Advantage

FERIC

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Contents

Using mechanized systems to harvest second-growth forests in coastal British Columbia: productivity and costs of loader-forwarding and grapple yarding operations

Abstract

The Forest Engineering Research Institute of Canada (FERIC) monitored the operational and economic feasibility of using mechanized systems for clearcut harvesting of second-growth on steep slopes in coastal British Columbia. The results are being presented in several "Advantage" reports. This report presents the results of the loader-forwarding and grapple yarding phases.

Keywords

Coastal British Columbia, Second-growth, Extraction, Loader-forwarding, Grapple yarding, Costs, Productivity.

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Introduction

Mechanical timber harvesting systems comprised of feller-bunchers, processors, loader-forwarders, and skidders—if used appropriately—offer opportunities to reduce harvesting costs without exceeding the limits of acceptable site impacts. At the request of its members, FERIC has been investigating the use of this equipment in second-growth stands in coastal British Columbia.

In the spring of 2002, TimberWest Forest Corp.'s Cowichan Woodlands Operation and Honeymoon Bay Operation undertook a series of trials to investigate the feasibility of using mechanized systems for clearcut harvesting on steep slopes. FERIC monitored the trials to determine the operational and economic feasibility of these systems. Because of the scope of this study, the results will be presented in several "Advantage" reports. The first report presented the results for the mechanized felling operation (Kosicki and Dyson 2003). This report presents the results of the loader-forwarding and grapple yarding phases.

Objectives

The primary goal of this study was to assess the economic and operational feasibility of using mechanized systems for clearcut harvesting on steep slopes. The objectives of this report on extraction methods were to:

- Determine overall productivities and costs for loader-forwarding and grapple yarding in second-growth stands.
- Identify factors that influence the performance of the two extraction methods.
- Evaluate swing yarders and loader-forwarders as components of roadside harvesting systems.
- Develop productivity and cost functions for extraction equipment.
- Determine and compare the optimum extraction distances for loader-forwarding and grapple yarding.

Harvesting systems

An overview of harvesting systems and equipment used in this project is shown in Table 1. Both manual and mechanical felling with feller-bunchers were used. Depending on block layout and terrain conditions, stems were extracted with loader-forwarders and/or swing yarders. At the roadside, the stems were decked for processing by mechanical dangle-head processors.

Description of sites and stands for extraction study

Extraction operations were observed in all four study blocks. Blocks A, C, and D were in the Honeymoon Bay Operation. Block A was located approximately 65 km west of Duncan. Blocks C and D were located approximately 50 km west of Duncan and 4 km north of Cowichan Lake. Block B was located approximately 15 km south of Mesachie Lake in the Cowichan Woodlands Operation. The harvesting prescription for Blocks A and B was clearcutting with reserves, and for Blocks C and D it was clear-cutting. Table 2 summarizes the site and stand features.

The sites in Block A were classified as the submontane variant of the Coastal Western Hemlock very wet maritime biogeoclimatic subzone (CWHvm1), whereas those in Blocks B, C, and D were classified as Coastal Western Hemlock very dry maritime western subzone (CWHxm2) (Green and Klinka 1994). The terrain in all blocks ranged from almost level (0–10%) to very steep (more than 50%). The average slope gradient in Block B was 35%, and was 45% in the other three blocks.

Table 1. Harvesting systems and equipment

Cutblock	A	B	C	D
Harvesting system	Clearcut, cold deck	Clearcut, cold deck	Clearcut, hot deck	Clearcut, cold and hot deck
Felling equipment	Madill T2200 feller-buncher with intermittent low-speed circular saw [a]	Tigercat 860 feller-buncher with high-speed circular saw [a]	Feller-buncher	Manual
Extraction equipment	Snorkel, loader-forwarders, swing yarder	Madill 144 yarder, uphill and downhill yarding [a] Madill 3800 loader-forwarder [a]	Cypress 7280 yarder, uphill yarding [a] Loader-forwarders	Cypress 7280 yarder, downhill yarding [a]
Processing equipment	Madill 3800 carrier with Waratah processing head	Madill 3800 carrier with Waratah processing head [a]	Madill 3800 carrier with Waratah processing head [a]	Madill 3800 carrier with Waratah processing head [a]

[a] Monitored by FERIC in shift-level and detailed-timing studies.

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Table 2. Site and stand descriptions				
	Block			
	A	B	C	D
Total area (ha)	43.0	29.9	35.0	52.2
Study area (ha)	17.4	29.9	5.9	5.9
Site characteristics [a]				
Ecological classification [b]	CWHvm1	CWHxm2	CWHxm2	CWHxm2
Elevation range (m)	150–300	300–400	330	400–870
Terrain	gentle to steep	gentle to steep	steep	steep
Slope				
Range (%)	10–70	10–70	20–65	5–80
Average (%)	45	35	45	45
CPPA terrain classification [c]	2.3.4	1.2.4	1.2.4	1.2.4
Species composition (%)				
Douglas-fir	81	89	80	70
Western hemlock	18	10	20	30
Spruce, redcedar, alder, maple	1	1	-	-
Net merchantable volume (m^3/ha)	500	513	547	419

[a] From Silviculture Plan.
[b] Green and Klinka 1994.
[c] Mellgren 1980.

Forest cover in all blocks included second-growth Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) in varying proportions. Blocks A and B also had a small proportion of Sitka spruce (*Picea sitchensis*), western redcedar (*Thuja plicata*), red alder (*Alnus rubra*), and bigleaf maple (*Acer macrophyllum*).

Extraction operations and equipment

The study area in Block A was located above a single haul road, and loader-forwarding in a downhill direction was prescribed (Figure 1).

Block B was accessible to harvesting equipment from in-block spur roads (Figure 2). Loader-forwarding in a downhill direction, and grapple yarding in both uphill and downhill directions, were prescribed.

In Block C, the steep ground beneath the single haul road was prescribed for grapple yarding in an uphill direction (Figure 3). A portion of the study area with insufficient deflection at the block's backline was prescribed

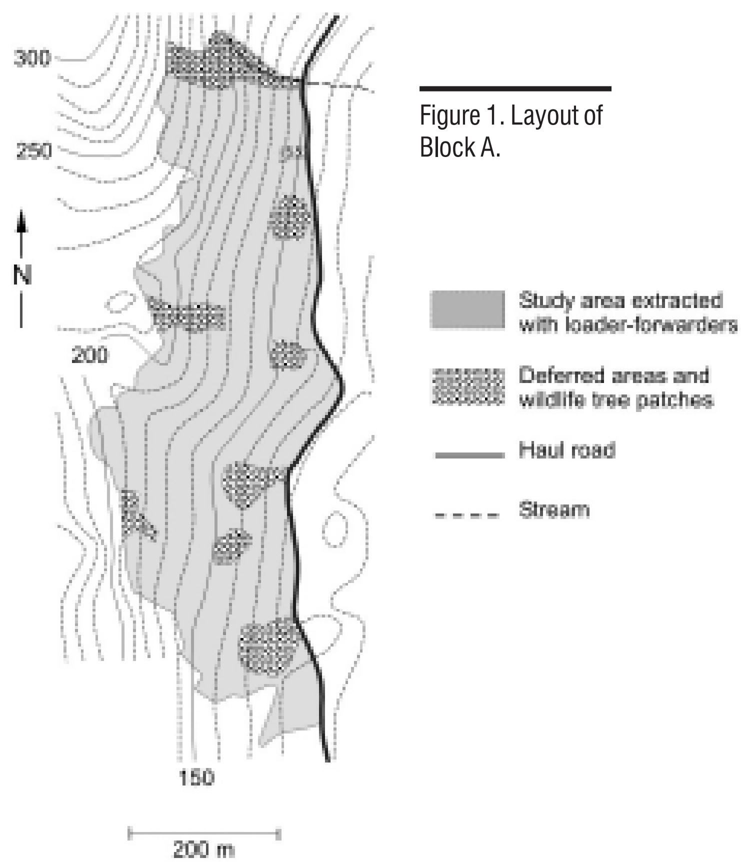


Figure 1. Layout of Block A.

