FORMEC 2010
Forest Engineering: Meeting the Needs of the Society and the Environment
July 11 – 14, 2010, Padova – Italy

INNOVATIVE METHODS FOR STEEP TERRAIN HARVESTING

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Keywords: Innovation, mechanised cable logging, steep slopes, felling and bunching.

Abstract: *Felling and bunching of trees for subsequent extraction has been used extensively in ground-based operations to increase productivity in both thinning and clearfelling. Steeper terrain (slopes in excess of 35%) has traditionally been seen as the sole preserve of chainsaw felling, where bunching for increased payload is not possible. Recent developments have enabled the production of steep terrain harvesters capable of operating safely on slopes between 35 – 55%.*
Some logging contractors, however, have taken innovative approaches to enable safe and efficient mechanised operation on steeper slopes. Two separate contractors in New Zealand have used similar, yet different approaches in a grapple yarding operation where both hand-felled and mechanically felled trees on steep terrain were shovelled and bunched by an excavator log loader for grapple yarder extraction. This was achieved by securing the excavator via a wire rope and a winch, located either on a separate bulldozer in one case or on the excavator itself in the other contractor's case. Both systems are studied in detail and described in terms of productivity, mechanical and financial feasibility.
The studies showed that felling, shovelling and bunching for grapple yarder extraction has a number of advantages in terms of yarder utilisation, and increased harvesting system productivity. Results indicated a 33% increase in trees hauled per cycle with bunched wood compared to unbunched wood extracted with the use of a spotter or by the yarder operator alone.

1. Introduction

Bunching of trees for subsequent extraction has been used extensively in ground-based operations to increase productivity in both thinning and clearfelling (Hartsough, 1990; Brown et al., 1996). Steeper terrain (slopes in excess of 35%, or 20º) has traditionally been seen as the sole preserve of chainsaw felling, where bunching for payload is not possible. However, developments in the late 1990's have seen the production of steep terrain harvesters capable of operating safely on slopes between 35 – 55% (20º – 30º). Integration of tilting operator cabins and specially designed tracked machine chassis (Figure 3) has increased the operational capability of harvesters on steep terrain (Stampfer, 1999; Torgersen, 2001). A study of the effect of slope on the productivity of the Königstiger steep terrain harvester indicated increases in slope from 25% to 50% reduced overall harvester productivity from 25 m^3/PMH to 18 m^3/PMH (Stampfer, 1999). European literature shows that bunching for yarder extraction has been concentrated primarily in thinning operations. Heinimann et al. (1998) reported felling and bunching of trees using a Skogsjan 687 harvester in a commercial thinning operation with a Syncrofalke yarder in the eastern Austrian Alps, where bunching with the harvester increased cable yarder productivity by 25%. Other countries have reported the use of tree bunching for yarder extraction. In Canada, a number of reports noted bunching of clearfelled trees for yarder extraction using a feller-buncher or feller-director. Peterson (1987) reported a 10% increase in trees yarded per productive machine hour (PMH) and 36% more trees yarded per haul in bunched versus unbunched wood (extracted piece size 1.5 m^3). Other studies of mechanically felled and bunched wood in cable yarding compared grapple yarding with hand-set chokers. Results showed high productivity of grapple yarded wood over short haul distances

(MacDonald, 1990). Although feller-bunchers have been the preferred machine type for bunching in steep terrain elsewhere in the world, their use in New Zealand has been limited.

Hemphill (1991) examined the potential for feller-bunchers in New Zealand cable yarder operations and pointed out some of the constraints for this application:

- Large clearfell tree size (US operations were only economic with trees smaller than 1 m^3);
- High cost of capital relative to labour costs and difficulty with machine servicing in isolated regions;
- A large proportion of cable terrain being too steep for machines;
- Soils too wet or clayey affecting bearing strength;
- Insufficient volume to sustain mechanised systems.

