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Harvesting Productivity and Cost of Clearcut and Partial Cut in Interior British Columbia, Canada

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ABSTRACT : Clearcutting has been the dominant harvesting method in British Columbia (representing 95% of the total area harvested annually). However forest managers are increasingly recommending the use of alternative silvicultural systems and harvest methods, including various types of partial cutting, to meet ecological and social objectives. In this study we compared harvesting productivity and harvesting costs between treatments through detailed and shift level time studies in 300-350 year-old Interior Cedar-Hemlock stands in British Columbia, Canada. Recommendations for improving operational planning/layout and the implementation of clearcut and partial cutting silvicultural systems were made. Harvesting costs varied in the ground-based clearcut treatments from $10.95/m^3$ - $15.96/m^3$ and $16.09/m^3$ - $16.93/m^3$ in the group selection treatments. The ground-based group retention treatment had a cost of $13.39/m^3$, while the cable clearcut had a cost of $15.70/m^3$. An understanding of the traditional and alternative wood products that could be derived from the harvested timber was imperative to increasing the amount of merchantable volume and reducing the corresponding harvesting costs. Stand damage was greatest in the group selection treatments; however, mechanized felling showed an increase in stand damage over manual felling while grapple skidding showed a decrease in skidding damage compared to line skidding.

Keywords : Alternative harvesting, Clearcutting, Partial cutting, Western red cedar, Stand damage

INTRODUCTION

Forest management in British Columbia (BC) is rapidly changing due to increasing emphasis on ecological and social goals that include the management of non-timber resources such as visual quality and wildlife habitat (Weetman, 1996; Arnott and Beese, 1997; Kohm and Franklin, 1997; Jull et al., 1997). The use of alternative silvicultural systems, including partial cutting, are being increasingly considered for achieving these management goals. Since clearcutting has been a dominant harvesting method in BC, knowledge and experience with partial cutting is limited for many of BC's forest ecosystems. Also, it has been traditionally viewed that the low market value of the Interior Cedar-Hemlock (ICH) stands make it more difficult to practice partial cut silvicultural systems in these stands (Sinclair, 1984). Partial cutting generally is considered to be more expensive than clearcutting (Daigle, 1995).

For example, Thibodeau et al. (1996) compared logging productivity and costs of partial cut and clearcut treatments in a second growth ICH stand with an age of 130 years and moderately gentle terrain in north western BC, and found that the cost of a ground-based partial cut harvesting system was 1.98 times higher than that of a ground-based harvested clearcut. Two studies in old growth ICH stands near Revelstoke, BC, found that harvesting costs to be 1.1 to 1.4 times higher than that of a clearcut (Walters, 1997a; Walters, 2001). A cable skyline system partial cut in a cedar dominant stand in east central BC, costs 3.77 times higher than a conventional ground-based clearcut (Pavel, 1999).

Layout costs for the partial cut were 1.9 to 4 times that of clearcut units due to more intensive timber cruising,

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layout and marking of internal patch cut boundaries, increased tree marking, and designated skid trail networks (BCMOF, 1996; Thibodeau et al., 1996; Walters, 1996; Walters, 1997a; Walters, 2001). This is similar to other interior forest types in Canada and the United States where partial cut layout costs ranged from 2.4 to 6.3 times that of clearcut units (Kellogg et al., 1991; Kellogg et al., 1996; Dunham, 2001 and 2004; Sambo, 2003)

Tree marking in partial cuts allows fellers to be free from selecting trees to be felled, thus increasing their productivity (Bennett, 1997). Tree marking must take into consideration the safety of the feller through individual tree characteristics (i.e. lean, and distribution of branches), and the characteristics of adjacent trees (Moore, 1991). When hand felling, stumps should be close to ground level to minimize hang-ups (Pavel, 1999). The primary consideration of the feller is safety (Moore, 1991). In decadent western red cedar, felling is dangerous and difficult due to a lack of holding wood and a result of both branches and tops being prone to breakage during falling.

Advantages of mechanized felling compared to manual felling include better worker safety, better control of stems to reduce breakage and residual tree damage and improved skidding efficiency through tree bunching (Kluender and Stokes, 1994; Thibodeau et al., 1996; Parker, 2002). In addition, felling by mechanical means in both partial and clearcut harvesting in the ICH in east central BC resulted in cost savings from 40 to 50% compared to manual felling (Thibodeau et al., 1996) even with increased ownership and operating costs.

The orientation of openings and extraction network should be designed and oriented to facilitate enhanced felling and skidding productivity. Patch openings should be designed to “funnel” trees in the direction of the skid trail. This funnelling can result in improved skidding / yarding and felling productivity while reducing residual stand damage (Bennett, 1993; Thibodeau et al., 1996; Kosicki, 2000a).