Figure 2. Layout of Block B.

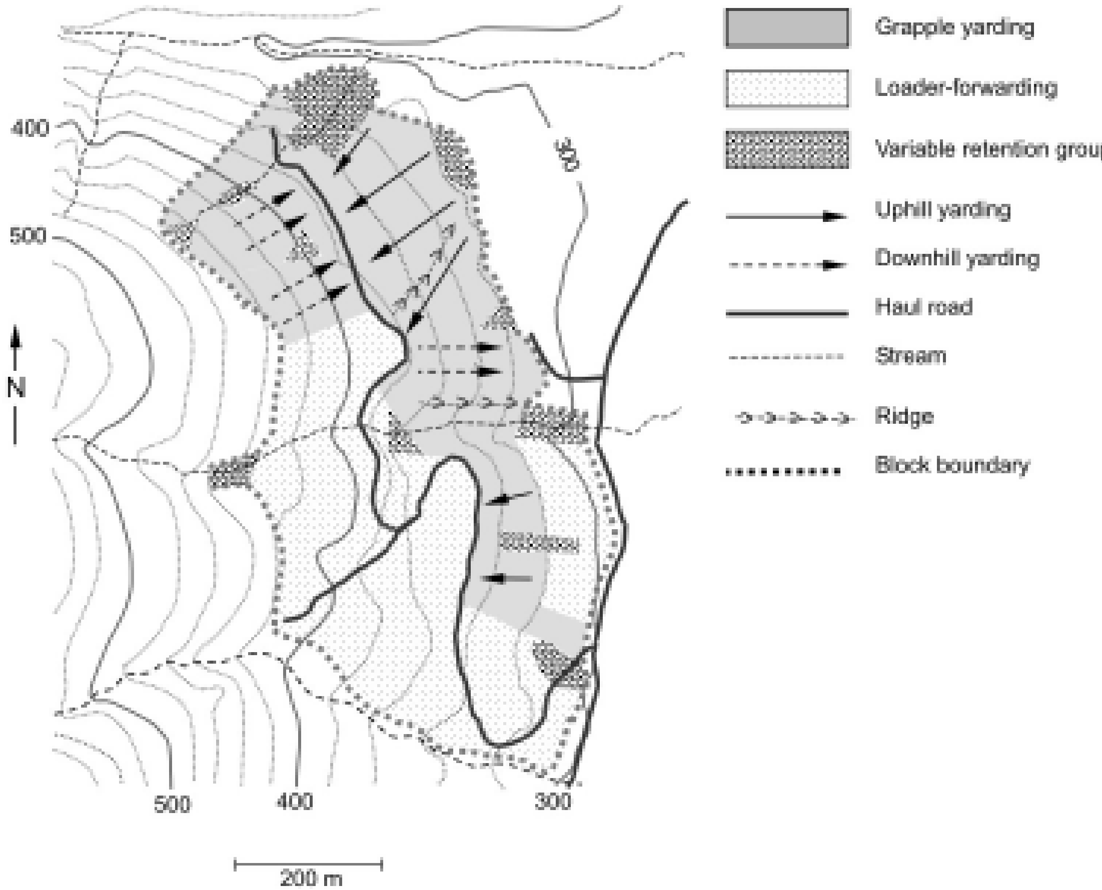
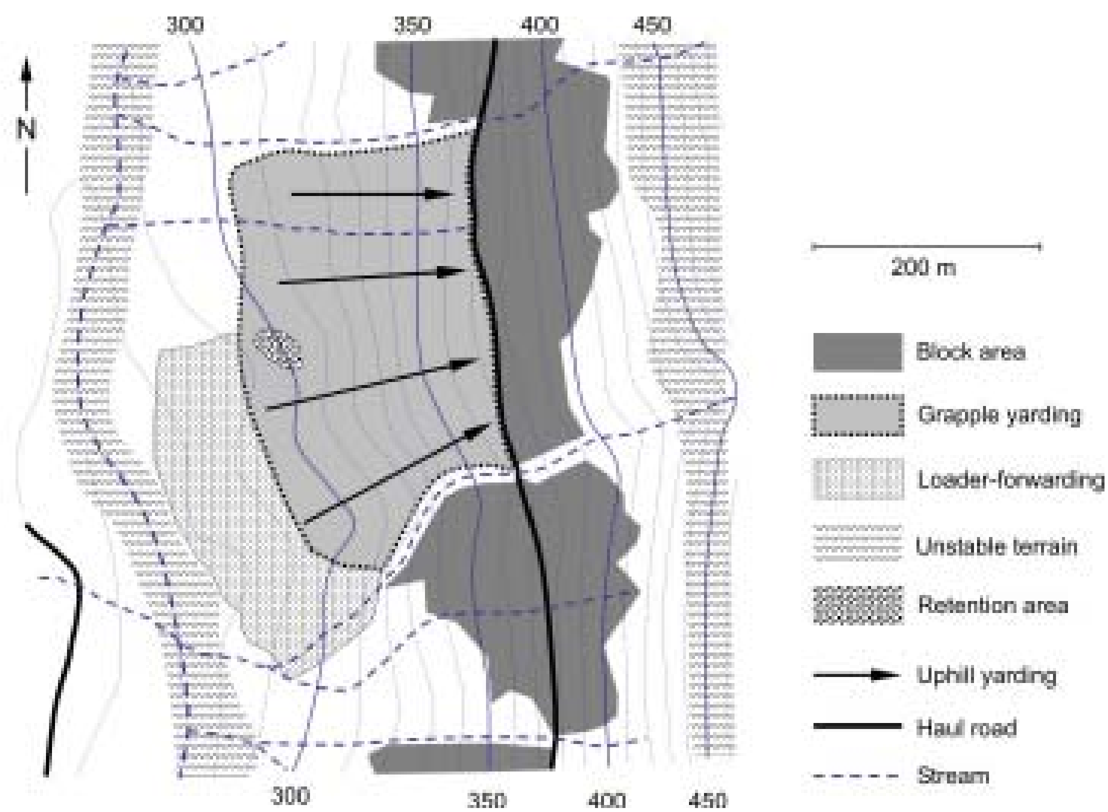


Figure 3. Layout of Block C.



for loader-forwarding and then grapple yarding.

The study area in hand-felled Block D was located above a haul road and grapple yarding in a downhill direction was prescribed (Figure 4).

In Blocks B and D, a grapple with a maximum opening of 288 cm was used. The grapple used in Block C was smaller and had a 224-cm opening.

At roadside, the stems were decked for hot and/or cold processing by dangle-head processors.[1] In Blocks A and B, only cold processing was done. In Block C, because of limited decking area, the hot processing system was the only option. In Block D, the majority of the yarded stems was cold processed and only a small number of stems was hot processed.

Study methods

FERIC observed the harvesting operation and collected shift-level and detailed-timing data. Shift-level data were obtained from data-logger charts, operators' reports about daily production and major delays (>15 min/occurrence), and TimberWest's scale records containing net harvest volumes. Forwarding and yarding cycles were detail-timed at frequent intervals throughout the study period.

Shift-level and detailed-timing studies on the grapple yarding operation were conducted in Blocks B, C, and D. The loader forwarding was studied in Block B. In Blocks A and C, FERIC's observations focused mainly on forwarding techniques.

For the detailed-timing study of the loader-forwarder, five cycle elements were identified: swinging with empty grapple, swinging loaded (this encompassed grappling, swinging, and placing the load), moving the machine, handling debris, and in-cycle delays. Slope class, swing distance, number of stems per cycle, and reason for in-cycle delays were also recorded. The collected data were analyzed to determine the relationship between forwarding distance and forwarding cycle

[1] In a "hot processing" system, extraction and processing phases occur simultaneously, and the supply buffer between these phases is generally small. In a "cold processing" system, processing usually starts after the extraction phase has been completed, and the supply buffer between both phases is generally large.