Hemphill (1991) also summarised the "suitable" factors in NZ favouring feller-buncher use as the reduced labour requirement of mechanised felling, the safer work environment and the systematic harvest planning employed in New Zealand assisting application of these systems. Harvesting trees on steep terrain has always been problematic in terms of worker safety, and also in terms of system productivity. The felling phase is particularly so because manual faller mobility is restricted and directional felling on slopes is time consuming. For machinery, there are technological and regulatory limits to machine operations on slopes. The NZ Safety and Health in Forest Operations Code of Practice (OSH, Dept of Labour, 1999) states that feller-bunchers and excavators should not operate on slopes exceeding 22 degrees (40%).

One of the contractors, Ross Wood, first began to consider the concept of a winched excavator in 2000 and laid more detailed plans in 2004. Early experiments (with tentative OSH permission) used excavators and a feller-buncher attached to a yarder. The current system uses a half sprocket and hauler drum, holding 400 m of one inch swaged cable (Figure 1a). In late 2008, another contractor (Nigel Kelly) with the assistance an engineering company, modified a new Hitachi excavator loader, installing a winch drum between the tracks (winch weight 3.5 tonnes) (Figure 1b). This prototype winched excavator was fitted with a felling head and so was able to both fell and bunch on steep slopes. Both contractors pursued their developments independently. Scion initiated a study on these operations in terms of productivity, mechanical and financial feasibility.

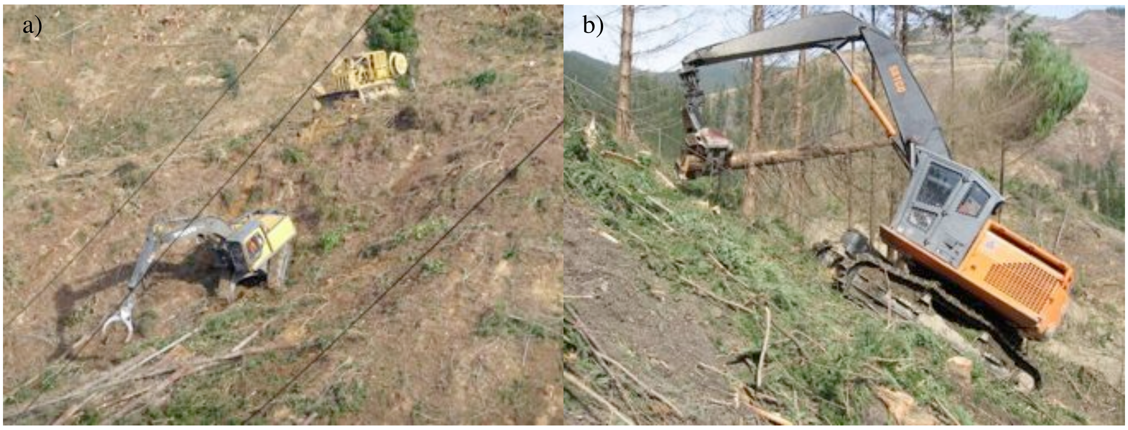

Figure 1. a) An excavator attached to a winch mounted on a bulldozer (Wood Contracting Ltd) and b) An excavator, with integrated winch, attached to a stump (Kelly Logging Ltd).

2. Methods

Time and motion study methods were used to evaluate the productivity of the extraction and processing phases of the operation. The haul cycles of the yarder were observed with haul distances measured by laser range-finder. Video recordings were made for later analysis. Felling and processing cycles were timed from video recordings. This consisted of division of the haul cycle into time elements. The relationships between these elements and other observed factors were then analysed. Costings were estimated using calculated productivity and representative costs from the Informe equipment survey (Forme, 2009).

2.1. Case study 1: Wood Contracting Ltd

The extraction phase of the system comprised the use of an excavator log loader to bunch stems and present them to the grapple yarder. In situations where terrain became too steep for operating the free-moving excavator safely, it was secured by a pre-tensioned cable to a bulldozer-anchor (Figure 1a). In this way the cable-secured excavator was able to operate on terrain that would have been previously inaccessible to such machines. The stand was 27 years old *Pinus radiata* with an average tree size of 0.85 m^3, stocking of 497 stems/ha and top tree height of 29.9 m. The block was comprised of spur ridges about 250 – 300m long and 100 – 150m wide separated by native forest in the adjacent gullies (Figure 2a). A ridge-top road was located at the top of the spurs along which landings were located. There was a stream running at the bottom of the block which required trees to be extracted away from to minimise stand damage. The terrain was generally steep and broken and soil type was Moutere gravel. Some tracks existed from previous operations and these were used by the bunching machines during the operation, but the block had not been contour tracked, which was a common harvesting method used in the past.

