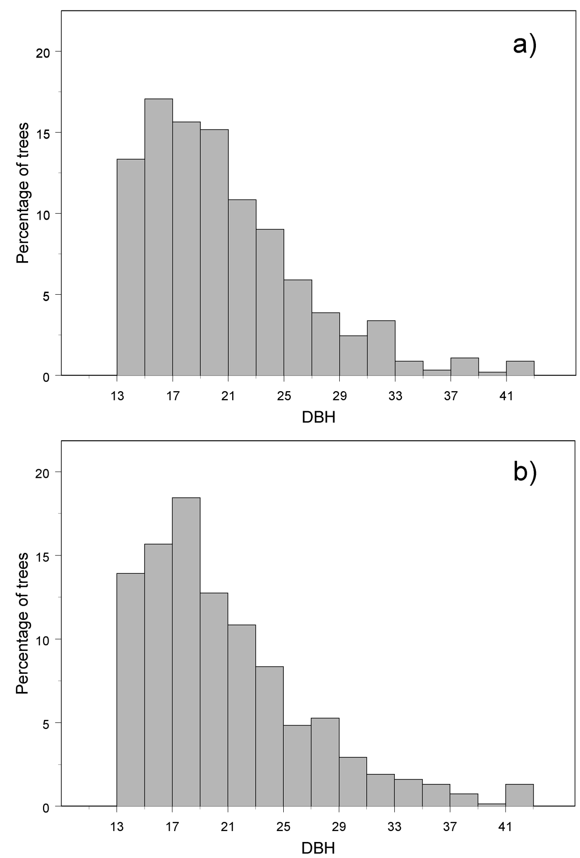

Figure 4. ~ *Diameter class distribution of the trees harvested by the two harvesting systems: (a) feller buncher and two processors and (b) harvester-processor.*

extraction tracks and returned uphill to the roadside to start a new track, which increased the travelling times in comparison with the travelling times of the processor. The positioning time of the harvester-processor was also slightly longer than the processor. In the case of the harvester-processor, the operator spent more time selecting the trees to be removed and positioning the head, while in the case of the processor, this time element only included the pick up of trees from the pile that had been previously felled by the feller buncher.

Average cycle times for the feller buncher were approximately two times shorter than the processor and approximately three times shorter than the harvester-processor. The longest times per tree were obtained with the work elements processing (harvester-processor and processors) and felling (feller buncher). The shortest cycle times were obtained on favorable conditions (gentle terrain and small piece size), especially with the harvester-processor and the processor.

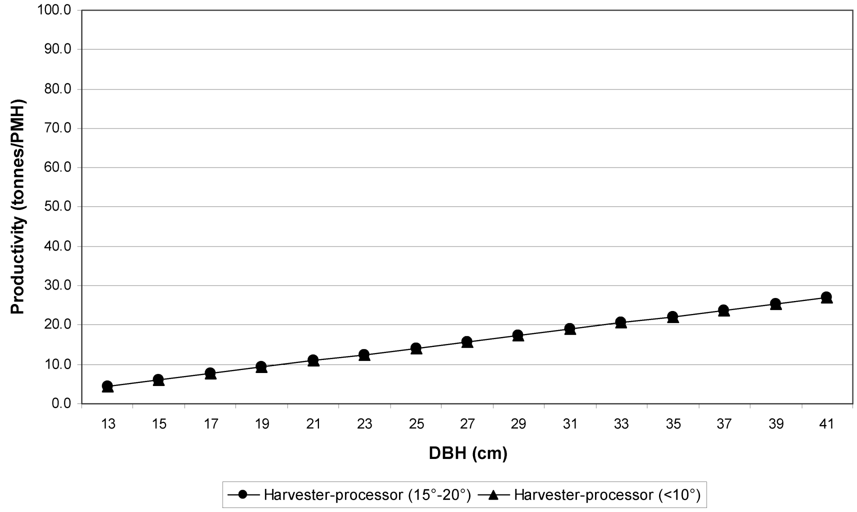

Figure 5. ~ *Productivity of the harvester-processor for a range of tree diameters on steep (15° to 20°) and gentle (<10°) terrain.*

