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Feasibility, Costs and Benefits of Mechanised Delimbing on Slopes

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

The goal of the FFR harvesting research programme is to substantially improve productivity and reduce costs through developing technologies for mechanised harvesting in New Zealand's steep terrain forests. As part of the FFR harvesting programme, development of tree felling machinery for steep country harvesting is underway. FFR Intermediate Outcome 1 has developed the capability of machinery to operate on steep slopes. Once this is operational, opportunities for extending harvesting functions on steep terrain become practicable. Part of this programme is to investigate the feasibility of tree length delimbing on steep slopes.

Delimbing on the slope offers potential downstream productivity advantages in terms of haul mass (through not hauling bark, limbs and tops), while still enabling high production payloads through bunching of tree stems. This creates site management advantages through opportunities to disperse residues (tree limbs and tops) produced across the harvesting area, creating a mat for machine travel, thus substantially reducing the environmental footprint. This volume hauled to the landing currently has no market, and represents an environmental hazard and a disposal cost. Delimbing on the slope mitigates operational and environmental issues associated with accumulating wood residues on the landing.

The productivity of 25 different harvesting system combinations was compared. Systems included tree-length delimbing and log-length processing. Each process in a system fed the process following it. Productivity and worked hours were calculated for each process and the system as a whole.

From discussions with industry professionals, tree length delimbing on steep slopes was considered to be technically feasible. The modelled productivity comparison of a number of systems showed that:

- Bunching was found to be the key determinant of cost, whether trees were delimbed or not.
- Delimbing produced marginal gains in both productivity and cost.
- Processing on the slope was higher cost than current processing systems
- Effective processing on the slope would require new ideas for moving bundles of logs.
- Stacking logs on steep slopes may only be achievable by stacking them behind high stumps.

It was found that tree length delimbing on steep slopes has advantages in terms of reducing unmerchantable material being extracted to the landing. This might also aid recovery of stem waste at the landing (binwood for energy) and reduce the risk of collapse of slash piles ("bird's nests"). In terms of silviculture, ground hindrance to manual re-planting might also be reduced due to concentration of branch material in defined areas. There may also be reduced soil losses due to slash mats retaining the surface soil. On the negative side, there may be additional cost incurred through the necessity for water controls to haul routes as trees are concentrated into lines. The productivity-related disadvantages of delimbing or processing on steep slopes outweighed the benefits of these non-production values.

It is recommended that stems should be bunched for extraction whether trees were delimbed or not. Since delimbing on the slope produced some benefits in terms of productivity and cost future research should focus on steep slope feller-delimber-buncher performance of different tree-length delimbing directions and the resulting effects on delimbing time and stem breakage. Additional data are required of effects on extraction productivity from extracting delimbed and bunched stems, uphill, butt-first. Regarding processing on the slope, achieving an economic haul size at least four or five processed logs would be necessary per haul, to match current harvesting systems. Improvements to productivity could also be achieved if bunches of logs could be accumulated in designated places on steep slopes, rather than being scattered. To achieve this result some innovative brainstorming looking at novel technology would be required.

BACKGROUND

Intermediate Outcome 1 of the FFR harvesting research programme (Mechanisation on Steep Terrain) has developed the capability of machinery to operate safely on steep slopes. This has created the opportunity to disperse woody biomass (tree limbs and tops) produced across the harvesting area, creating a mat for machine travel, thus substantially reducing the environmental footprint of ground-based machinery.

Delimbing on the slope offers potential advantages in terms of haul mass (through not hauling bark, limbs and tops volume), while still enabling high production payloads through bunching tree stems. This volume hauled to the landing currently has no market, and represents an environmental hazard and a disposal cost. Delimbing on the slope also avoids the operational and environmental issues associated with accumulating wood residues on the landing.

A comparison of the potential advantages and disadvantages of delimbing on the cutover versus on the landing is shown in Table 1.

Table 1: Advantages and disadvantages of delimbing on the cutover vs. landing

	Delimb on cutover	**Delimb on landing**
Advantages	• Limbs remain at felling site • Creates a pad for the felling machine and reduces soil disturbance • Removing limbs reduces tree weight and break out/haul force required • Increases effective payload (merchantable volume of each drag) • Provides opportunity to bunch delimbed stems	• Limbs and tops could be utilised as wood fuel • Less handling of stem on cutover • Delimbing is undertaken immediately prior to log processing • Operating environment is better than on slope
Disadvantages	• Limbs may be moved off hillside by overland flow during storms and cause issues downstream • A delimbing head adds complexity and weight to a felling machine • Additional handling of stems required after felling • Potential ingress of sap stain bacteria	• Concentration of limbs and tops on landing ("bird's nest) creates a disposal problem • Limbs carry dirt and stones which are a problem for motor-manual delimbing • Limbs on stems increase break out and haul force required • Additional handling of stems required after extraction

Success of the FFR harvesting research programme Intermediate Outcome 2 (Increased Productivity of Cable Extraction) results in the ability to haul smaller pieces at a faster rate enabling economic hauling of logs instead of tree stems, and providing the opportunity to develop lighter and cheaper yarding equipment.