Skidding productivity is affected by weather, skidding distance and slope (Mitchell 2000). Tree size and felling method may also dictate skidding equipment and methods. Mechanical felling allows for the bunching of logs, making the use of grapple skidders economically viable. When bunching is not possible, logs may be more efficiently removed by a line skidder (Kluender and Stokes, 1994; Thibodeau et al., 1996). The use of line skidders may be economical in a small scale operation at a lower production rate as a lower capital investment is required compared to grapple skidders (Kluender and Stokes, 1994). In addition, the use of line skidders promotes manual felling, also reducing overall capital investment. The skidding cost per cubic meter, when using a line skidder, a 60% removal treatment is 1.85 times higher in cost than a conventional clearcut as a result of longer skid distances and less volume delivered to the landing per turn (Thibodeau et al., 1996).

Cable partial cutting costs ranged from 1.31 to 1.46 times more expensive than cable clearcut units because residual trees in a partial cut increased time and cost for road changes (Bennett, 1997; Riggs et al., 1996). Differences in tree size, species composition and terrain characteristics between the Coastal Western Hemlock (CWH) and ICH biogeoclimatic zones render these results to be inaccurate for the interior of BC. A study in the interior of BC on a cedar dominant stand stated that partial cutting was operationally feasible but failed to provide any economic benefits (Walters, 1997b). Second growth partial cutting in the ICH had yarding cost of $14.56/m^3 while an old growth stand had a yarding cost of $12.11/m^3 (Pavel, 1999; Dunham and Gillies, 2000). No published results exist for clearcut yarding in the ICH.

Effective use of the loader is essential to ensure that the landing is clear and safe and that trucks are loaded with a minimum delay (Pavel, 1999). The loading cost per cubic meter in partial cuts ranges from 1.31 to 1.46 times greater than in clearcut units as a result of increased non-productive time in the partial cut units (Bennett, 1997).

The majority of residual stand damage is located along skid trails where the most harvesting activity occurs (Pavel, 1999; Bennett, 1997). In ground-based partial cuts, the orientation of harvest units and directional felling play an important role in reducing stand damage (Thibodeau et al., 1996).

The overall goal of this study was to determine the production rates, costs, and residual stand damage of partial harvesting systems in ICH stands. Improved knowledge regarding the costs of implementing alternative silvicultural methods is imperative for forest managers to meet non-timber values of the area while meeting the demand for cedar products. The specific objectives are:

1. to determine planning/layout cost for partial cut and clearcut units,
2. to compare production rates (m^3/hr) and cost (\$/m^3) for various silvicultural prescriptions using ground-based and cable harvesting systems,
3. to develop harvest production prediction models based on appropriate independent variables, and
4. to quantify residual stand damage for the different partial cutting prescription units.

Study Methods

The research was conducted on two sites in the Interior Cedar- Hemlock biogeoclimatic zone (Ketcheson et al., 1991), 32 and 35 km west of McBride, British Columbia, Canada. The sites were dominated by western red cedar (*Thuja plicata*) with minor components of Engelmann spruce (*Picea engelmanii*), western hemlock (*Tsuga heterophylla*), and subalpine fir (*Abies lasiocarpa*) (Table s1 and 2). The stands within the study area had an average age of 300-350 years and high incidence of defect; scaling data indicated combined decay, waste, and breakage total ranging from 51 to 68%.

At the East Twin site there were three treatments: a group selection (70% retention) and two clearcut units (0% retention) (Fig. 1). At the Minnow site there were three treatments: a group selection (70% retention), a group retention (30% retention) and a clearcut (0% retention) unit (Fig. 2). In the group selection treatments the primary goal of the layout crew was to design a skid trail system that would allow for multiple entries while maintaining visual quality.

The East Twin site was harvested by two contractors; Contractor A harvested the ground-based treatment units (70% retention and 0% retention) using a ground-based harvesting system consisting of hand felling, skidding with rubber-tired and tracked line skidders, manual delimbing/

Table 1. East Twin study site and stand description

Silvicultural treatment	Group selection ground-based	Clearcut - ground-based	Clearcut - cable
Elevation Range (m)	900-1050	900-1050	900-1050
Aspect	NW	NW	NW
Treatment size (ha)	8.7	1.1	6.7
Harvested area (ha)	2.1	1.1	6.7
Previously harvested area (ha)	0	0	0
Slope (avg.)	0-50% (20%)	0-30% (15%)	30-130% (55%)
Species (%)[a]			
Western red cedar	86.6	79.1	90.3
Subalpine fir	3.4	9.3	2.8
Engelmann spruce	10.0	5.6	2.2
Western hemlock	0.0	6.0	4.8
Stems/ha[a]	404.7	424.3	424.3
Avg. DBH (cm)[a]	56.2	53.2	53.2
Avg. ht (m)[a]	36.7	33.5	33.5
Gross vol. (m^3/ha)[a]	1074.6	908.0	908.0
Net merchantable vol (m^3/ha)[b]	349.0	441.6	433.0

[a] Provided by the BC Ministry of Forestry Cruise report.
[b] Net merchantable volume per tree was calculated from the provided merchantable volumes from the BC Ministry of Forestry