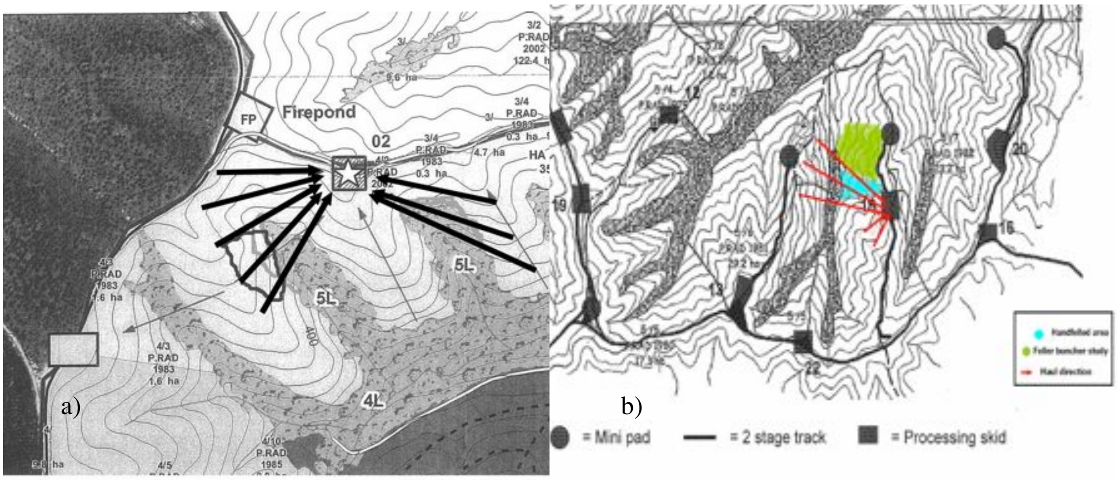

Figure 2. a) Study area with haul directions (Wood Contracting Ltd). Area logged using cable-secured excavator is outlined. And b) Study area with haul directions and outlined locations of bunched and unbunched trees (Kelly Logging Ltd).

Two excavators, a Komatsu PC220 and a Volvo EC290, were used to bunch the trees for extraction by the yarder, a Pacific 1188 swing yarder, equipped with a grapple. Bunching was often supplemented by shovelling, where large bunches were successively swung by the excavator over relatively shorter extraction distances towards the landing or roadside. Since only one machine was required to bunch/present trees for breakout, the other machine continued bunching/shovelling. On the cutover, several different tree and bunch layouts were observed: machine felled (unbunched, bunched into small bunches, and shoveled into large bunches) and hand felled, unbunched trees.

The excavators were both modified with cable attachment draw bars for either a Ropemaster sheave, or direct connection by shackle. The operator's seats were racing car-style full harness seats. The Komatsu D85 tractor-winch (an ex-roller crusher) to which an excavator could be attached, was equipped with a fairlead on top of the blade which generated good downward pressure on the 7/8 inch swaged cable. The tractor winch was operated by a remote-control system designed by Salcom Technologies, a Christchurch company supplying telecommunications to the industry (http://www.salcom.co.nz/). For winching in, the operator had to select one of three winch speeds (effectively, tractor engine throttle speeds). For pulling out cable (a fourth selection), the torque converter of the tractor supplied braking power. On loss of power (the tractor idles when the system is in use) a powerful brake was able to be applied to lock the cable in position. The main breakout method involved using the bunching excavator to present a bunch of tree butts to the yarder grapple for extraction (Figure 3). The excavator operator called advice over a radio link to the yarder operator for locating the grapple at the right spot for a secure grip. Other breakout methods used a spotter to aid the location of the grapple, or the yarder operator spotted his own haul.