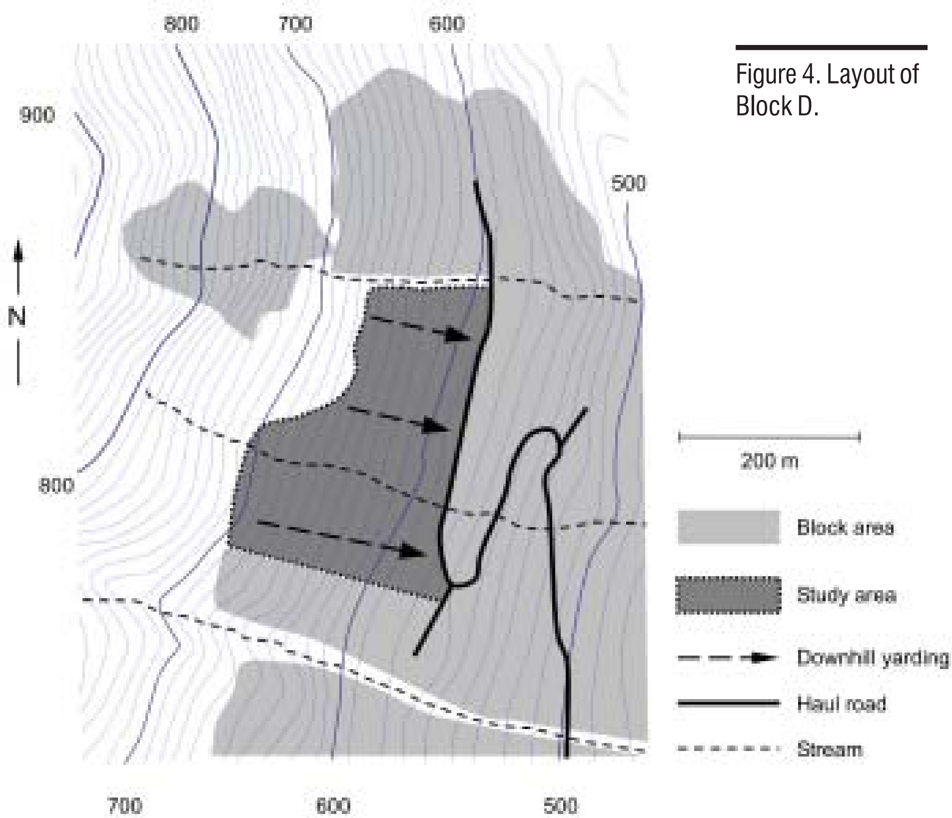


Figure 4. Layout of Block D.

Table 3. Technical specifications for the Madill 3800 loader-forwarder

	Madill 3800
Engine	Detroit Diesel 60
Power (kW)	242 @ 2200 rpm
Maximum boom reach (m)	13.4
Lift capacity at 9 m reach (kg)	10 400
Carbody clearance (cm)	76
Track dimensions (m)	
Width	3.81
Length	5.18
Travel speed (km/h)	up to 4.5
Mass (kg)	35 300
Ground pressure (kP)	60

Figure 5. Madill 3800 loader-forwarder in Block B.

Figure 6. Madill 144 swing yarder in Block B.

Figure 7. Cypress 7280 swing yarder and Madill 3800 processor in Block C.

time. A one-way analysis of variance (ANOVA) was used to test whether the forwarding cycle times and swing distances were affected by slope class. The results were used to develop relationships between forwarding distance and forwarding time for each slope class, and then combined with shift-level data to derive productivity and cost functions.

Detail-timed yarding cycles were divided into six elements: outhaul, hookup, inhaul, deck, in-cycle delays, and move yarder and backspar. Outhaul and inhaul distances, number of stems per cycle, and reasons for observed delays were also recorded. Using regression techniques, the timing data were analyzed to determine the relationship between outhaul and inhaul times and distances. The results of the regression analysis were then combined with average values for hookup, deck, and move yarder and backspar to develop an equation for predicting delay-free cycle time and to derive productivity and cost functions.

Hourly loader-forwarder and yarder costs were calculated using FERIC's standard costing methods (Appendix I). These costs do not include supervision, profit, and overhead, and are not the actual costs for the contractor or the company studied.

Results and discussion

Overview of extraction operations

Extraction operations in the four study blocks (A, B, C, and D) were performed from early May to late July 2002.

Study blocks A, B, and C were clearcut with feller-bunchers except in a few small areas which had to be felled manually. All of Block D was felled manually.

Loader-forwarding in study blocks was performed with a Madill 3800 loader-forwarder (Table 3 and Figure 5).

Grapple yarding was done in Block B by a Madill 144 swing yarder (Figure 6) while Cypress 7280 yarders were used in Blocks C and D (Figures 7 and 8). Hitachi and John Deere excavators were used as backspars in

Blocks B and C, respectively. In Block D, the yarder's running line was anchored to the stumps along the backline of the block.

All extraction equipment was operated by TimberWest crews. The crews for the grapple consisted of two or three workers, depending on the terrain and yarding system.

Shift level study

Loader-forwarding

In study block B, the Madill 3800 loader-forwarder worked a total of 19 shifts, or 156 h, on a single-shift basis for five days per week. Table 4 summarizes shift structure, productivities in cubic metre per productive machine hour (PMH) and scheduled machine hour (SMH), and costs per cubic metre. Shift lengths ranged from 5 to 9 h and averaged 8.8 h. For the monitoring period, utilization was 93%, and almost all delays were caused by mechanical problems related to hydraulic components.

Figure 8. Cypress 7280 swing yarder in Block D.

The total volume extracted by the loader-forwarder was 7270 m^3. At an average extraction distance of 60 m, the Madill 3800's overall productivity was 46.7 m^3/PMH. For a utilization rate of 93%, this translated into 43.5 m^3/SMH. The extraction cost with the Madill 3800 was calculated at \$3.36/m^3, based on an hourly rate of \$146/SMH (Appendix I).

Table 4. Shift-level summary and productivity for the Madill 3800 loader-forwarder in Block B

Description	Total
Productive shifts (no.)	19
Productive machine hours (PMH)	155.6
Mechanical delays (MD) (h)	9.4
Non-mechanical delays (NMD) (h)	2.0
Total all delays (h)	11.4
Scheduled machine hours (SMH)	167
Average shift length (h)	8.8
Utilization (PMH/SMH) (%)	93
Availability [(SMH-MD)/SMH] (%)	94
Stems (no.)	7670
Total volume (m^3)	7270
Average forwarding distance (m)	60
Average volume (m^3/stem)	0.95
Productivity	
Stems/productive shift	404
Stems/PMH	49
Stems/SMH	46
m^3/productive shift	383
m^3/PMH	46.7
m^3/SMH	43.5
Hourly machine cost (\$/SMH)	146.15
Cost (\$/m^3)	3.36

Grapple yarding

Table 5 summarizes shift structures, productivities in cubic metre per PMH and SMH, and costs per cubic metre for yarders in three study blocks. All yarders were scheduled to work five days per week and 8.5 h per shift. The yarders in Blocks B and D were employed on a single shift basis, and the yarder in Block C periodically worked two shifts per day. Actual shift lengths ranged from 5.3 h to 9 h. The average shift lengths for Blocks B, C, and D were 7.9, 8.0, and 8.5 h, respectively. For the monitoring period, utilization varied from 77% (Block C) to 90% (Block B).