Cutting tree stems to log length on the slope using log optimisation processes would be a production option where no economic market exists for the woody biomass residues. This will eliminate the residue problem arising on cable landings, as offcuts arising from log manufacture will be dispersed across the slope.

Potential advantages with bunching logs instead of tree stems include enabling design of smaller / cheaper yarding machines in the future (lower fuel consumption), and also potentially mitigating the impact of increasing piece size of the future forest resource.

A comparison of the potential advantages and disadvantages of cutting-to-length on the cutover versus on the landing is shown in Table 2.

Table 2: Advantages and disadvantages of cutting-to-length on the cutover vs. landing

	Cut-to-length on cutover	Cut-to-length on landing
Advantages	• Lighter shorter pieces (logs versus stems) • Opportunity for smaller landing size • Improved deflection (tower closer to edge of landing) • Lower breakout force required • Opportunity for optimising payload by bunching logs • No heads being hauled (fewer pieces to hook on) • Heads and offcuts remain on cutover	• Potential higher processing productivity • Less handling of stem on cutover (no processing) reduces stem damage • Operating environment is better than on slope
Disadvantages	• More pieces to handle per drag (unless bunched) • Debris may wash off hillside and cause issues downstream • Logs rolling into gullies	• Heads (tops) and offcuts on the landing pose a disposal issue (unless carted as binwood or utilised as wood fuel) • More debris on landing

Previous research has summarised some of the reasons why the feasibility of pre-emptive log cutting on the cutover should be investigated[1]. The extraction of log lengths, as opposed to full stems allows the formation of smaller landings, and logs are easier to land than full stems. This allows smaller haulers to be employed, and also allows a greater selection of pieces to build the optimum payload size for the available cable deflection. The report focussed on the potential value lost in pre-emptive log cutting on the cutover rather than the payload volume and productivity of extracted wood. The report concluded that “with the use of an appropriate strategy only about 1% total potential value is sacrificed”.

In a second study, extraction of partially processed stems (processed logs) on the cutover was reported to be more productive than the extraction of tree length stems (Evanson & Blundell, 1992). The authors concluded that partial processing on the cutover was more productive because more pieces per haul were extracted than with tree length extraction.

In another study, log extraction was compared with stem extraction using a Washington 88 swing yarder[2]. No significant difference was found in productivity when compared on a productive machine hour basis. It was reported that landing-related delays reduced productivity by 21% in log length operations and only by 12% in stem length operations. The main reason for delay was greater re-processing of log lengths produced in the bush was required at the landing. The author stated “The amount of re-measuring and re-cutting was much higher than expected in the log length operation”. In log length extraction there were shorter element times for hook on, break out and inhaul, but in stem length extraction larger haul volumes were delivered.

This report investigates the feasibility, costs and benefits of mechanised delimbing on the slope, including impact on subsequent operations.

Delimbing and cutting to length (CTL) on steep slopes are two potential options for future harvesting operations. An assumption is that the basic carrier for these functions will be a steep slope feller buncher similar to the ClimbMAX Steep Slope Harvester. Because there are quantitative and non-quantitative advantages to leaving branch material on the slope, as opposed to at the landing, it was felt that economic feasibility should depend primarily on system productivity. For many steep slope operations, most branch material from the tree remains on the slope because of tree breakage and subsequent bunching or extraction.

METHODS

Economic feasibility was tested by:

1. Developing a matrix of options for both uphill and downhill extraction for all the combinations of felling direction (uphill/downhill); delimbing orientation (butt first/head first); and breaking out (butt pull/head pull).
2. Confirming the basis for assumptions on increased/reduced cycle elements (either previous measured data or new measured data).
3. Completing a productivity analysis for each option on the basis of the above.
4. Balancing the system productivity of each option on the basis of the yarder operating at full capacity.
5. Completing the cost analysis for each option on the basis of the above.
6. Producing recommended preferred options (in terms of productivity, cost, quality, safety and environmental factors) leading to conclusions about whether it is worth pursuing in further engineering developments and/or field trials.

Calculations:

A spreadsheet model was constructed to compare the productivity of 25 different harvesting system combinations (Table 3). Some systems included tree-length delimbing, and some systems included log-length processing.