Figure 3. a) Bunching excavator presenting load for grapple yarder extraction (Wood Contracting Ltd.) and b) Felling and bunching on broken terrain at the bottom of a slope (Kelly Logging Ltd.).

The processor, located on the landing with the yarder, was a Hitachi EX330 Zaxis equipped with a Waratah 624 Super Harvester head. The processor cleared the chute and processed 18 grades from a single position. The processor did not stockpile extracted trees (no surge pile). The landing was also shared by a Hitachi EX225 excavator loader which fleeted the processed logs and cleared slash. There was insufficient room for the 14 different stacks required so a Hitachi ZW180 was used to fleet shorter logs in 4 tonne loads some 200m to another landing, and load trucks. A Bell Ultra Logger was stationed at the second landing for fleeting. A Hitachi EX300 was used as a mobile tail hold and a Komatsu PC400 was used as a mobile tether for the yarder's three guy lines.

2.2. Case study 2: Kelly Logging Ltd.

The stand was 25 years old *Pinus radiata* with an average tree size of 1.92 m^3 and stocking of 201 stems/ha. The setting was composed of a steep narrow gully and less steep upper slopes lying between two long spurs (Figure 2b). Maximum haul distance was around 300 m.

During the study the feller buncher (Hitachi ZX280 upper/ZX 330LC track base, Satco 630 Felling head) operated on slopes closer to the hauler, only secured by the winch when felling and bunching the steeper upper slopes. The feller buncher featured a winch located between the tracks to the rear of the machine and held 310m of 7/8 inch swaged wire rope. The winch was driven by the track drive motors on a 50/50 power-sharing basis. Estimated weight of the winch unit was 5 tonnes. The track frame had been extended 500mm to the rear and the track featured double grouser extensions, chamfered at the ends. A Satco 630 Directional felling head and Satco boom were used. All engineering work was carried out by A.W. Trinder Engineering, Nelson, New Zealand. The winch controls were integrated with the track drive controls (touch screen display) so the operator could pre-select uphill or downhill winch/travel functions (or no winch used). The operator was secured in position by a full (four-point) restraint racing car-type harness. The yarder(Thunderbird 6355 Yarder) used a grapple. Excavators were used for tailhold (Hitachi ZX330 – Operator spotter) and mobile guyline (Hitachi EX400) functions. The chute was cleared by a Hitachi ZX380 with a long reach boom. Extracted trees were delimbed and processed by a Waratah 626 Bigwood mounted on a Hitachi ZX380 excavator. Trees were picked from a surge pile and delimbed completely before processing into logs, which were then pre-sorted for fleeting. Fleeting was carried out by a Hitachi ZX240 Excavator and a Volvo L90F wheeled loader.
The haul lines moved progressively to the north during the study (Figure 2b). The blue area indicates the area that was hand felled. Most of the steeper lower slopes on the far side of the gully were also hand-felled. The operating method was for the feller-buncher to fell and bunch standing trees, sometimes bunching head-first and sometimes butt-first using two distinct swings interspersed with a change of grip. Trees were felled into the stand, or downhill parallel to the stand edge (Figure 3b). Windthrown trees had

the rootballs cut off and were then bunched with the other trees. Part of the setting was handfelled so that extraction of bunched wood could be compared. The hand-felled area was felled by a single faller using a mainly downhill felling pattern (Figure 4).

Figure 4. Feller-director felled and bunched trees laid on the slope on the left and handfelled trees can be seen on the right of the photograph, below the hauler pad (Kelly Logging Ltd).

Grappling of trees was assisted by the tailhold operator, who called in advice by radio. Trees were hauled in to the chute which was cleared by a Hitachi EX380 excavator loader. The processing method involved a distinct delimb phase before processing into logs. This was because the trees featured numerous large branches. Logs were presented for fleeting in several distinct stacks. On occasion, a single log would be carried to a nearby stack.