Combining the cycle times of the feller-buncher and the processor reveals that this system requires substantially more time to process an individual tree than one machine felling and processing. Although this system may take advantage of the focused repetitive tasks for each machine (felling, bunching, and processing), rather than a longer of series of tree felling and processing steps (harvester-processor), it is the performance of the processor machine, and in particular the processing time, which explains why this system has longer cycle times than the first system (harvester-processor). For the processor to decrease the processing times, it would be necessary for the operator to quickly pick up the trees from the pile and reduce the breakage during the processing of small size trees. In addition, to reduce the total time of the system per tree, it is important that the feller buncher operator controls the number, size, and disposal of the trees in the pile, as well as the distance between piles. Previous studies have shown that good bunching techniques were effective in reducing the cycle times and improving the productivity of systems such as the one investigated in this study (Winsauer et al. 1984, Wang et al. 2004),

Table 5. ~ *Multiple regression models for the productivity of machines.*

Harvester-processor
Productivity (tonnes/PMH) = –5.93 + 0.80 DBH (cm)
(0.26)[a] (0.01)
Residual standard error: 1.864 on 681 df
r^2 = 0.87, 682 observations
F-statistic: 4,544 on 1 and 681 df; *p*-value = 0
Feller buncher
Productivity (tonnes/PMH) = –26.44 + 2.76 DBH (cm) – 0.10 Slope (°)
(0.81) (0.02) (0.04)
Residual standard error: 5.325 on 1,474 df
r^2 = 0.89, 1,474 observations
F-statistic: 6,485 on 2 and 1,474 df; *p*-value = 0
Processors
Productivity (tonnes/PMH) = –1.84 + 1.64 DBH (cm) – 0.36 Slope (°)
(0.70) (0.02) (0.02)
Residual standard error: 3.334 on 1,497 df
r^2 = 0.66, 1,499 observations
F-statistic: 1,442 on 2 and 1,497 df; *p*-value = 0

[a] Standard errors of parameter estimates are shown in parentheses.

Regression Models for Predicting Productivity and Costs

Three regressions models were developed for predicting productivity in tonnes per PMH (dependent variable) as a function of the independent variables DBH and slope. The statistically significant models (two-sided *p*-value < 0.05) are presented in **Table 5**. While only DBH was statistically significant in the model developed for the harvester-processor, both DBH and slope were statistically significant in the models developed for the feller buncher and the processors (two-sided *p*-value < 0.05). In terms of the magnitude of the change, DBH was the main variable impacting the productivity of the feller buncher (95% confidence interval from 2.71 to 2.80 tonnes per PMH). The productivity of the processor was more sensitive to a variation of slope (95% confidence interval from 1.3 to 2.3 tonnes per PMH).

Variation of Productivity

Figure 5 presents values of productivity (tonnes/ PMH) versus tree diameter (piece size) for the harvester-processor (harvesting system 1) obtained from the regression model. The results indicate that a rise in productivity of about 2.5 times is obtained when moving from diameter class 13 cm to diameter class 27 cm and an increase of about 5.5 times when moving from the same small diameter class to the biggest diameter class (41 cm). There is no apparent impact of slope because the variable is not statistically significant (two-sided *p*-value < 0.05) in the model.

The productivity pattern displayed for tree diameters with the harvester-processor are smaller in comparison with those obtained with the feller buncher and the two processors. When comparing the productivity of the harvester-processor with only one processor, however, their productivity patterns are very similar.

Values of productivity (obtained with the regression models) versus tree diameter and ground slope for the feller buncher and the processors (harvesting system 2) are presented in **Figure 6**. The pronounced rise in productivity is the result of the ability of the feller buncher to maintain a consistent rate of felling regardless of tree size and hence the benefits of increasing tree volume are not attenuated. Conversely, in the cases of the harvester-processor and the processors, the productivity of the machines is impacted by their inability to maintain a consistent falling or processing rate as tree size increases, which attenuates the impact of increasing volume with diameter.