Table 2. Minnow study site and stand description

Silvicultural treatment	Group selection	Group retention	Clearcut
Elevation Range (m)	1050-1200	1050-1200	1050-1200
Aspect	SW	SW	SW
Treatment size (ha)	11.2	10.7	7.4
Previously harvested area (ha)	0.2	1.5	0.0
Harvested area (ha)	3.6	6.1	7.4
Slope (avg.)	0-50% (30%)	0-30% (15%)	0-40 (30%)
Species (%)[a]			
Western red cedar	60.4	46.5	75.0
Subalpine fir	19.4	27.3	11.4
Engelmann spruce	18.3	24.6	13.0
Western hemlock	1.9	1.6	0.3
Stems/ha[a]	349	288	394
Average DBH (cm)[a]	44.7	47.1	48.2
Average height (m)[a]	25.4	26.0	25.9
Gross vol. (m^3/ha)[a]	819.8	659.4	1122.1
Net merchantable vol (m^3/ha)[b]	367.6	308.8	359.2

[a] Provided by the BC Ministry of Forestry Cruise report.
[b] Net merchantable volume per tree was calculated from the provided merchantable volumes from the BC Ministry of Forestry

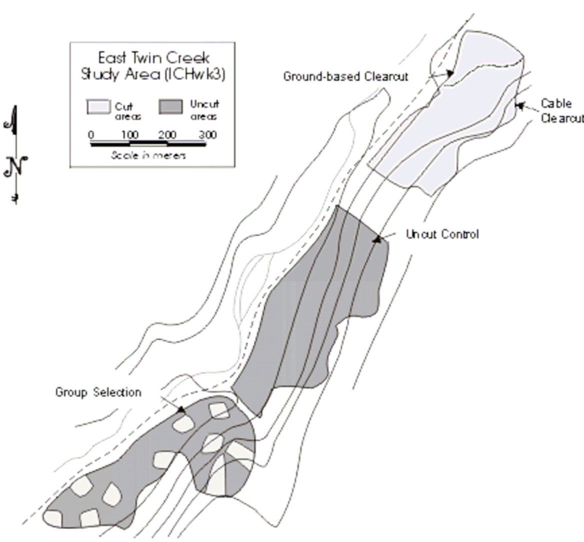

Fig. 1. East Twin study site map.

bucking, and loading with a front end wheel loader. Contractor B harvested the cable unit (100% removal) using an adapted running skyline system with a non-slackpulling carriage consisting of hand felling, yarding with a tower yarder, manual delimbing/bucking, and loading with a heel boom log loader. Contractor A and B had separate fellers with similar amount of felling experience (20 years). During

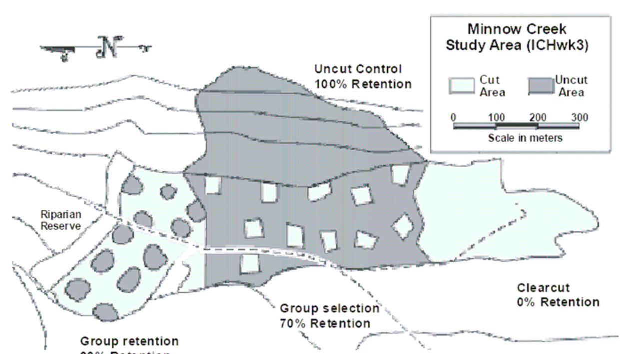

Fig. 2. Minnow study site map.

felling, snow was present (<20 cm) on the site, but shovelling was not required for the majority of trees.

The Minnow site was harvested by Contractor C. Contractor C harvested all three ground based treatment units (70% retention 30% retention, and 0% retention) using a semi-mechanized ground-based harvesting system consisting of mechanized felling, minor hand felling, skidding with rubber-tired grapple skidders, manual delimbing/bucking, and loading with a front end wheel loader. Snow did not present a challenge for mechanized or manual felling (<20 cm).

A field-based, observational study was conducted to evaluate the effect of various silvicultural prescriptions on harvesting productivity and cost in the ICH stands. Replication and modification of treatments and harvesting systems was not possible due to time and cost constraints. Comparison of costs among alternative logging systems requires accurate production data. The collection of this data was difficult due to the variations in the logging environment (Olsen and Kellogg, 1983). The methods used for timing included shift level studies, detailed time studies, and activity sampling on landing areas. To successfully calculate the productive and non-productive time, detailed time studies were conducted, using a hand held data logger. This data was then used to determine the cycle element durations, and calculate interactions between equipment, personnel, and harvesting attributes. In activity sampling, sampling intervals were set at 20 seconds to ensure the accuracy of the data as recommended by Olsen and Kellogg (1983).

Planning and layout costs were calculated by dividing the total cost of planning and layout by the total volume removed for each treatment. The cost per unit volume were determined for each treatment and site using volume data obtained from the BC Ministry of Forests (BC MOF) along with person hours and corresponding hourly costs provided by consultants.

Harvesting costs were calculated using the Forest Engineering Research Institute of Canada's (FERIC) standard costing methods and were based on local standard contractor rates for workers. A multiple regression analysis was completed for felling and primary transportation elements of the harvesting operation. To understand better the influence of tree size and skidding distance on harvesting cost, standardized values of tree size and skidding distance were used to compare costs for planning and layout, skidding, processing, and loading between silvicultural treatments. To determine the utilization of the western red cedar, harvested from this site, three mills were asked to provide a list of their products.