The highest productivity—78.8 m^3/PMH (71.0 m^3/SMH) in Block B—can be attributed to good preparation of bunches for yarding (mechanical felling with a feller-buncher), multiple-stem cycles, and the high average volume of 0.95 m^3/stem. The lowest yarding productivity—22.1 m^3/PMH (19.4 m^3/SMH) in Block D—resulted from manual felling (dispersed stems), single-stem loads, and the small average volume of 0.44 m^3/stem. The yarding costs varied

Table 5. Shift-level summary and productivity for the Madill 144 swing yarder in Block B, and the Cypress 7280 swing yarders in Blocks C and D

Element	Block B	Block C	Block D
Productive shifts	12	16	15
Productive machine hours (PMH)			
Yarding (h)	84.9	96.2	107.8
Road changes (h)	-	2.7	3.5
Total PMH	84.9	98.9	111.3
Mechanical delays (MD) (h)	8.2	14.1	8.9
Non-mechanical delays (NMD) (h)	1.2	15.7	7.3
Total all delays (h)	9.4	29.8	16.2
Scheduled machine hours (SMH)	94.3	128.7	127.5
Average shift length (h)	7.9	8.0	8.5
Utilization (PMH/SMH) (%)	90	77	87
Availability (SMH-MD)/SMH (%)	91	89	93
Total volume (m^3)	6 692	4 304	2 469
Total stems (no.)	7 044	4 250	5 662
Average volume (m^3/stem)	0.95	1.01	0.44
Productivity			
Stems/PMH	83	43	51
Stems/SMH	75	33	44
m^3/productive shift	558	269	165
m^3/PMH	78.8	43.5	22.1
m^3/SMH	71.0	33.4	19.4
Hourly machine cost ($/SMH)	323.79	335.30	315.84
Cost ($/$m^3$)	4.56	10.04	16.28

Table 6. Summary of detailed timing for the Madill 3800 loader-forwarder

Description	Total
Productive time (min)	993
Productive machine hours (PMH)	16.6
Total cycles (no.)	1170
Payload (stems/cycle)	
Minimum	1
Maximum	12
Average	2.92
Average volume (m^3/stem)	0.95
Average payload (m^3/cycle)	2.77
Swing distance (m/cycle)	
Minimum	0
Maximum	35
Average	14.8
Average cycle time (min, %)	
Swing unloaded	0.16, 19
Swing loaded	0.39, 46
Move	0.18, 21
Debris	0.07, 8
Delays	0.05, 6
Total	0.85, 100

from \$4.56/m^3 (Block B) to \$16.28/m^3 (Block D).

Detailed-timing study

Loader-forwarding

The Madill 3800 loader-forwarder was detail-timed for 16.6 h, and the study results are summarized in Table 6. Forwarded payloads consisted of 1–12 stems and averaged 2.92 stems and 2.77 m^3 per cycle. The forwarded payloads were moved over an average distance of 14.8 m/cycle. The average forwarding time and distribution of the cycle time elements were close to average times and distributions reported by Gillies (2001) and Sambo and Sutherland (2003) for loader-forwarding operations.

Results of the one-way analysis of variance (ANOVA) indicated that the differences in average cycle times for the first two slope classes (0–10% and 11–20%) were not significant. For these classes, the average cycle time was 0.84 min. For the third slope class (21–30%), the cycle times were significantly greater and averaged 0.90 min. The differences in average swing distances (16.8 m, 14.1 m, and 15.5 m for the first, second, and third slope classes, respectively) were significant.[2] Results of analyses for cycle times and swing distances were combined to derive a relationship between forwarding distance and forwarding time (Figure 9). For all forwarding distances and slope classes 11–20% and 21–30%, forwarding times were 18% greater than those for slope class 0–10%. Derived forwarding times, the average payload of 2.77 m^3/cycle, and actual utilization of 93% were used to derive the relationship between forwarding distance and estimated forwarding productivity in m^3/SMH (Figure 10). For the slope class 0–10%, forwarding productivities were 18% greater than those for the slope class 11–30%. Forwarding costs in \$/m^3 as a function of forwarding distance are presented in Figure 11. For the slope class 0–10%, the estimated forwarding costs are about 85% of those for the slope class 11–30%.

Forwarding productivity and cost were very sensitive to forwarding distance. Doubling the forwarding distance resulted in a 50% reduction in productivity and a 100% increase in extraction cost per cubic metre.

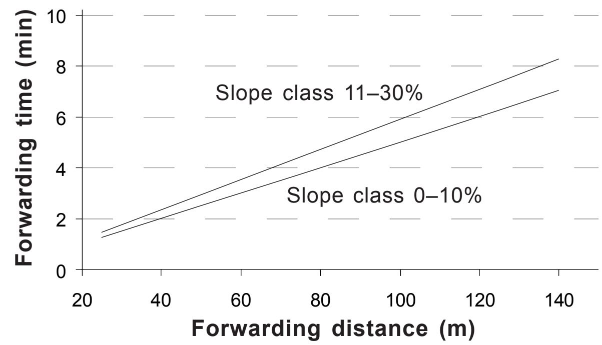


Figure 9. Predicted forwarding time for the Madill 3800 loader-forwarder as a function of forwarding distance.

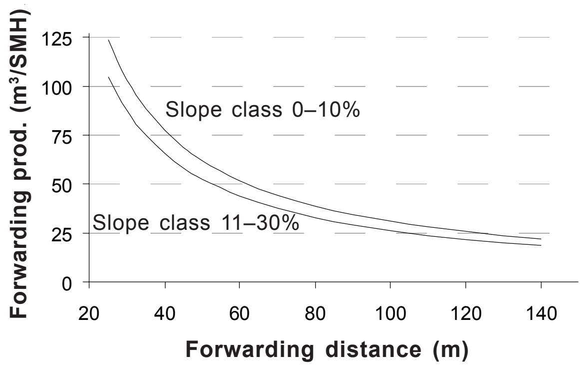


Figure 10. Predicted forwarding productivity for the Madill 3800 loader-forwarder as a function of forwarding distance.

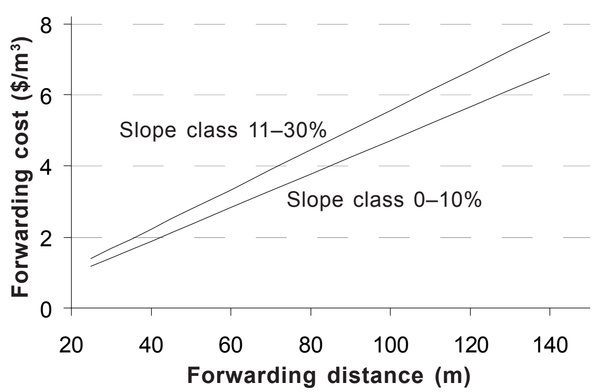


Figure 11. Predicted forwarding cost for the Madill 3800 loader-forwarder as a function of forwarding distance.

Grapple yarding

The detailed-timing results for the yarding operation are summarized in Table 7. The average yarding distances varied from about 100 m in Block B (uphill and downhill yarding combined), to 190 m in Block C where a considerable portion of the yarding that was detail-timed was done close to the backline of the block. Average numbers of stems per cycle were very different among the study blocks and had pronounced effects on payload volumes and, consequently, on yarding productivity. An overview of the percent distribution in number of stems per cycle is shown in Table 8.

When uphill yarding in mechanically felled Block B, one-stem payloads made up 34% of all payloads, and those consisting of four or more stems accounted for 28%. In this case, the average of 2.75 stems/cycle and volume of 0.95 m^3/stem produced an average payload of 2.61 m^3/cycle.