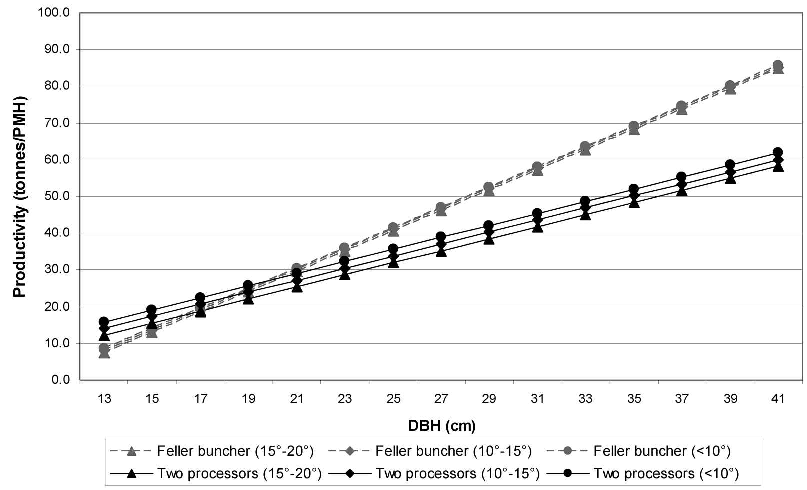

Figure 6. ~ *Productivity of the feller buncher and two processors for the range of tree diameters and ground slopes evaluated in the study.*

For small-diameter trees (< 17 cm), the two processors are more productive than the feller buncher, which is explained by the low volume of these trees and by the lack of an accumulation device with the feller buncher.

When using the results obtained with the above regression models to compare the harvesting systems for the average diameter (19 cm), the mean productivity was estimated to be approximately 14 tonnes per PMH (95% confidence interval from 12.5 to 15.7) and 15 tonnes per PMH (95% confidence interval from 13.2 to 16.8) greater from the feller buncher and processors than from the harvester-processor working alone, regardless of ground slope. A t-test revealed that these differences were statistically significant (two-sided p-value = 0).

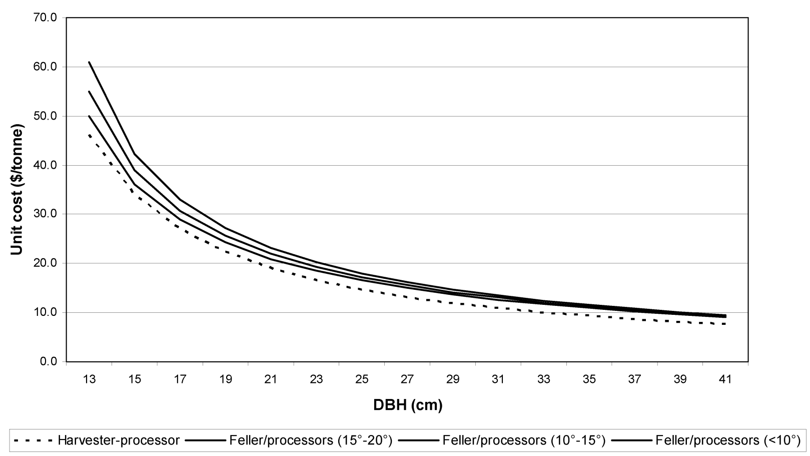

Figure 7. ~ *Unit costs of the harvesting systems (harvester-processor and feller buncher/processors) for the range of tree diameters and ground slopes evaluated in the study.*

Terrain slope has a considerable effect on processor productivity, little effect on the feller buncher productivity, and no effect on the productivity of the harvester-processor (**Figs. 5 and 6**). Harvesting machines in the two systems were tracked vehicles. They had no major problems of stabilization on steep terrain, and their harvesting heads were robust enough to process trees of a wide size range that were removed during the thinning operation. On steep terrain, however, the processor operator had to spend some time positioning the machine before processing the trees and ensuring the correct piling of the logs so that they would not roll off the processed piles. In the case of the harvester-processor, previous studies have found differences in the harvester productivity attributed to slope (Stampfer and Steinmüller 2001, Bolding and Lanford 2002); however, these studies reported reductions of productivity on much steeper slopes than those found in this study. It is believed that the harvester-processor productivity would be affected on steeper slopes (> 25°) than the slopes in this study. On steeper slopes, the feller buncher with two processors may be more productive (Pope 2008).

Variation of Costs

Figure 7 shows the impact of piece size and slope on the unit cost ($/tonne) of both harvesting systems. The costs were calculated with the productivity values obtained from the regression models (**Figs. 4 and 5**) and with calculated hourly machine costs ($/SMH). Over all of the slope classes, the second harvesting system (feller buncher and processors) was more expensive than the harvester-processor working alone regardless of tree diameter (piece size). The difference varies between less than $2.00/tonne with the largest piece size, where slope has less impact, to between $4.00/tonne and $14.00/tonne with the smaller piece sizes and where the impact of slope is more pronounced. The differential of unit costs between the two harvesting systems on moderately steep (15° to 20°) and gentle (< 10°) terrain is presented in **Figure 8**. From these results, it is evident the effect that slope has on the productivity and cost of the harvesting systems, especially in small-diameter trees, for the second harvesting system (feller buncher and processors).