While sampling stand damage at the East Twin site, it was noted that all stand damage occurred within 5 meters of a skid trail or opening. As a result, the sampling method was changed to a systematic 25-meter wide strip along the edge of these features into the remaining standing timber for the Minnow Creek site. Residual stems were calculated by subtracting the number of harvested trees in each treatment from density information provided in the cruise data.

RESULTS AND DISCUSSION

Planning and layout

As expected the lowest planning and layout costs were observed in the ground-based clearcuts, followed by the cable clearcut, group retention treatment, and finally group selection treatments (Table 3). The need for deflection line in the cable treatment made it more expensive than a ground-based clearcut. In the group retention, higher layout costs than a ground-based clearcut was due to the need to mark the leave tree patches and cruise requirements. The layout in the group selection treatments was the most expensive in both locations due to the need to designate and mark patches, skid trail locations and greater unit perimeters than in the other treatments. In hindsight, only the outer edge of selection or retention patches could

Table 3. Planning and layout costs

Location	East Twin			Minnow		
Harvesting system	Ground-based		Cable	Ground-based		
Silvicultural treatment	Group selection	Clearcut	Clearcut	Group selection	Group retention	Clearcut
Total cost ($)	1923.75	245.31	2045.74	2285.00	2178.22	1201.31
Final volume (m^3)	733.00	458.80	2987.90	1323.26	1883.62	2657.78
Layout / planning cost ($\$/m^3$)	2.62	0.53	0.68	1.73	1.16	0.45

have been marked, reducing the layout costs.

During harvesting it was found that one of the fellers was colour blind. Marking colours should be “colour blind” friendly as roughly 10% of the male population is color blind (Neitz et al., 1989), this will ensure appropriate trees are retained or removed. Colours such as red and greens should be avoided. The layout costs were lower for the group selection treatment in Minnow over that of East Twin. This may be attributed to the increased experience of the crew, having implemented the layout after observing the harvesting of East Twin.

A sensitivity analysis showed that tree size expressed as merchantable volume has a large effect on planning and layout costs. Planning and layout costs in the group selection at East Twin would have been 1.6 times higher if the merchantable volume per tree was the same as in the clearcut at Minnow.

Harvesting operations

Felling

In all treatments the cedar was generally manually felled in a downhill direction as the trees were leaning and weighted by branches to fall in that direction. Trees were generally mechanically felled uphill. Breakage occurred in less than 2.0% of the felled timber. In the partial cut, trees were felled towards skid trails unless tree conditions safety or felling constraints made this impossible.

In all but one case, the Minnow group retention treatment, manual felling resulted in the lowest cost ($/m^3) as result of high hourly production (Table 4). While mechanized felling was utilized at Minnow, manual felling was utilized to fell trees on steeper slopes (>35%), due to limited traction, and for large solid spruce trees, as multiple cuts and pushing would have resulted in unnecessary stump pull and butt shatter. As manual felling was utilized top fell a proportion of each unit, weighted mechanized and manual felling costs were calculated to determine the contribution of the each felling method to the total felling cost.

As such, observed manual felling costs in Minnow were higher than those in East Twin due to the spread-out locations of the trees to be felled; this was especially the case for the Minnow group retention treatment. While mechanized felling costs were slightly greater, safety was improved. In addition, mechanized felling resulted in increased skidding productivity (Table 5).

At East Twin, felling production in the cable clearcut was the highest as a result of the fastest cycle time of 1.97 min./tree. The group selection cycle time (3.13 min./tree) was faster than that of the ground-based clearcut (3.58 min./tree). However, the higher volume per tree, 1.54 m^3/tree for the ground-based portion of the clearcut versus 1.22 m^3/tree for the group selection treatment, resulted in a larger volume harvested in the ground-based clearcut per cycle. A study in south east BC that had a tree size of 0.93 m^3/tree had similar manual felling costs ranging from $2.11/m^3 to $2.28/m^3 (Kockx and Krag, 1993). These results indicate that total cycle time, tree size, and decay percentage can have a significant effect on the production. A significant relationship between tree diameter and manual felling cycle time was found ($p<0.05$; Fig. 3).

Table 4. Felling costs

Location	East Twin			Minnow		
Harvesting system	Ground-based		Cable	Ground-based		
Silvicultural treatment	Group selection	Clearcut	Clearcut	Group selection	Group retention	Clearcut
Net volume per tree (m^3)	1.22	1.54	1.47	1.05	1.07	0.91
Volume per hour (m^3/hr)	23.37	25.81	44.76	44.85	47.79	42.52
Labour and equipment cost ($/hr)	50.00	50.00	50.00	153.24	153.24	153.24
Observed felling cost ($/m^3)	2.14	1.94	1.12	3.42	3.21	3.60
Weighted avg felling cost ($/m^3)	2.14	1.94	1.12	2.96	3.15	3.22
Standardized costs ($/m^3)	2.61	2.99	1.65	3.11	3.37	2.93