Table 3: Harvesting systems compared in the analysis

1	Fell and Bunch	Downhill fell	Sideslope bunch	(tip first)			Extract Uphill	Extract butt-first
2	Fell and Bunch	Cross slope fell	Sideslope bunch	(butt first)			Extract Uphill	Extract butt-first
3	Fell and Bunch	Uphill fell	Sideslope bunch	(butt first)			Extract Uphill	Extract butt-first
4	Fell and Delimb	Uphill fell	Downhill delimb	(butt first)			Extract Uphill	Extract tip-first
5	Fell and Delimb	Cross slope fell	Sideslope delimb	(butt first)			Extract Uphill	Extract butt-first
6	Fell and Delimb	Downhill fell	Downhill Delimb	(tip first)	2 stage		Extract Uphill	Extract butt-first
7	Fell and Delimb	Downhill fell	Uphill Delimb	(butt first)			Extract Uphill	Extract butt-first
8	Fell/Delimb/Bunch	Uphill fell	Downhill delimb	(butt first)	Sideslope bunch	2 stage (tip first)	Extract Uphill	Extract butt-first
9	Fell/Delimb/Bunch	Downhill fell	Uphill delimb	(butt first)	Sideslope bunch	(tip first)	Extract Uphill	Extract butt-first
10	Fell/Delimb/Bunch	Cross slope fell	Sideslope delimb	(butt first)	Sideslope bunch	(butt first)	Extract Uphill	Extract butt-first
11	Fell/Delimb/Bunch/Process	Uphill fell	Downhill delimb	(butt first)	Sideslope process	2 stage (butt first)	Extract Uphill	Extract 2 logs
12	Fell/Delimb/Bunch/Process	Cross slope fell	Sideslope delimb	(butt first)	Sideslope process	(butt first)	Extract Uphill	Extract 2 logs
13	Fell/Delimb/Bunch/Process	Downhill fell	Uphill delimb	(butt first)	Sideslope process	(tip first)	Extract Uphill	Extract 2 logs
14	Fell and Bunch	Downhill fell	Sideslope bunch	(tip first)			Extract Downhill	Extract butt-first
15	Fell and Bunch	Cross slope fell	Sideslope bunch	(butt first)			Extract Downhill	Extract butt-first
16	Fell and Bunch	Uphill fell	Sideslope bunch	(butt first)			Extract Downhill	Extract butt-first
17	Fell and Delimb	Uphill fell	Downhill delimb	(butt first)			Extract Downhill	Extract butt-first
18	Fell and Delimb	Cross slope fell	Sideslope delimb	(butt first)			Extract Downhill	Extract butt-first
19	Fell and Delimb	Downhill fell	Uphill Delimb	(butt first)			Extract Downhill	Extract tip-first
20	Fell/Delimb/Bunch	Uphill fell	Downhill delimb	(butt first)	Sideslope bunch	2 stage (tip first)	Extract Downhill	Extract butt-first
21	Fell/Delimb/Bunch	Downhill fell	Uphill delimb	(butt first)	Sideslope bunch	(tip first)	Extract Downhill	Extract butt-first
22	Fell/Delimb/Bunch	Cross slope fell	Sideslope delimb	(butt first)	Sideslope bunch	(butt first)	Extract Downhill	Extract butt-first
23	Fell/Delimb/Bunch/Process	Uphill fell	Downhill delimb	(butt first)	Sideslope process	2 stage (butt first)	Extract Downhill	Extract 2 logs
24	Fell/Delimb/Bunch/Process	Cross slope fell	Sideslope delimb	(butt first)	plus Sideslope process	(butt first)	Extract Downhill	Extract 2 logs
25	Fell/Delimb/Bunch/Process	Downhill fell	Uphill delimb	(butt first)	Sideslope process	(tip first)	Extract Downhill	Extract 2 logs

Each process in a system fed the process following it. Productivity and worked hours were calculated for each process and the system as a whole. Most times and values, as well as costs, were changed to suit a particular analysis.

Assumptions:

Felling, bunching, extraction, processing cycle element times were mostly taken from published research reports (Table 4). Where element times and values, such as trees/haul were not available, they were estimated.

- All felling, bunching, and processing on the slope was by ClimbMAX Steep Slope Harvester.
- Each system was balanced according to 6.5 hauler productive machine hours.
- Tree size was 2.0 m3
- Initially 7.0 Productive Machine Hours (PMH) was used for the felling cycle (prior to system balancing)
- Hauler utilisation was fixed at 6.5 PMH.
- The ratio of fixed to variable system costs was 0.6.
- All extraction was by grapple.
- Extraction and processing was of tree-lengths only – small piece/head extraction was not considered.
- Machine and system costs were sourced from Informe Harvesting[3].

Table 4: Data used from published production studies (or those in preparation*).