In manually felled Block D, 82% of all payloads consisted of a single load, and payloads of three, four, or more stems made

2 The reason for the shortest swing distance, of 14.1 m for the slope class 11–20%, is unknown.

Table 7. Summary of detailed timing for the Madill 144 swing yarder in Block B and for the Cypress 7280 swing yarder in Blocks C and D

	Block B uphill	Block B downhill	Block C uphill	Block D downhill
Productive machine hours (PMH)	24.7	8.2	11.4	12.3
Productive time (min)				
Yarding	1195	363	548	685
Move yarder and backspar	253	94	86	18
Delays <15 min	33	32	52	37
Total productive time	1481	489	686	740
Total cycles (no.)	740	286	336	548
Average cycle time (min)	2.00	1.72	2.04	1.35
Distribution of cycle time (min/cycle)				
Outhaul	0.29	0.28	0.45	0.36
Hookup	0.48	0.36	0.31	0.32
Inhaul	0.45	0.37	0.65	0.32
Deck	0.39	0.26	0.22	0.25
Move yarder	0.34	0.34	0.26	0.03
Delays	0.04	0.11	0.15	0.07
Total stems (no.)	2035	654	561	672
Average volume (m^3/stem)	0.95	0.95	1.01	0.44
Total volume (m^3)	1933	622	567	296
Average payload (stems/cycle)	2.75	2.29	1.67	1.23
Average payload volume (m^3/cycle)	2.61	2.18	1.69	0.54
Average yarding distance (m)	94	106	190	140
Productivity				
Stems/PMH	82	80	49	54
m^3/PMH	78	76	50	24

Table 8. Summary of payload sizes of the Madill 144 swing yarder in Block B and for the Cypress 7280 swing yarder in Blocks C and D

	Block B uphill	Block B downhill	Block C uphill	Block D downhill
No. of stems in cycle payload (% dist.)				
One	34	45	52	82
Two	21	23	33	14
Three	17	12	12	3
Four or more	28	20	3	1
Average stems per cycle (no.)	2.75	2.29	1.67	1.23
Average volume (m^3/stem)	0.95	0.95	1.01	0.44
Average volume (m^3/cycle)	2.61	2.18	1.69	0.54

up only 4% of all payloads. Low average number of stems (1.23 stems/cycle), combined with an average volume of 0.44 m^3/stem, resulted in extremely small payloads averaging 0.54 m^3/cycle.

In mechanically felled Block C, a small grapple with a maximum opening of 224 cm was used. This resulted in the relatively small number of stems per cycle (1.67) and low volume of 1.69 m^3/cycle. Additionally, the windrows prepared for yarding by the loader-forwarder were too tight to be penetrated by the grapple. As a result, 85% of all payloads consisted of one or two stems.

In Block B, the difference in number of stems per cycle for uphill and downhill yarding (2.75 and 2.29 stems/cycle, respectively) resulted because the sampling of downhill yarding included several cycles of manually felled stems.

In Block B, productivities for both yarding directions were similar and averaged about 76 m³/PMH. In Block C, yarding of payloads with an average volume of 1.69 m³/cycle resulted in a relatively small productivity of 50 m³/PMH. In Block D, the average cycle time of 1.35 min couldn't compensate for small payload volumes of 0.54 m³/cycle, and the recorded productivity was only 24 m³/PMH.

Cycle time, productivity, and cost of yarding

Regression analysis based on the detailed-timing data found a significant relationship between outhaul and inhaul times and yarding distances (Equations 1 to 8, Appendix II). These equations, combined with the average hookup, deck, move yarder, and delay times per cycle in Table 7, were used to derive yarding cycle times for the four study areas (Equations 9 to 12, Appendix II).

Figure 12 presents predicted yarding cycle times as functions of yarding distances. The differences in cycle times resulted mainly from differences in terminal times (hookup and unhook times). The almost parallel nature of regression lines for yarding cycle time in all studied areas indicates that the average outhaul and inhaul speeds were similar or even identical (as for Block C and downhill yarding in Block B where the lines coincided).

The shift-level and detailed-timing results were combined to estimate productivity during scheduled yarding time, using an assumed long-term utilization rate of 90% (Equation 13, Appendix II). As Figure 13 shows, for a given distance the four study areas showed substantial differences in yarding productivity. The highest productivities were achieved in Block B, and the difference between uphill and downhill yarding was negligibly small. The difference between productivities in Block C and in the downhill-yarded portion of Block B resulted from the 20% difference in payload volumes. For all yarding distances, productivities in Block C were 80% of those in the downhill-yarded portion of Block B. In Block D, short cycle times were not able to compensate for small cycle loads, and the yarding productivity was far below the productivities achieved in Blocks B and C.

Yarding costs in \$/m³ were computed using Equation 14 in Appendix II. For the four study areas and a common distance of 100 m, these costs ranged from \$4.54/m³ to \$12.67/m³ (Figure 14). Because the yarder costs in \$/SMH varied only slightly

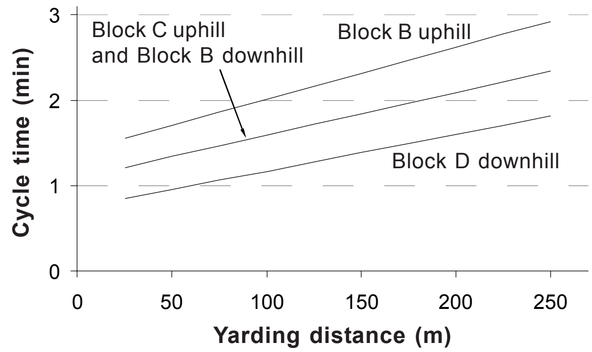


Figure 12. Predicted cycle times for grapple yarding in study blocks as a function of yarding distance.

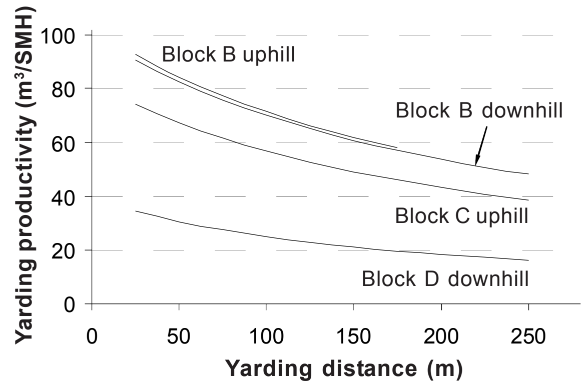


Figure 13. Predicted productivity for the Madill 144 swing yarder in Block B and Cypress 7280 swing yarder in Blocks C and D.

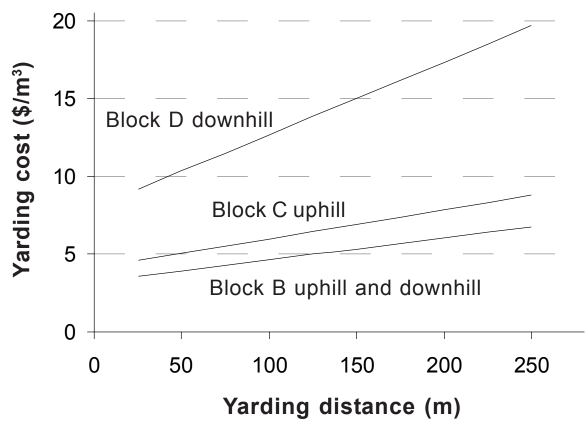


Figure 14. Predicted yarding costs for the Madill 144 swing yarder in Block B and Cypress 7280 swing yarder in Blocks C and D.

(Appendix I), the differences in costs in \$/m³ reflected the differences in yarding productivities in m³/SMH.

Effect of felling phase on grapple yarding performance

Yarding of manually and mechanically felled stems in Block B gave an opportunity to determine the effect of the felling system on swing yarder performance (Table 9). For each felling mode, the differences between averages for hookup, deck, and cycle times were very small and statistically not significant. However, the average payload sizes in numbers of stems per cycle differed significantly. Payloads of stems felled and bunched by the feller-buncher averaged 2.45 stems/cycle and were about 43% greater than the cycle payloads of hand-felled stems. Since the hand-felling in Block B was necessary because of terrain (the slope gradient exceeded the capabilities of the feller-buncher) and not because of tree size, it was assumed that the volumes of hand- and mechanically felled stems did not differ significantly and averaged 0.95 m^3/stem. Based on this assumption, the average payload volumes for yarding of hand- and mechanically felled stems were 1.62 and 2.33 m^3/cycle, respectively. Yarding productivities and costs for hand- and mechanical felling, using an assumed utilization rate of 90%, are shown in Figures 15 and 16. For all distances, yarding of mechanically felled stems was about 38% more productive than for hand-felled stems, and yarding costs were about 28% less.