Table 5. Skidding costs

Location	East Twin		Minnow		
Equipment utilized	Line skidder		Grapple skidder		
Silvicultural treatment	Group selection	Clearcut	Group selection	Group retention	Clearcut
Net. volume per turn (m^3)	7.13	6.69	5.09	4.94	5.13
Total cycle time (min)	21.34	18.51	13.14	8.99	14.47
Average distance (m)	238.70	140.80	246.80	133.90	273.70
Volume / hour (m^3/hr)	20.09	21.72	23.25	32.95	21.29
Hourly cost ($/hr)	89.74	89.74	116.26	116.26	116.26
Skidding cost ($/$m^3$)	4.47	4.13	5.00	3.53	5.46

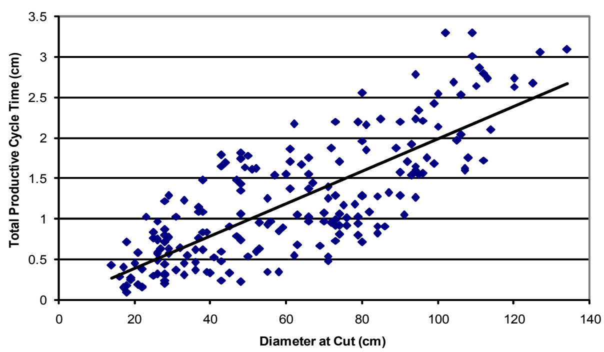

Fig. 3. Relationship between total productive cycle time for felling and tree diameter for the East Twin cable treatment unit

Total productive time (min.) = 0.040 + 0.020 * Tree diameter

n = 194 R^2 = 0.613 S.E. of Estimate = 0.469

At Minnow, mechanical felling, using a Timberjack 618 feller-buncher, in the clearcut had the fastest cycle time of 1.35 minutes per tree, however, production was highest in the group retention treatment due to the greatest merchantable volume per tree. The second highest production occurred in the group selection, again due to a higher merchantable volume per tree. The clearcut felling cycle time was the shortest, but the observed mechanical felling cost was $3.60/$m^3$ due to the lowest average merchantable volume per tree. Felling costs were similar to two FERIC studies in the interior of BC due to similar production $3.44 m^3 to $3.77 m^3 (Gillies, 2002) and $2.71 m^3 to $3.39 m^3 (Sambo, 2003).

Skidding

Skidding productivity was greatest in the Minnow treatments (Table 5), however due to high ownership costs of the grapple skidder at Minnow, the East Twin treatments had lower costs with the exception of the Minnow group retention treatment. Higher productivity in the Minnow group retention treatment was due to the low skidding distance and gentle slope. Given a standardized skidding distance and merchantable volume per stem, the grapple skidder was the most cost effective (Table 6). The East Twin clearcut had a higher standardized cost due to proportionally higher travel times than that of the East Twin group selection and a greater cubic meter per piece.

Table 6. Skidding costs given a standardized skidding distance of 100 meters and merchantable volume per stem of 1m3

Location	East Twin		Minnow		
Equipment utilized	Line skidder		Grapple skidder		
Silvicultural treatment	Group selection	Clearcut	Group selection	Group retention	Clearcut
Net. volume per turn (m^3)	5.86	4.35	4.83	4.60	5.63
Total cycle time (min)	17.86	16.87	10.21	8.34	10.45
Volume / hour (m^3/hr)	19.69	15.47	28.38	33.09	32.33
Hourly cost ($/hr)	89.74	89.74	116.26	116.26	116.26
Skidding cost ($/$m^3$)	4.56	5.80	4.10	3.51	3.60

At East Twin, the average skidding distance in the group selection was 284 m, which was 143 m longer than in the clear cut. In the group selection, an additional 1.5 logs were delivered to the landing each turn, but resulted in a longer cycle time. The average total cycle time in the group selection was 2.83 min. greater than the clearcut. In the clearcut and group selection, 0.6% and 1.1% of the total cycle time was spent waiting for the track skidder to clear and develop skid trails. An additional 0.23-min. wait for the feller per cycle was also incurred in the group selection. These delays could have been avoided through better planning by the contractor.

At East Twin through a general linear model analysis, the following factors significantly influenced the delay-free total productive time: number of log skidded per turn, and skidding distance. Average slope, treatment, skid trail designation, and number of chokers available were not significant factors ($p>0.05$).

Total productive time (min) = 8.321 - 0.023 * Distance (m) + 0.745 * Number of logs per turn

n = 139 R^2 = 0.521 S.E. of Estimate = 3.243

At Minnow, the highest productivity was observed in the group retention treatment due to gentle slopes and a shorter average skidding distance equivalent to half of the average skidding distances in the group selection and clearcut treatments. While a greater number of logs per cycle were delivered to the landing in the clearcut, a lower average volume per log and greater cycle time still resulted in it having the lowest productivity and highest costs. Studies by Hedin and DeLong (1993) and Kellogg et al. (1991) also found that m^3/log and number of logs/turn had a significant impact on harvesting cost. A significant relationship was determined between total productive time, treatment, distance, slope, maximum length of logs in a turn, and number of logs per turn ($p<0.05$).