Phase	Average Value	Notes	Source
Fell downhill	33 sec	Scarf and backcut all trees	Kelly 2013*
Fell downhill treefall	6 sec		Kelly 2013
Fell cross-slope	33 sec	As for downhill fell, longer tree fall element	Kelly 2013
Fell cross-slope treefall	10 sec		Kelly 2013
Fell uphill	44 sec	Longer scarf and backcut	Kelly 2013
Fell uphill treefall	6 sec		Kelly 2013
Sideslope bunch	39 sec		Kelly 2013
Delimb cross-slope (butt first)	38 sec		LIRO 20/2 1995[4]
Process sideslope	73 sec		LIRO 19/5 1994[5]
Grapple unbunched	34 sec		FFR HTN 03-02[6]
Grapple bunched	38 sec		FFR HTN 03-02[6]
Extract downhill (tip first) unbunched	0.9 trees	Inhaul (39 sec), Outhaul (25 sec), Trees/haul	FFR HTN 05-06**
Extract uphill (butt first) bunched	1.6 trees	Inhaul (49 sec), Outhaul (26 sec), Trees/haul	FFR HTN 03-02[6]
Extract uphill (butt first) unbunched	1.1 trees	Inhaul (49 sec), Outhaul (26 sec), Trees/haul	FFR HTN 03-02[6]
Extract downhill (butt first) bunched	1.4 trees	Inhaul (45 sec), Outhaul (23 sec), Trees/haul	FFR HTN 04-10[7]

*** FFR Technical Note In preparation**

**** FFR Technical Note In preparation**

Other Assumptions

- Felling uphill against the tree lean took more time than felling downhill.
- Felling cross-slope involved a longer tree-fall element, than felling uphill or downhill.
- Felling uphill resulted in a felled/extracted piece size increase of 5%.
- Bunching cross-slope after tree-length delimbing butt first, took longer.
- Delimbing uphill took longer than delimbing downhill.
- Delimbed trees were faster to inhaul (by -10%) and faster to process (-5%).
- All extraction was by grapple swing yarder (150 m average haul distance, AHD).

- Relative to grapple extraction of bunched trees by the butt: unbunched tree systems had fewer trees/haul (1.1) and shorter grapple times (-10%).
- An average of only two processed logs could be extracted per haul when using a grapple.
- Processed log extraction was associated with longer grapple times (+50%) and fewer tree-equivalents/haul (0.8).
- Chute clearance was assumed to keep pace with extraction productivity.
- Sorting and loading productivity was estimated at $60m^3$/hr.
- Balancing of systems was done on the basis of 6.5 productive hours of extraction per day.

RESULTS

Technical and Economic Feasibility

Initially, all twenty-five systems were assumed to be technically feasible and the economic viability of each system was ranked (Table 5).

A steep-slope feller buncher was considered capable of being fitted with a Satco 424 Delimbing head (3.2 tonnes), and was costed at $165,000. It was compared to the same machine fitted with a Satco 630 Feller-director head (2 tonnes) which was costed at $72,000. There was some reluctance to consider uphill delimbing as technically feasible, but advice from industry professionals (such as Mr James Callahan from Satco) suggested that a sufficiently powerful machine equipped with a Satco delimbing head, with sharpened "trailing" edges could do so, but with a suggested 30% increase in delimbing time. There was a similar response to tip-first delimbing (poor delimbing quality). In contrast, Waratah harvester heads were not considered to be easily adapted to tip-first delimbing or processing. These suggestions meant that the trialled systems might operate without new technology or machinery having to be introduced.

Table 5: Twenty-five systems ranked on economic feasibility (ranked from lowest cost to highest cost).