Table 9. Summary of detailed timing for downhill yarding of hand-felled and mechanically felled stems in Block B

	Hand-felled stems	Mechanically felled stems	Hand- and mechanically felled stems
Productive time (min)	114	376	489
Productive machine hours (PMH)	1.9	6.3	8.2
Total cycles	66	220	286
Average cycle time (min)	1.73 [a]	1.72 [a]	1.72
Distribution of cycle time (min)			
Outhaul [b]	0.32	0.26	0.28
Hookup	0.32 [a]	0.38 [a]	0.36
Inhaul [b]	0.39	0.36	0.37
Deck	0.25 [a]	0.27 [a]	0.26
Move yarder and backspar [c]	0.34	0.34	0.34
Delays [c]	0.11	0.11	0.11
Load (stems/cycle)	1.71 [d]	2.45 [d]	2.29
Volume (m^3/stem)	0.95	0.95	0.95
Volume (m^3/cycle)	1.62	2.33	2.18
Average yarding distance (m)	126	100	106
Productivity			
Stems/PMH	59	85	80
m^3/PMH	56	81	76

[a] The difference between average element times for hand and mechanical felling is not significant at $\alpha = 0.05$.

[b] Outhaul and inhaul times for both methods of felling are given by Equations 3 and 4 in Appendix II, respectively.

[c] Calculated as an average from the total element time and number of downhill yarding cycles.

[d] The difference between average numbers of stems per cycle for hand and mechanical felling is significant at $\alpha = 0.005$.

Loader-forwarder vs. grapple yarding

Figure 17 compares predicted extraction costs in $/m³ in Block B for the Madill 3800 loader-forwarder and the Madill 144 swing yarder. The line for the loader-forwarder represents extraction costs for the slope class 11–30%. Extraction costs for the Madill 144 are plotted for both yarding directions. For short extraction distances, up to about 75 m, loader-forwarding is a cost-effective solution. For distances longer than 75 m, grapple yarding has lower extraction costs.

The location of the coordinates of the intersection is moderately sensitive to changes in hourly machine costs and productivity of the loader-forwarder. For example, a decrease of the Madill 3800's extraction productivity by 20% would move the intersection point of the cost lines for the loader-forwarder and swing yarder from 75 m to 60 m (i.e., grapple yarding would become less costly than loader-forwarding at 60 m than at 75 m).

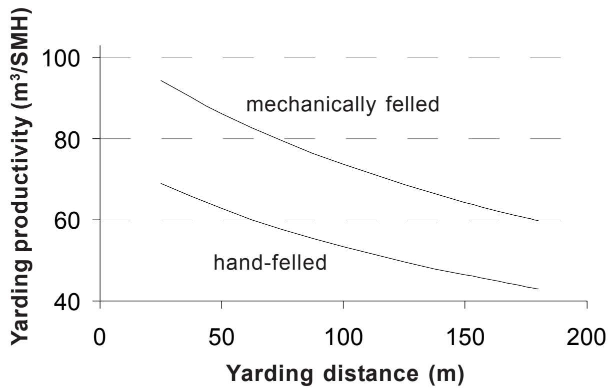


Figure 15. Predicted yarding productivities for hand- and mechanically felled stems in Block B.

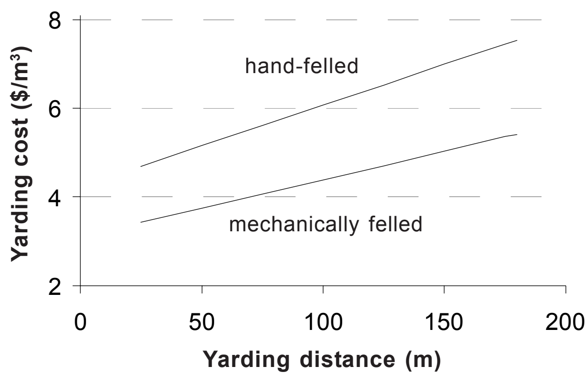


Figure 16. Predicted yarding costs for hand- and mechanically felled stems in Block B.

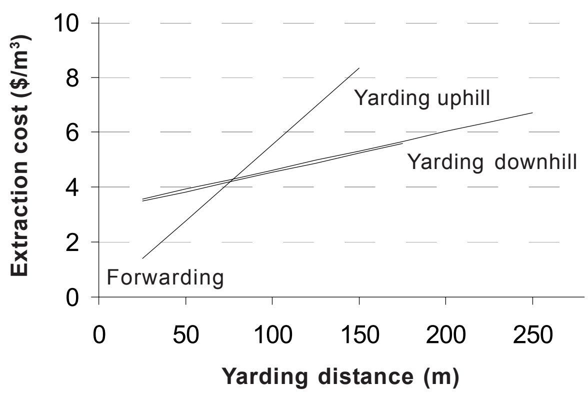


Figure 17. Predicted extraction costs for the Madill 3800 loader-forwarder and the Madill 144 swing yarder in Block B.

Loader-forwarding and grapple yarding combination compared to a single extraction mode only

The potential use of a loader-forwarder and a swing yarder in the same block requires the operation planner to make a decision on extraction modes and, if both machines are chosen, the distribution of the block area extracted by each method. Consequently, these decisions will determine the block volume extracted by the loader-forwarder and yarder. Because the two machines have different hourly machine costs and productivities, the distribution of the block volume will affect the total extraction costs.

To examine this effect, a theoretical analysis was made, based on results of loader-forwarding and grapple yarding in Block B. Additional block characteristics assumed in this analysis are shown in Table 10.

The results of the cost analysis are shown in Figure 18. The bar diagram shows the cost components and total costs of yarding and forwarding by yarding distance. If the planner decided to use only a swing yarder to extract the total volume of 8 250 m³, the maximum yarding distance would be 200 m, and the extraction costs would include the yarder mobilization cost estimated at $786, the direct yarding cost calculated at $37 923, and the road change cost calculated at $3 792. The total cost of $42 501 for this variant is represented in Figure 18 by the bar for the yarding distance of 200 m.

If the planner preferred to use a loader-forwarder only, the extraction costs would include the loader mobilization cost of $300 and the direct forwarding cost of $45 833. The total forwarding cost of $46 133 is represented in Figure 18 by the bar for the yarding distance of 0 m. This cost is about 9% greater than the yarding costs in the previous variant.

If the planner decided to forward the 60-m area adjacent to the road, the yarding will occur over 140 m (from 60 m from the road to the backline of the block at 200 m). For this option, 30% of the block volume would be forwarded, and the remaining 70% would be yarded. Extraction costs, represented by the bar for the yarding distance of 140 m, would be $37 976, which is less than the extraction costs for the yarder-only or the loader-forwarder-only option.

Figure 18 demonstrates that the minimum extraction cost would be achieved when a 75-m-wide strip adjacent to the road is loader-forwarded and the remaining portion

Table 10. Assumed characteristics of Block B for theoretical extraction cost analysis

Description	Total
Harvested area (ha)	15
Extracted volume (m^3)	8 250
Harvested volume (m^3/ha)	550
Road length (m)	725
Extraction distance (m)	200
Estimated mobilization cost ($) [a]	
Loader-forwarder	300
Swing yarder	786
Worksite or yarding road change cost ($)	
Loader-forwarder	negligible
Swing yarder	3 792

[a] Gord Vaughan, Coastal Pacific Logging Consultants Ltd., Parkville, B.C., personal communication, July 2003.