Total productive cycle time (min) = 0.278 + 0.017D + 0.316 Lg + 0.103 Ln + 0.027S - 0.647 Gs - 0.086 Gr

Where: D = Distance skidded (m)
Lg = Number of logs
Ln = Maximum length logs in a turn (m)
S = Slope (%)
Gs = Group selection treatment (if yes = 1, no = 0)
Gr = Group retention treatment (if yes = 1, no = 0)

n = 1066 R^2 = 0.629 S.E. of Estimate = 2.60

Hoe chucking

Hoe chucking is the movement of felled timber with an excavator, using its bucket and thumb, and placing the timber into bunches. It is used where slopes do not permit ground skidding for distances up to 50 meters. Hoe chucking was only required in the group selection and clearcut treatments on the Minnow site and had an observed cost of \$6.34/m^3 and \$4.67/m^3, respectively. When these costs are weighted by contribution, these costs were \$1.02/m^3 for the group selection and \$1.17/m^3 for the clearcut treatment.

Yarding

As expected a cable harvesting system was the most expensive method of primary transportation used to harvest a clearcut treatment (Table 7). This cost difference (\$2.28/m^3) between Minnow clearcut and the East Twin cable unit was due to dissimilarity in tree piece size. With a standardized piece size of 1 m^3 the yarding cost climbs to \$11.37/m^3 and the difference grows to \$6.39/m^3.

The yarding was downhill with distances ranging from 35 to 225 meters with an average distance of 125 meters.

Table 7. Yarding costs

Harvesting system	Cable
Silvicultural treatment	Clearcut
Pieces per cycle (no.)	2.59
Volume per cycle (m^3)	3.81
Average yarding distance (m)	155.98
Volume per hour (m^3/hr)[b]	24.25
Yarder cost (\$/hr)[b]	187.58
Yarding cost (\$/m^3)[b]	7.74

While the production was similar to other skyline studies, 32.49 m^3/PMH versus 25.7 m^3/PMH to 37.9 m^3/PMH (Hedin and Delong, 1993), the yarding costs were considered low in comparison to the costs reported from other studies in cedar dominant stands in the province. This might be the result of the wages of the crew ranging from $20 to $25 per hour plus benefits where wages elsewhere in the province are on average $10/hr higher plus benefits. It was found that the number of logs and distance had a significant effect on the total productive time.

The productive yarding time constitutes 75.1% of the total cycle time. This is higher than that found in the study by Pavel near Kitwanga, BC (1999), which found that only 55% of the total cycle time was actually productive. Yarder setting change time accounts for 11% of the total cycle time, this is between two FERIC skyline analyses that were 10% (Dunham and Gillies, 2000) and 15% of the total cycle time (Kosicki, 2000b). Approximately 19% of the non-productive time, or 2.52% of the total cycle time, was spent on repairs.

Processing

Processing for all sites was manually completed using a chainsaw at the landing. The primary consideration was to maximize value. Balanced harvest components allowed for the Minnow group selection and retention units to have the lowest processing costs (Table 8). A standard piece size of 1 m^3 intensifies this result.

Processing over mature western red cedar presents a number of challenges. This species is known for pocket and butt rot and as such requires extra steps be taken during manual processing (Fig. 4). During processing, multiple cuts at 0.75m intervals were required to determine where the timber was commercially valuable. As increased merchantable volume decreased the cost, it was important to process the cedar for saw logs and post and rail timber, as post and rail material allows for a thinner merchantable shell. In the East Twin group selection treatment, additional processing of cedar for post and rail timber could have increased the merchantable volume by as much as 0.60 m^3/ tree, dropping the processing costs by $0.51/$m^3$ and resulting in a total harvesting cost of $10.78/$m^3$. Hemlock, spruce, and subalpine fir generally did not have any decay, thus was faster to process for the bucker.

Loading

Loading costs appear to be independent of treatment

Fig. 4. Pocket and ring rot in western red cedar.

Table 8. Processing costs

Location	East Twin			Minnow		
Harvesting system	Ground-based		Cable	Ground-based		
Silvicultural treatment	Group selection	Clearcut	Clearcut	Group selection	Group retention	Clearcut
Volume (m^3)						
Cedar - saw logs	504.8	382.1	1732.0	369.6	457.5	925.9
Cedar - post & rail	168.3	0.0	1061.6	405.8	385.0	646.0
Spruce & subalpine fir	60.0	103.7	76.5	515.8	1019.3	1073.4
Hemlock	N/A	N/A	117.8	32.0	21.8	12.4
Total	733.0	485.8	2987.9	1323.3	1883.6	2657.8
Time (hr)	45.25	18.75	138.00	57	79	128
Cost ($/$m^3$)	1.54	1.02	1.15	1.08	1.05	1.21

and more dependent on a balanced harvesting operation and volume per tree (Table 9). The Minnow treatments had the loader being productive on the landing 69.7% to 79.0% of the time while on the East Twin treatments, the front-end wheel loader was only productive 46.7% to 47.5% of the time. The hydraulic track loader was productive 71.3% of the time for the cable treatment but due to higher ownership costs had a higher cost per m^3. When standardized to a uniform piece size, the Minnow treatments have the lowest loading costs followed by the East Twin ground-based treatments and finally the cable unit.