									Rate	Production
22	Fell/Delimb/Bunch	Cross slope fell	Sideslope delimb	(butt first)	Sideslope bunch	(butt first)	Extract Downhill	Extract butt-first	$23.62	464
20	Fell/Delimb/Bunch	Uphill fell	Downhill delimb	(butt first)	Sideslope bunch	2 stage (tip first)	Extract Downhill	Extract butt-first	$23.62	464
1	Fell and Bunch	Downhill fell	Sideslope bunch	(tip first)			Extract Uphill	Extract butt-first	$23.66	477
10	Fell/Delimb/Bunch	Cross slope fell	Sideslope delimb	(butt first)	Sideslope bunch	(butt first)	Extract Uphill	Extract butt-first	$23.70	492
2	Fell and Bunch	Cross slope fell	Sideslope bunch	(butt first)			Extract Uphill	Extract butt-first	$23.72	477
21	Fell/Delimb/Bunch	Downhill fell	Uphill delimb	(butt first)	Sideslope bunch	(tip first)	Extract Downhill	Extract butt-first	$23.73	464
3	Fell and Bunch	Uphill fell	Sideslope bunch	(butt first)			Extract Uphill	Extract butt-first	$23.74	477
9	Fell/Delimb/Bunch	Downhill fell	Uphill delimb	(butt first)	Sideslope bunch	(tip first)	Extract Uphill	Extract butt-first	$23.97	492
8	Fell/Delimb/Bunch	Uphill fell	Downhill delimb	(butt first)	Sideslope bunch	2 stage (tip first)	Extract Uphill	Extract butt-first	$24.30	492
14	Fell and Bunch	Downhill fell	Sideslope bunch	(tip first)			Extract Downhill	Extract butt-first	$24.87	431
15	Fell and Bunch	Cross slope fell	Sideslope bunch	(butt first)			Extract Downhill	Extract butt-first	$24.92	431
16	Fell and Bunch	Uphill fell	Sideslope bunch	(butt first)			Extract Downhill	Extract butt-first	$24.93	431
5	Fell and Delimb	Cross slope fell	Sideslope delimb	(butt first)			Extract Uphill	Extract butt-first	$29.85	362
7	Fell and Delimb	Downhill fell	Uphill Delimb	(butt first)			Extract Uphill	Extract butt-first	$29.88	362
6	Fell and Delimb	Downhill fell	Downhill Delimb	(tip first)	2 stage		Extract Uphill	Extract butt-first	$30.14	362
4	Fell and Delimb	Uphill fell	Downhill delimb	(butt first)			Extract Uphill	Extract tip-first	$31.11	346
19	Fell and Delimb	Downhill fell	Uphill Delimb	(butt first)			Extract Downhill	Extract tip-first	$33.60	330
17	Fell and Delimb	Uphill fell	Downhill delimb	(butt first)			Extract Downhill	Extract butt-first	$33.82	306
18	Fell and Delimb	Cross slope fell	Sideslope delimb	(butt first)			Extract Downhill	Extract butt-first	$33.82	306
11	Fell/Delimb/Bunch/Process	Uphill fell	Downhill delimb	(butt first)	Sideslope process	2 stage (butt first)	Extract Uphill	Extract 2 logs	$35.10	250
12	Fell/Delimb/Bunch/Process	Cross slope fell	Sideslope delimb	(butt first)	Sideslope process	(butt first)	Extract Uphill	Extract 2 logs	$35.10	250
13	Fell/Delimb/Bunch/Process	Downhill fell	Uphill delimb	(butt first)	Sideslope process	(tip first)	Extract Uphill	Extract 2 logs	$35.27	250
23	Fell/Delimb/Bunch/Process	Uphill fell	Downhill delimb	(butt first)	Sideslope process	2 stage (butt first)	Extract Downhill	Extract 2 logs	$38.84	225
24	Fell/Delimb/Bunch/Process	Cross slope fell	Sideslope delimb	(butt first)	plus Sideslope process	(butt first)	Extract Downhill	Extract 2 logs	$38.84	225
25	Fell/Delimb/Bunch/Process	Downhill fell	Uphill delimb	(butt first)	Sideslope process	(tip first)	Extract Downhill	Extract 2 logs	$38.84	225

Systems No. 13 and No. 25 (Table 5 and Figure 1) both involve tip-first log processing. These systems were deemed technically feasible, but uneconomic since effective log making was deemed practicable only when starting at the most valuable part of the tree. Tip-first processing, as well as delimbing, was confirmed as being feasible (Satco). Waratah soft-clamp systems were declared incompatible with tip-first delimbing and processing.

The benchmark system (No. 1) was that of a ClimbMAX harvester felling and bunching (tip-first) for butt-first extraction, uphill.

Processing on the Slope

Table 5 shows that systems involving processing on the slope were found to be the least economic (systems 23, 24, 25: $38.84/m^3 for butt-first delimbing and processing, uphill extraction butt-first) due mainly to reduced haul size of estimated 0.8 equivalent trees/haul or two logs at 1.6 m^3 total (1.6 trees/haul baseline for bunched trees).

Increasing the trees per haul equivalent by 25% to 1.0 reduced the rate 21% to $30.80/m^3. For the same system, reducing grapple time from 57 sec to 38 sec reduced the rate by 11% to $34.78. A more economical European hauler (with integral grapple loader) matched to the 0.8 tree haul size, with a lower daily cost (two thirds of the $1250 daily rate, or $825/day) excluding a clearance machine, and including a breaker out, would reduce the rate by 15% to $32.98.

A further refinement to the system would be to exclude a dedicated loader. This would bring the cost per tonne down to $30.19/tonne.

Systems Rated by Cost

The cheapest system (No. 22) was a Fell, Delimb, Bunch system for downhill extraction butt-first with a harvest rate of $23.62/tonne (464 tonnes/day). The system featured cross-slope felling, side-slope delimbing (butt first), side-slope bunching (butt first), and extraction downhill (butt-first).