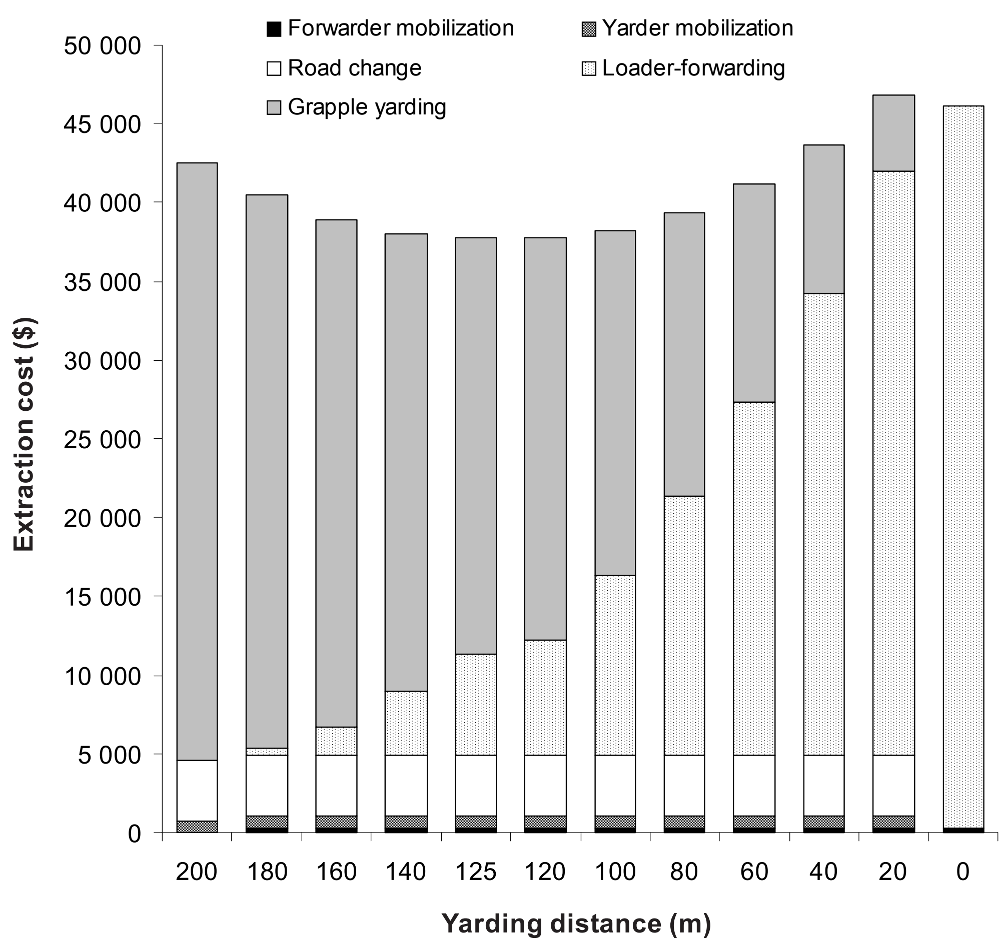


Figure 18. Total extraction costs as a function of yarding distance. Forwarding distance may be calculated as the difference of the block width of 200 m and selected yarding distance (e.g., for a yarding distance of 160 m, the forwarding distance is 40 m).

of the block is grapple yarded.[3] For this option, the total cost of $37 734, represented by the bar for the yarding distance of 125 m, is 11% less than for the yarding-only option, and 18% less than for the loader-forwarder-only option.

Optimum road spacing

The impact of road spacing on extraction, road construction, and total costs in $/m³ is shown in Figure 19 (loader-forwarding) and Figure 20 (grapple yarding). In these graphs, forwarding and yarding cost trendlines in $/m³ are based on study results in Block B, and the road construction cost curves in $/m³ are plotted for a construction cost of $52 000/km and an average volume of 550 m³/ha. The total-cost curve for downhill loader-forwarding shows that its minimum is achieved for a road spacing of 180 m. For uphill grapple yarding, the optimum road spacing is 370 m. However, because the curves are very flat, even relatively large deviations from the optimum spacing result in small changes to the total costs (e.g., for grapple yarding, reducing road spacing from 370 to 250 m would result in a 5% increase in total costs). This low sensitivity of the total costs gives a harvesting planner considerable flexibility in block layout and road location.

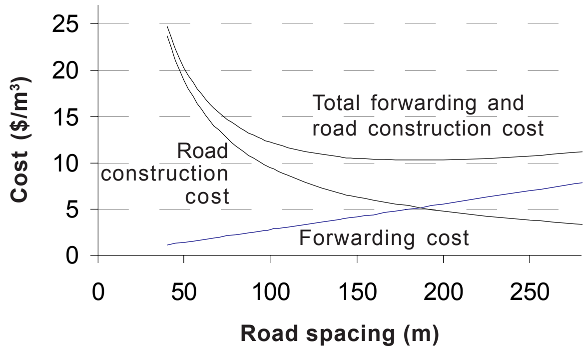


Figure 19. Downhill loader-forwarding cost, road construction cost, and their sum as functions of road spacing.

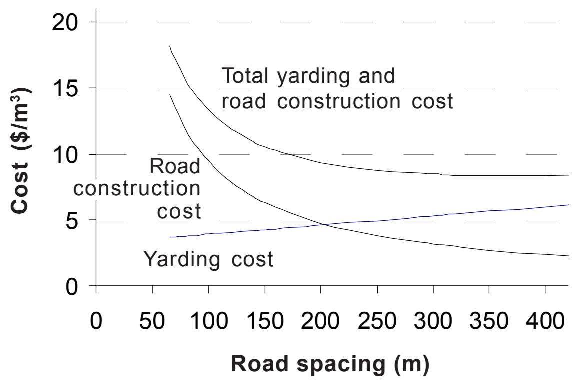


Figure 20. Uphill grapple yarding cost, road construction cost, and their sum as functions of road spacing.

Conclusions

The study results indicate that a loader-forwarder and swing yarder, used in the same block, can complement each other very well. The swing yarder's fast outhaul and inhaul, lack of slope limitations, and ability to extract large-volume payloads make it very efficient for long-distance extraction on moderate to very steep slopes with adequate deflection and with few obstacles. Because of its low speed, the loader-forwarder is better suited for short extraction distances. If slope permits, it may be best employed to forward stems from strips adjacent to the roads and from areas inaccessible to grapple yarding (e.g., small confined pockets, areas with poor deflection, or areas with heavy accumulation of obstacles).

For the terrain and stand conditions observed in this study and an average extraction distance of 60 m, the Madill 3800's overall productivity was 43.5 m³/SMH at a cost of $3.36/m³. For downhill extraction, loader-forwarding productivity for the slope class 0–10% was 18% greater than for the slope class 11–30%. Forwarding productivity and cost are very sensitive to forwarding distance. Doubling the forwarding distance resulted in a 50% decrease in productivity and a 100% increase in extraction costs per cubic metre.

For the three study blocks, grapple yarding productivities and costs were very different and strongly affected by the felling mode (manual or mechanical), number of stems in the payload, and average volume per stem. The greatest productivity and lowest cost (78.8 m³/PMH and $4.56/m³) were attributed to good preparation of bunches for yarding (mechanical felling with a feller-

[3] Changes to the maximum extraction distance and to the mobilization and road change costs affect the total extraction costs, but the minimum total costs would still be achieved when the width of the forwarded strip is 75 m.

buncher), multiple-stem loads, and high average volume per stem. The lowest yarding productivity and highest cost (22.1 m^3/PMH and \$16.28/m^3) resulted from manual felling (dispersed stems), single-stem loads, and small average volume per stem.

The results of the study on loader-forwarding and grapple yarding in similar terrain and stand conditions showed that the extraction costs can be minimized by careful assignment of extraction modes to the block area. For the terrain and stand conditions observed in this study, the minimum extractions costs are achieved if a 75-m-wide strip of felled timber adjacent to the road is loader-forwarded, and the rest of the harvest area is grapple yarded.