Summary of harvesting costs

The unit cost on the East Twin site ($/$m^3$) was lowest in the ground-based clearcut treatment (Table 10). The ground-based clearcut had the lowest costs because of minimal planning and layout requirements, and a higher volume of merchantable timber extracted per tree. The cable clearcut treatment had the second lowest unit cost as the result of lower felling and moving costs due to shorter total felling cycle time and greater total volume being removed from the treatment, respectively. The group selection had the highest cost as a result of having the lowest merchantable volume per tree and long skidding distance. The skidding distance in the group selection was nearly twice that of the ground-based clearcut.

On the Minnow site, the highest costs were observed in the group selection treatment as a result of having steep slope conditions and long skidding distances similar to that of the clearcut while having the added constraints to skidding and felling as a result of treatment. In addition the planning and layout costs were highest, $1.73/$m^3$, in the group selection because of the need to designate removal patches and skid trails compared to the group retention, where retention patches and skid trails were easy to mark due to gentle terrain, and the clearcut, where only the boundary and main skid trail were laid out and

Table 9. Loading costs

Location	East Twin			Minnow		
Harvesting system	Ground-based		Cable	Ground-based		
Silvicultural treatment	Group selection	Clearcut	Clearcut	Group selection	Group retention	Clearcut
Equipment	Wheel loader	Wheel loader	Hydraulic loader	Wheel loader	Wheel loader	Wheel loader
Volume (m^3/hr)	16.20	25.91	21.65	19.36	20.70	22.03
Hourly cost ($/hr)	86.16	86.16	108.51	91.97	91.97	91.97
Cost ($/$m^3$)	5.32	3.33	5.01	4.75	4.44	4.18

Table 10. Summary of harvesting costs

Location	East Twin		Minnow			
Harvesting system	Ground-based		Cable	Ground-based		
Silvicultural treatment	Group selection	Clearcut	Clearcut	Group selection	Group retention	Clearcut
Layout / planning cost	2.62	0.53	0.68	1.73	1.16	0.45
Felling cost	2.14	1.94	1.12	3.35	3.21	3.49
Skidding / yarding cost	4.47	4.13	7.74	5.00	3.53	5.46
Hoe chucking costs	N/A	N/A	N/A	1.02	0.00	1.17
Processing cost	1.54	1.02	1.15	1.08	1.05	1.21
Loading cost	5.32	3.33	5.01	4.75	4.44	4.18
Total Costs	16.09	10.95	15.70	16.93	13.39	15.96
Standardized Cost[a]	19.63	16.86	23.08	17.56	13.82	15.18

[a] standardized merchantable volume per stem of 1 m^3

marked.

Treatment, machinery utilized, skidding/yarding distance, yarding road changes, and the balance of operations can all affect harvesting costs, however net merchantable volume per tree can have also have an affect (Lynford, 1934; Mann and Mifflin, 1979; Kluender et al., 1997). Once the merchantable volume per piece is standardized, the harvesting costs with a semi-mechanized system have a lower cost than that of a conventional system for the same treatment type. Besides additional layout requirements, the group retention treatment had harvesting costs similar to that of a clearcut. This was expected as the retention treatment had patch spacing that was at two tree lengths apart and as a result had little or no effect on felling or skidding productivity. The cable clearcut had the highest harvesting cost.

Stand damage

Stand damage in the East Twin clearcut units was minimal and the damage present was on the lower portion of the stem, signifying skidding/yarding damage (Table 11). This reduced felling damage was the result of the felling and skidding/yarding practices utilized, trees were felled downhill or into openings and top choked. In the Minnow treatments trees were felled uphill and bunched into groups to facilitate the use of a grapple skidder. This resulted in increased felling and skidding damage on boundary features (Table 12). On site observations confirmed this while it was noted that felled trees rubbed against the residuals while swinging the feller-buncher. This was confirmed by damage being located higher on the stem than possible from skidding. This damage could have been reduced by changing feller-buncher swinging and felling practices and occasionally top skidding.

As expected, stand damage was greatest along skid trails or at the opening of harvest patches. In the case of the East Twin group selection treatment this damage was partially the result of the creation of bladed skid trails and two sharp corners. While damage could be decreased through the use of rub structures or an incentive program (Kosicki, 2000a), damage could also be reduced by laying out skid trails as straight and flat as possible and placing skid trail corners within harvest features. This would not only re-

Table 11. Summary of the stand damage survey at the East Twin site

Silvicultural treatment	Group selection			Clearcut	Clearcut
Harvesting System	Ground-based				Cable
Feature	Skid trails	Openings	Both	Unit boundary	Unit boundary
Damage summary					
% of residual stand[a]	2	0.4	0.2	n/a	n/a
No. injuries/tree	1.2	1.1	1.6	2	1.5
Average Size					
Width (cm)	17.1	13.1	20.1	14	12
Length (cm)	45.8	30.1	42.2	23	42
Area (cm^2)	783.2	393.1	846.3	322	504
Height (cm)[b]	135.6	82	81.2	37.3	125
Percent of total damage[c]					
Stem	86.5	100	100	100	100
Stem and root	12.1	0	0	0	0
Root	0.7	0	0	0	0
Crown	0.7	0	0	0	0

[a] Residual trees = total population - calculated from cruise and harvesting data
[b] Measured from base of tree to middle of damage
[c] Damage classes: Stem - Stem damage only, Stem and root - Stem and root damage combined, Root - Root damage only, and Crown - All crown damage.