The balanced system is shown below:

Balanced System	Productive Hours
ClimbMAX	8.7
Large/Small Swing yarder	6.5
Clear Chute (excavator)	6.7
Processor	7.0
Sorter/Load	7.7
Loader	7.7

Bunched tree systems all came in at under $25/tonne cost, whether extracted uphill or downhill with butt-first extraction. Processing on the slope was the most expensive option with either uphill or downhill extraction. The high cost was largely driven by the reduced average haul size (an assumption of 0.8 tree equivalents/haul). Table 6 illustrates the change in rate as variables of grapple time and trees/haul are changed (the higher cost relates to a longer grapple time and a reduced trees/haul value). This variation is further explored in Figure 1.

Table 6: Sensitivity analysis / Extraction – Grapple time, Trees per haul: two examples

	Bunched	1	Unbunched	19	Source
		Fell and Bunch Downhill fell Sideslope bunch (tip first) Extract Uphill Extract butt-first		Fell and Delimb Downhill fell Uphill Delimb (butt first) Extract Downhill Extract tip-first	
	Mean	Range (95%CL)	Mean	Range (95%CL)	FFR HTN 03-02 FFR HTN 05-06
Grapple time (sec)	38	35 – 42	26	20 – 36	
Trees/haul	1.6	1.5 – 1.7	0.9	0.8 – 1.0	
System Cost Range		$25.54 (433T) $22.08 (522T)		$38.02 (270T) $29.98 (349T)	
Percentage rate decrease		13%		21%	

Comparison of Systems Based on Variation in Grapple Time and Trees/haul

The different systems were compared based on variation of two key variables: grapple time and trees per haul. Some systems were assessed on the basis of plus/minus 10%, while others, where data were available, were assessed on 95% confidence limits.

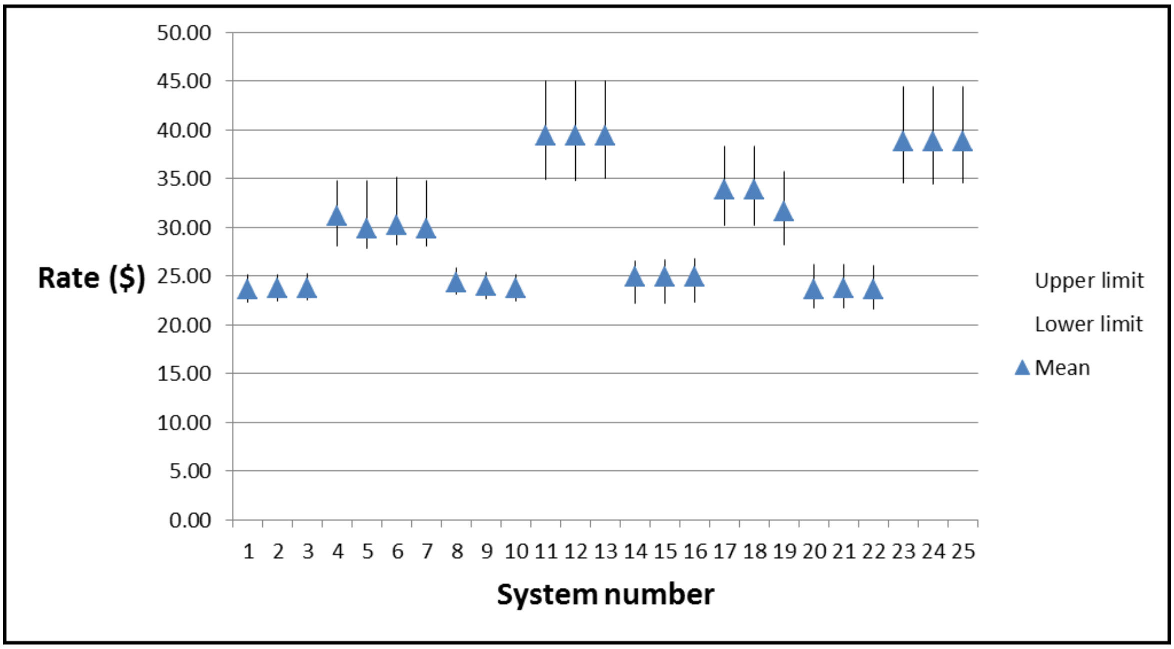

Figure 1: Comparison of systems based on variation in grapple time and trees/haul.

Systems were ranked for similarity of rates and separated into two distinct groups. The first set of lower rates were characterised by lack of processing on the slope, and mostly butt-first extraction.

Uphill and downhill haul directions featured in both groups. Felling and bunching rates were lower than Felling and Delimbing rates, reflecting the increased number of butts/haul in bunched systems.