Implementation

During the observed harvesting operation, FERIC identified conditions for successful and effective use of the Madill 144 and Cypress 7280 swing yarders and the Madill 3800 loader-forwarder to harvest second-growth forests on steep slopes:

- Productive and cost-efficient extraction with loader-forwarders and swing yarders requires careful layout of the block, detailed planning of all harvesting phases, and careful assignment of the extraction modes to the block area.
- Low sensitivity of the total extraction and road construction costs in \$/m^3 to road spacing gives harvest planners a high degree of freedom in laying out blocks and designing road systems. Reasonable deviations from the optimum road spacing, dictated by terrain or stand features, should not unduly increase the combined extraction and road construction costs.
- If the terrain and stand conditions permit, using feller-bunchers is recommended, particularly in areas with low stand and stem volumes. Bunches that are properly oriented, aligned, and sized will improve cycle load volumes, productivities, and costs of both extraction systems.
- If the block (or a portion of it) is suitable for forwarding as well as for yarding, assign the 75-m-wide strips adjacent to the roads to a loader-forwarder, and the remaining areas to swing yarders. This will minimize total extraction costs.
- Grapple yarding in conjunction with hot processing is operationally feasible. However, because of unavoidable interactions between the yarder and processor and the subsequent loss in productivity, hot processing should be used only when absolutely necessary (e.g., limited decking area for yarded logs and safety requirements).

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Appendix I

Machine costs[a] ($/scheduled machine hour (SMH))

	Madill 3800 loader-forwarder	Madill 144 swing yarder	Hitachi backspar	Cypress 7280 swing yarder	John Deere backspar
OWNERSHIP COSTS					
Total purchase price (P) $	550 000	1 000 000	150 000	1 300 000	85 000
Expected life (Y) y	8	12	5	12	5
Expected life (H) h	16 000	24 360	10 150	23 027	10 000
Scheduled hours per year (h)=(H/Y) h	2 000	2 030	2 030	1 919	2 000
Salvage value as % of P (s) %	30	30	20	30	20
Interest rate (Int) %	5	5	5	5	5
Insurance rate (Ins) %	2	2	2	2	2
Salvage value (S)=(s•P/100) $	165 000	300 000	30 000	390 000	17 000
Average investment (AVI)=((P+s)/2) $	357 500	650 000	90 000	845 000	51 000
Loss in resale value ((P-S)/H) $/h	24.06	28.74	11.82	39.52	6.80
Interest=((Int•AVI)/h) $/h	8.94	16.01	2.22	22.02	1.27
Insurance=((Ins•AVI)/h) $/h	3.58	6.40	0.89	8.81	0.51
Total ownership costs (OW) $/h	36.58	51.15	14.93	70.35	8.58
OPERATING COSTS					
Wire rope (wc) $	-	24 084	-	21 078	-
Wire rope life (wh) h	-	950	-	950	-
Rigging & radio (rc) $	-	14 000	-	14 000	-
Rigging & radio life (rh) h	-	5 700	-	5 700	-
Fuel consumption (F) L/h	40	55	5	55	5
Fuel (fc) $/L	0.75	0.75	0.75	0.75	0.75
Lube and oil as % of fuel cost (fp) %	10	10	10	10	10
Track & undercarriage replacement (Tc) $	30 000	60 000	30 000	60 000	0 [b]
Track & undercarriage life (Th) h	20 000	8 000	20 000	8 000	-
Annual operating supplies (Oc) $	2 000	10 000	500	10 000	500
Annual repair and maintenance (Rp) $	82 000	100 000	18 000	110 000	13 000
Shift length (sl) h	8.5	9.0	-	8.5	-
Wages $/h					
Operator	23.80	26.80	-	26.80	-
Labourer No. 1	-	26.10	-	26.10	-
Labourer No. 2	-	22.97	-	22.97	-
Total wages (W) $/h	23.80	75.87	-	75.87	-
Wage benefit loading (WBL) %	35	35	-	35	-
Wire rope (wc/wh) $/h	0.00	25.35	-	22.19	-
Rigging & radio (rc/rh) $/h	0.00	2.46	-	2.46	-
Fuel (F•fc) $/h	30.00	41.25	3.75	41.25	3.75
Lube and oil ((fp/100)•(F•fc)) $/h	3.00	4.13	0.38	4.13	0.38
Track & undercarriage (Tc/Th) $/h	1.50	7.50	1.50	7.50	-
Operating supplies (Oc/h) $/h	1.00	4.93	0.25	5.21	0.25
Repair and maintenance cost ((Rp/h) $/h	41.00	49.26	8.87	57.32	6.50
Wages and benefits (W•(1+WBL/100)) $/h	32.13	102.42	-	102.42	-
Prorated overtime ((1.5•W-W)•(sl-8)•(1+WBL/100))/sl) $/h	0.95	5.69	-	3.01	-
Total operating costs (OP) $/h	109.58	242.98	14.74	245.49	10.88
TOTAL OWNERSHIP AND OPERATING COSTS (OW+OP) $/h	146.15	294.13	29.66	315.84	19.46

[a] The costs used in the study are not the actual costs incurred by the company, and do not include indirect costs such as crew and machine transportation, overhead, profit, and risk.

[b] No track and undercarriage replacement planned.

Appendix II

Regression, productivity, and cost equations for grapple yarding

Linear equations for outhaul and inhaul

Equation 1: Outhaul, Block B, uphill yarding

$OUT = 0.09 + 0.0020(YD)$ $n = 717$ $r^2 = 0.563$ $S.E.E. = 0.080$

Equation 2: Inhaul, Block B, uphill yarding

$IN = 0.06 + 0.0041(YD)$ $n = 720$ $r^2 = 0.627$ $S.E.E. = 0.157$

Equation 3: Outhaul, Block B, downhill yarding

$OUT = 0.06 + 0.0021(YD)$ $n = 285$ $r^2 = 0.549$ $S.E.E. = 0.076$

Equation 4: Inhaul, Block B, downhill yarding

$IN = 0.06 + 0.0028(YD)$ $n = 285$ $r^2 = 0.473$ $S.E.E. = 0.124$

Equation 5: Outhaul, Block C, uphill yarding

$OUT = 0.14 + 0.0016(YD)$ $n = 318$ $r^2 = 0.412$ $S.E.E. = 0.101$

Equation 6: Inhaul, Block C, uphill yarding

$IN = -0.02 + 0.0034(YD)$ $n = 321$ $r^2 = 0.546$ $S.E.E. = 0.163$

Equation 7: Outhaul, Block D, downhill yarding

$OUT = 0.05 + 0.0022(YD)$ $n = 493$ $r^2 = 0.627$ $S.E.E. = 0.095$

Equation 8: Inhaul, Block D, downhill yarding

$IN = 0.02 + 0.0021(YD)$ $n = 505$ $r^2 = 0.623$ $S.E.E. = 0.088$

Where

OUT = outhaul time (min)
IN = inhaul time (min)
YD = yarding distance (m)
n = number of observations
r^2 = coefficient of determination
S.E.E. = standard error of estimate

Cycle time equations

Equation 9: Block B, uphill yarding

$$CT = 1.41 + 0.0061(YD)$$

Equation 10: Block B, downhill yarding

$$CT = 1.10 + 0.0049(YD)$$

Equation 11: Block C

$$CT = 1.09 + 0.0050(YD)$$

Equation 12: Block D

$$CT = 0.74 + 0.0043(YD)$$

Where:

CT = cycle time (min)
YD = yarding distance (m)

Productivity and cost equations

Equation 13: $\text{Productivity} = \dfrac{60(CV)(U)}{CT}$

Equation 14: $\text{Cost} = \dfrac{HC}{\text{Productivity}}$

Where:

HC = hourly cost ($/SMH)