3. Results

3.1. Case study 1: Wood Contracting Ltd.

A total of 44 feller-buncher cycles were timed with an average tree felling cycle time measured at 38.0 seconds (22.2 seconds for *felling*, 12.8 seconds *moving* between trees and 3.0 seconds *clearing* slash). Observed delay-free hourly productivity, with an average piece size of 0.85 m^3 was calculated at 80.5 m^3/PMH (=94.7 cycles/hr * 0.85 m^3). Over the two days of the study, 193 yarder cycles (Table 1) were recorded over haul distances ranging from 67 to 230 m, average haul distance 163 m. Yarder swing times (raise and lower grapple) were timed from video observations. Inhaul and outhaul times were timed directly. The average volume per cycle was 2.53 m^3 (2.98 trees/cycle * 0.85 m^3) with a delay-free cycle time of 145.7 seconds (Table 3) which translated to average delay-free hourly productivity of 62.6 m^3/PMH (=24.7 cycles/hr * 2.98 trees/cycle * 0.85 m^3). Including observed delays for tail hold moves and yarder turns (16.0 sec/haul) resulted in an average cycle time of 2.70 min and hourly productivity of 56.3

m^3/PMH. Low correlations were found between haul distance and inhaul/outhaul time (R^2 of 0.36 to 0.47). The different breakout methods resulted in different average number of trees hauled per cycle. Most of the cycles (N = 115) involved breakout by excavator presentation and the number of trees per cycle (Tc) were significantly (at p>0.05) greater (3.2 and 3.1 trees per cycle when presented by an excavator that is secured or not secured by a cable, respectively) than cycles grappled using a spotter (N = 23, Tc = 2.4) or by the yarder operator only (N = 13, Tc = 1.5). Of the spotted cycles, two thirds were from unbunched trees (N = 24). In terms of grappling method, grappling with excavator assistance (presentation of bunches by excavator) was the most productive. This method enabled significantly more trees to be grappled per haul compared to either using a spotter (+33%) or yarder operator alone (113% increase). This is comparable to results found by Peterson (1987) who reported a study of yarder extraction of bunched vs unbunched trees and found a 36% increase in trees yarded per haul. No significant difference (p>0.05) was observed between productivity of grappling from bunched/presented trees from large bunches and that from small bunches which were progressively accumulated ("bunch as you go").

Table 1. Yarder and processor cycle time elements (Wood Contracting Ltd)

Time Element	Cycle time (sec)	St. Dev.	Time Element	Cycle time (sec)	St. Dev.
Yarder			Processor		
Swing and Raise Grapple	23		Process (Avg 3.03 logs)	33	15.7
Outhaul (and grapple)	55.1	20	Clear slash	2.1	
Inhaul	50.6		Clear logs	0.5	
Swing and Lower Grapple	17	0.95			
Delay-free total	145.7		Delay-free total	35.6	
Delays:			Delays:		
Operational	31.5		Operational	11.4	
Mechanical	2.2		Mechanical	0	
Personal	0.7		Personal	0.9	
Total cycle time	180.1		Total cycle time (min)	47.9	

Forty-one yarder cycles were recorded with bunches grappled by excavator while it was secured by cable (Figure 1a). Half of these involved trees from a large bunch, with the excavator located on a track, and the rest occurred with the machine located on the slope, bunching machine-felled, unbunched trees. In each case, an average of over 3 stems per haul was extracted from both locations.
A total of 123 processing cycles were timed and average delay-free cycle time was calculated at 35.6 seconds to process an average of 3.03 logs per tree (Table 1). Observed delay-free hourly productivity was calculated to be 86.0 m^3/PMH (101.1 cycles/hr * 0.85 m^3).

Operational yarder delays that could be attributed to the buncher averaged approximately 5 sec per haul and commonly comprised situations where a presented bunch was not yet ready (still being accumulated by the buncher) at the point when the yarder grapple was poised for grappling. This value was approximately the same for extraction from progressively bunched or previously bunched (large bunches) trees. Tail hold moves and yarder turns (including guy line moves) were the main contributors to yarder operational delays. A single major tail hold move comprised 50% of the total operational delay recorded. Short tail hold moves averaged only 1.4 min per observation. They occurred on average every 12 haul cycles and comprised only 10% of operational delays. Yarder turns comprised 13% of operational delays. Delays due to either processing or sorting comprised 4% of the total delay time. Fewer tail hold moves were made when extracting from previously bunched large bunches (23 cycles/move) than in areas progressively bunched (8 cycles/move). A single major setting shift involved a tail hold move of approximately 700 m and took 104 min. This value was not included in the yarder's total cycle time. Social delays (meal breaks) were also excluded. A rope breakage which occurred on the last haul prior to the meal break was repaired during a meal break. On the second day of study, when one of the excavators