Effects on Branch Material left on the Cutover – The Case for Delimbing on the Slope.

There is evidence that branches and slash on the cutover can be beneficial agents in terms of site productivity, reduction of risk of sediment transport on steep slopes[8], and reduction in severity of rutting by tracked or wheeled machinery[9]. There are costs and risks associated with branch accumulation on landings (bird's nests). Costs arise from dispersal or pulling back of slash and waste material, while risks relate to the costs of dealing with the consequences of bird's nest collapses[10].

Landing residues comprises a combination of stem and branch waste, with branch waste a greater percentage of extracted volume for hauler extraction[11]. It was estimated from a study of seven hauler operations that an average 7.9% of extracted volume was branch waste and 4.7% was stem waste. It is reasonable to assume that a reduction in extracted branch material will reduce the costs of bird's nests retrieval.

Costs of bird's nests treatment in 1997[10] were quoted as:

- Retrieval: $500-$2500/landing
- Burning: $100-$1500/landing
- End-haul: $2000/landing

Assuming 1997 costs increased by 40% PPI change from 1997-2013[12], 2013 costs were estimated. In the absence of cost information being available or accessible, an estimate was made.

- Retrieval: $700-$3500/landing
- Burning: $140-$2100/landing
- End-haul: $2800/landing

The total tree volume extracted to a landing was estimated using FFR benchmarking results[13]. An average tower hauler setting of 15.1 ha was estimated to have a total of 7,580 m^3 extracted volume. Applying a retrieval cost of $3,500, translated to $0.46/$m^3$ extracted for retrieval of branch and stem waste. Confirmation of this value came from an estimate of recent costs of $2,000 to $5,000 for slash retrieval (McCloy, PF Olsen Ltd, pers. comm.). A general cost allowance for slash and waste handling (recovering larger pieces and disposing of slash), as well as water controls, was $1.00/$m^3$ extracted. For this investigation, it was assumed that delimbing on the cutover would eliminate retrieval of branch or stem waste. The absence of branch waste might make recovery of stem waste from landings more economic, owing to its separation from limbs, slash, and other contaminants.

Ranking of Harvesting Systems Changes: Lowest Rates

Offsetting the worst-case retrieval cost of $3500/landing ($0.46/m^3) of dealing with bird's nests meant an effective reduction in some harvesting rates. There were only two delimbing-related system ranking changes to the most favourable rate estimates, when the advantage of not carrying out bird's nest removal was considered. System Nos. 10 and 9 improved their rankings by one and three places respectively to $21.97 and $22.43. Both were Fell/Delimb/Bunch systems, delimb butt first and extract uphill, butt first.

Preferred system options were analysed by the following criteria:

1. Productivity and cost
2. Quality
3. Safety
4. Environmental issues

1. Productivity and Cost

When best-case variables for grapple time and pieces/haul were considered, systems involving bunching came out as lower cost/higher productivity systems. It appeared that system productivity was largely driven by increased extraction productivity through bunching (trees/haul). Felling and Delimbing, and processing-related systems were more expensive, again largely as a result of not bunching, or with log extraction, due to restricted haul volume (Table 7).

Table 7. Daily productivity of harvesting systems compared

System	Productivity ($/m^3) Average value	Daily production (m^3) Average value
Fell/Delimb/Bunch	$22.20	525
Fell and Bunch	$22.34	506
Fell and Delimb	$28.66	376
Fell/Delimb/Bunch/Process	$33.06	269

Systems involving delimbing cost could also be improved by an estimated $0.46/m^3 as a result of reduced requirements to retrieve bird's nests.

Contractor comments regarding extraction:

- Chute clearance is an issue with trees that must also be turned butt-first for processing. Chute clearance will be slower as a result.
- Steep chutes will require that the clearance machine hold the trees as the hauler grapple is opened. These trees may try to slide back downhill.
- Consideration might be given to choker extraction.

2. Quality

Trees delimbed on the cutover can be assumed to be of a similar delimbing standard to those on the landing. Mechanised processing of delimbed trees on the landing may lead to problems identifying large branches, as branch stubs may be obscured by dirt. Trees delimbed and bunched prior to extraction might lose more bark, making the wood more susceptible to sap stain. Trees delimbed on the cutover may suit operations where manual processing is required – there would be no requirement for static delimbers or machine-time to pull trees through the knives.

3. Safety

The effect on stability of machines delimbing in any direction on a steep slope is unknown. Effects may be similar to those experienced in bunching, as similar boom/stick motions are involved. Discussion with a ground-based harvester operator indicated that there was some concern over machine stability. Nigel Kelly stated that he would be willing to trial a delimbing head on his steep slope feller buncher if one was made available at no cost to his company.