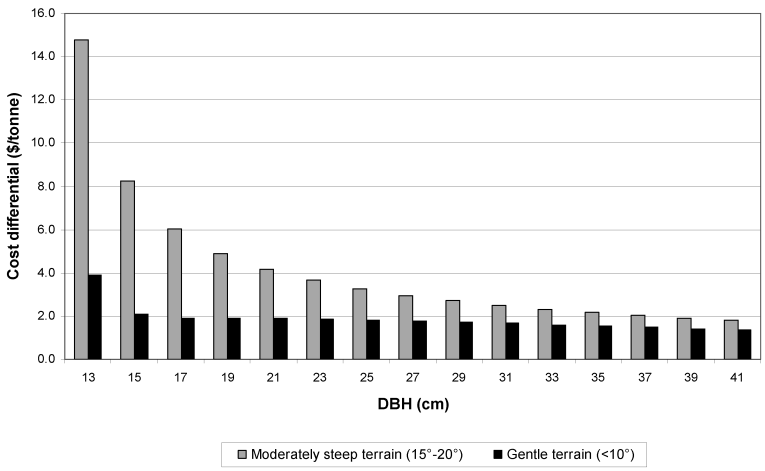

Figure 8. ~ *Cost differential (feller buncher and processors cost minus harvester-processor cost) on moderately steep (15° to 20°) and gentle (<10°) terrain calculated with data from the regression analysis.*

These results confirm those found in a previous trial (Holtzascher and Lanford 1997) that examined costs and productivity of cut-to-length systems used in the United States in thinning in Alabama.

The economics of this operation might be improved with the use of an accumulation device by the feller buncher that enables the felling and piling of several trees per cycle. Previous studies have recognized that the most important characteristic of the feller buncher is the existence of an accumulating head, without which production can drop up to 50 percent (Winsauer et al. 1984). Also, it would be worth considering a different and less costly feller buncher, even though it might be limited to harvesting compartments with flat or moderate slopes. A second strategy to make the operation more productive and less costly might be improving the techniques employed to debark small trees and delimb heavily branched trees.

Conclusions

Our research hypothesis was rejected according to the results obtained in this study. On moderately steep terrain (15° to 20°), the harvesting system consisting of a feller buncher and two processors is 14 to 15 tonnes/PMH more productive but $5.00/tonne more expensive than the harvesting system consisting of a harvester-processor (single-grip harvester), for an average tree diameter of 19 cm. Analysis of the harvesting systems indicates that the use of a feller buncher and two processors is more cost effective in favorable conditions (gentle terrain and tree diameter over 21 cm), although still more expensive than the harvester-processor. For an average tree diameter of 19 cm and 10° of slope, the feller buncher and two processors was only $2.00/tonne more expensive than the harvesting system consisting of a harvester-processor. Part of the cost differential between the two systems is explained by the performance of the two processors, which were unable to boost their productivity with the use of the feller buncher prior to processing. Higher capital costs associated with this harvesting system as compared to that of the harvester alone also help explain the difference in costs.

From the statistical analysis of the independent variables of interest, DBH was the productivity driver with a major impact on costs. This variable explained more than 85 percent of the variance in productivity of the harvester-processor and feller buncher, and more than 65 percent of the variance in productivity of the processors. The asymptotic curve of costs per tonne highlights the effect on productivity of trees with small diameters, especially when they are smaller than 21 cm. This is an important aspect of re-growth thinning.

Although statistically significant (two-sided p-value < 0.05) in the regression models, the variable slope (studied from 10° to 20°) contributed less than 5 percent of the variance in productivity of the feller buncher and the processors. The same variable was non-significant with the harvester processor, and therefore the model developed to predict its productivity included only DBH as the single independent variable.

Among the feller buncher work elements studied, felling and positioning combined were the most time-consuming activities, accounting for more than 60 percent of the total cycle time in all of the plots under study. Felling time was affected primarily by hang-ups when trees with big crowns and branches were harvested, and to some extent, by the work methods used by the operator to fell and lay down the trees. Likewise, processing was the most time-consuming activity for the harvester-processor and the processors. On average, this activity accounted for more than 42 percent and 70 percent of the cycle time, respectively.

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