was secured by cable, the tail hold attempted to move back up a spur and one of the yarder's working ropes became caught between the excavator's boom and stick. This incurred a delay of 17 min. Processor operational delays were largely composed of waiting for work (i.e. no stems to process), 11.3 sec per stem or 24% of total cycle time). Interference from the sorting loader comprised only 0.05 sec per stem.
Costings were estimated using calculated productivity and representative costs from the Informe equipment survey (Forme, 2009). Estimated system cost based on daily production of 344 m^3/day (62.6m^3/PMH * 5.5 PMH/day) is \$26.59/m^3.

3.2. Case study 2: Kelly Logging Ltd.

The Feller buncher (Feller director with an integrated safety winch) was observed working with, and without the use of the winch cable. When it was operating without the use (Figure 3b) of the winch cable (flatter terrain < 20º), a total of forty-nine (N = 49) felling cycles were recorded (Table 2), during which 1 tree and 12 heads were bunched, and 15 rootballs cut. An average of 8 trees was included in each bunch.

Table 2. Feller-buncher (with and without the use of winch cable) cycle time elements (Kelly Logging Ltd).

Element	Cycle time (sec)	%	Element	Cycle time (sec)	%
With winch cable (steep terrain)			**Without** winch cable (flatter terrain)		
Move	30.1	28	Move	15.2	18
Position head	7.9	7	Position head	5.3	6
Fell	15.2	14	Fell	18.4	20
Slew	3.2	3	Slew	2.8	3
Bunch	35.8	33	Bunch	27.1	31
Windthrow	5.7	5	Windthrow	12.8	15
Clear slash	6.5	6	Clear slash	3.2	4
Other	2.4	2	Other	3	3
Total	106.8 sec 1.78 min 33.7 trees/PMH		Total	85.9 sec 1.43 min 41.9 trees/PMH	

When the feller-buncher was operating with the use of the winch cable (35 degree maximum slope) fifty-five (N = 55) felling cycles were recorded during which 89 trees and 13 heads were bunched, and 7 rootballs cut. Two recorded set up times for securing the winch cable to a stump were 2.9 and 4.2 min. Travel speeds of the winched machine were estimated at 0.75 km/hr upslope, and 3.3 km/hr downslope.

In terms of the yarder productivity, observed haul cycles were divided into four types: singles - individual trees, possibly either machine or handfelled, but not appearing to be bunched; handfelled - felled by hand for the purposes of the study; bunched - trees felled and bunched by machine (visible bunches); gully - extracted from the gully, out of sight of study personnel (not used in comparative calculations). Over the study period, 173 haul cycles were observed, comprising 85 bunched, 31 handfelled and 55 single tree cycles. Bunched haul distance ranged from 27 to 256 m and handfelled (unbunched) distances ranged from 90 to 155 m. The number of trees grappled from bunches was significantly more than for single or handfelled trees (Table 3).

Table 3. Comparison of number of trees/haul for different haul types (Kelly Logging Ltd).

Cycle type	No. cycles	Mean no. butts/cycle *	Average Haul Distance	Bit only hauls %
Single	60	0.98(a)	204	10
Handfelled	30	1.00(a)	128	7
Bunched	118	1.64(b)	117	12
Gully	37	0.95	225	16

*Different letters indicate significant difference at p>0.05.