Some contractor comments regarding uphill felling:

- For trees with a severe downhill lean there is a risk of these trees, when cut, falling on to the felling machine.
- Trees that are felled uphill and hang up owing to heads not coming down cleanly through standing trees, will be delimbed and brought down with the delimb head some distance off the ground. This may unbalance the felling machine.
- Some tree stumps will be higher than normally acceptable because of a relatively high front cut (uphill) and an even higher cut from the downhill side. This is because of the terrain slope, and the design of the felling saw.

4. Environmental Issues

There is evidence that branch material or slash can reduce the severity of rutting from wheeled forwarders or harvesters in ground-based operations[9]. Observation during a recent soil disturbance assessment also suggests that slash could reduce rutting even on steep slopes for tracked machines. In terms of sediment generation on steep slopes, slash cover can reduce the effect of heavy rain acting directly on the soil surface, and is considered non-sediment generating[8]. Retained slash may increase establishment costs – planting targets for low versus high slash loadings can be fourteen per cent lower, (PF Olsen Ltd, pers. comm.). A reduction in extracted branch material could also result in a reduced requirement to retrieve material from bird's nests.

In a fell and bunch system, some branches will be broken off in the process of bunching. Some branches will be extracted, to be swept off the skid, to some degree less than the estimate of 7.9% of daily production [11]. This 7.9% value translates to approximately 15 tonnes per day of branches based on 190 tonne/day production in a non-bunching operation[14]. A fell and delimb operation might make skid salvage operations more efficient. In terms of silviculture, the difference between light and heavy planting hindrance was quoted as approximately $50 per hectare.

Slash from harvesting (branches and needles) also contributes to soil organic matter through decomposition. Some research suggests that in managed plantation forests grown for solid wood products and pulp, amounts of branch and leaf biomass removed for energy production are relatively small when compared to amounts cycled from tree to soil during the life of the stand[15]. If this is the case in plantation pine forests, delimbing on the slope may not contribute significantly to soil organic matter, and hence, soil fertility. This contrasts with an East Coast harvesting consent requiring delimbing on the cutover to ensure retention of nutrients for improving soil organic matter (McCloy, pers. comm.).

In terms of some negative effects of delimbing on the slope, delimbed trees might more readily slide downhill and contribute to an accumulation of trees in a waterway or gully. Slash composed of dry branches or slash accumulation generally might also slide freely and contribute to blockages, debris dams and downstream debris affecting third parties.

Extraction of trees tip-first, downhill may contribute significantly to soil disturbance as the butts, which are not suspended, dig into the ground, creating furrows (M. Speirs, pers. comm.). Trees extracted tip-first uphill may cause similar soil damage.

CONCLUSIONS

From discussions with industry professionals, tree length delimbing on steep slopes was found to be technically feasible. Conclusions from the modelled productivity comparison of a number of systems showed the following:

- Bunching was found to be the key determinant of lower cost, whether trees were delimbed or not.
- Delimbing produced a marginal gain in terms of productivity and cost.
- Processing on the slope coupled with known grapple extraction systems was found to be higher cost.
- Processing on the slope would require new ideas for moving bundles of logs.
- It is doubtful that stacking logs on steep slopes would be achievable without stacking behind high stumps.

RECOMMENDATIONS

It is recommended that stems should be bunched for extraction whether trees were delimbed or not. Since delimbing on the slope produced a marginal gain in terms of productivity and cost future research should focus on steep slope feller-delimber-buncher performance of different tree-length delimbing directions and the resulting effects on delimbing time and breakage. Additional data are required of effects on extraction productivity from extracting delimbed and bunched stems, uphill, butt-first. Feller-buncher productivity studies should be paired with soil disturbance assessments.

Regarding processing on the slope, achieving an economic haul size at least four or five processed logs would be necessary per haul, to match current harvesting systems. Improvements to productivity could also be made if bunches of logs could be accumulated in designated places on steep slopes, rather than being scattered. Some brainstorming would be required to design novel technology to achieve this result.

One system that might be tested is the use of a Kaiser Spyder[16, 17] to feed logs to one or more grapples. This would cut grappling time and enable a rapid inhaul. Cleanup of gullies and streams should be undertaken as extraction progressed. Accumulation of logs at the lowest possible point, or in swathes downslope, would mean less unproductive travel of the Spyder. Log extraction could be prioritised according to value or susceptibility to sap stain, and log inventory could be managed differently. A Spyder or Menzi Muck[18] could also be teleoperated, as these machines have computerised operating systems.

Recovery of small pieces derived from either the head of the tree or the stem, as a result of tree breakage, is a separate, but important, area of interest. A modelling approach could be used to determine the marginal cost of not recovering this material.

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