In bunched tree cycles, 28% of hauls had 2 trees and 15% had 3 trees. In handfelled cycles, only 7% of hauls had 2 trees and no hauls had three trees. There was no significant difference between numbers of trees grappled from single and handfelled trees. There was no significant difference found between mean grapple times for bunched (0.61 min/cycle) and handfelled (0.53 min/cycle) trees. Mean grapple time for singles was significantly longer (0.80 min/cycle) than for bunched or handfelled trees. Hauler productivity could not be confidently compared for bunched and handfelled cycles. Because of the small sample size of handfelled cycles, there was no significant difference between key haul cycle elements other than for grapple time. Inhaul and outhaul times were not strongly correlated to haul distance (R^2 of 0.48 and 0.41, respectively). With key haul cycle elements held constant and number of butt logs varied with presentation, an indicative comparison of hauler productivity for handfelled and bunched trees can be made (Table 4). For handfelled cycles estimated hauler productivity is 24.4 Trees/Hr. For bunched cycles productivity is estimated at 40.0 Trees/Hr.

Table 4. Standardised cycle time elements used in the productivity comparison of bunched and unbunched trees (Kelly Logging Ltd).

Element	Raise	Outhaul (130m)	Grapple	Inhaul (130m)	Other	Tailhold shift	Guyhold shift	Total
Mean time per cycle (min)	0.23	0.41	0.59	0.74	0.05	0.36	0.08	2.46

A total of forty (N = 40) tree processing/logmaking cycles were timed. Average delay-free cycle time was calculated to be 1.9 min for trees (butts) producing 4.3 logs per tree, and 0.9 min for tops. Delay-free productivity was calculated at 30.1 trees/hr*1.92 m^3/tree that is, 27.7 m^3/PMH (assuming tops comprise 10% of pieces processed).

Costs were estimated using calculated productivity and representative costs from the INFORME forestry equipment survey (Forme, 2009). Estimated system cost for mechanised felling and bunching based on daily production of 456 m^3/day is $20.97/$m^3$ (76 m^3/PMH *6.0 PMH/day). Estimated system cost for manual felling and no bunching based on daily production of 350 m^3/day is $25.41/$m^3$ (50 m^3/PMH *7.0 PMH/day).

4. Conclusions

These studies describe innovative harvesting operations. In one operation, system productivity was high despite a relatively small extracted piece size (0.85 m3). The use of excavator bunching/presenting resulted in a significantly larger haul size to be extracted than grapple yarding using a spotter (3.2 vs 2.4 trees/haul). This translated to a 33% increase or an estimated 17m3/PMH or 92m3/day extra production. Yarder cycle time when grappling from large bunches was not significantly more productive than that when grappling individual small bunches. The contractor reported that since commencing operation in 2006, an estimated 70-75% of the areas logged by the crew was logged using free-moving excavator bunching and shovelling. The winched excavator method was reserved for areas judged too steep for normal methods, and used selectively, according to the situation.

In the second operation , although terrain slopes were not excessively steep, a significant area exceeded the recommended operational guidelines for standard excavators (22 degrees). By virtue of the specialised machine used, the harvesting system maintained a high rate of productivity by providing bunched trees for grapple yarder extraction. The high productivity rate of this harvesting system, and in a larger tree size, was achieved mainly through the grappling of an increased number of trees (two or more trees on more occasions) per haul cycle from bunched trees. There was no difference observed between elemental grapple times for bunched and handfelled trees. This further reinforces the conclusion that the principal reason for an increase in productivity from bunched cycles was the ability to grapple more trees.
In high hauler/yarder production operations there is frequently an imbalance in productivity rates between felling, extraction and processing. This is sometimes addressed or counterbalanced by lower effective

machine utilisation of hauling or yarding equipment, and extended processing and fleeting hours. Other advantages to bunching or shoveling in yarder operations may include reducing the number of rope and hauler shifts. Shoveling may also aid access for yarder extraction to areas where there is a blind lead or may even reduce the number of hauler setups (pads) required in a setting. Further research will examine better definition of conditions for safe operation of free-moving excavators on steep terrain, and their bunching and shoveling productivity under differing terrain conditions.

Acknowledgements

The assistance and co-operation of the following individuals, groups and companies is appreciated: Future Forests Research Ltd, Contractors Ross Wood, Nigel Kelly and their logging crews, Hancock Forest Management Ltd and Nelson Forests Ltd.

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