Table 12. Summary of the stand damage survey at the Minnow study site

Silvicultural treatment	Group selection			Group retention		Clearcut
Feature	Skid trails	Openings	Both	Unit boundary	Patch boundary	Unit boundary
Damage summary						
% of residual stand[a]	0.9	1.3	0.8	n/a	1.3	n/a
No. injuries/tree	1.9	1.1	2	2.2	1.9	1.6
Average size						
Width (cm)	13.8	15.5	15.3	12.9	10.6	14.8
Length (cm)	34.6	39.9	42.3	41.7	22.2	42.8
Area (cm^2)	538.1	675.4	843	668.7	250.6	859.1
Height (cm)[b]	103.6	124.5	140.5	307.3	178.9	248.5
Percent of total damage[c]						
Stem	88	94.1	100	93.2	93.3	90.5
Stem and root	12	4.9	0	0	0	0
Root	0	0	0	0	0	0
Crown	0	0	0	6.8	6.7	9.5

[a] Residual trees = total population - calculated from cruise and harvesting data
[b] Measured from base of tree to middle of damage
[c] Damage classes: Stem - Stem damage only, Stem and root - Stem and root damage combined, Root - Root damage only, and Crown - All crown damage.

move the costs of these rub features but likely improve skidding cycle times and thus productivity.

While stand damage did occur in all treatments, as the timber in the treatments is already over mature and contains but and pocket rot, the introduction of pathogens is negligible to fibre quality or mortality. In all cases damage to the stem was also not severe enough to result in mortality. There was a concern regarding wind firmness and corresponding safety in several cases as the result of root damage from the creation of bladed trails, yet two years after harvest, all trees with root damage were still standing.

CONCLUSION

Tree volume, amount of internal decay, and efficiency of harvesting elements were the most important factors affecting final harvesting cost. As expected the planning and layout costs were the lowest in the clearcut treatments ($0.45/$m^3$ - 0.68/m^3), followed by the group retention ($1.16/$m^3$), and selection treatments ($1.73/$m^3$ - $2.62/$m^3$). Harvesting costs varied in the conventional system treatments from $10.95/$m^3$ - $16.09/$m^3$ and from $13.45/$m^3$ - $17.37/$m^3$ in the semi-mechanized system treatments. The cable system had a cost of $15.70/$m^3$. It was expected that the harvesting costs would be lowest in the ground-based clearcut treatments followed by the group retention treatments, group selection and cable clearcut. It was also expected that the semi-mechanized system would be more cost effective than the conventional system. It was found that the semi-mechanized group retention treatment was the most cost effective. The semi-mechanized group selection was cheaper than the conventional group selection treatment due to a higher production rate common with mechanized harvesting operations. The cable clearcut was the most expensive treatment.

An understanding of the traditional and alternative products that can be derived from the harvested timber was key in increasing the amount of merchantable volume and reducing the corresponding harvesting costs. As such it is recommended that all possible product options be explored prior to processing to ensure the merchantable volume is maximized.

Stand damage was greatest in the group selection treatments; however mechanized felling showed a significant stand damage increase over manual felling as a result of felling practices. This was not expected as mechanized felling according to the literature results in greater control of the felled stem. Had the trees been felled toward the inside of harvest openings or skid trails this damage would have been greatly reduced. As expected, grapple skidding resulted in a lower level of stand damage than that of line skidding, this however may have been the result of poor skid trail layout and design in the line skidder treatment.

Suggestions for Alternative Harvesting Operations

Partial cutting less often used in the interior of BC and specifically cedar dominant stands due to the perceived additional costs over clearcutting. As partial cutting becomes more common place, planning, layout, and harvesting costs will continue to decrease as operator knowledge increases. Based on this study, the following general suggestions may improve both clearcut and partial cut harvest of interior cedar stands:

1. Mark only the outer edge of retention or selection patches.
2. Mark patches and boundaries with colour blind friendly colours, red and greens should be avoided.
3. Improved skid trail layout; straight and level with any corners located with harvest openings will reduce stand damage, eliminate the need for rub features and associated costs, while likely improve skidding cycle times and thus productivity.
4. Larger over mature cedar can be mechanically felled by multiple cuts; however this practice is not suitable for large solid trees due to stump pull.
5. Match cuts when using multiple cuts to fell a tree, it will decrease volume loss during processing.
6. Felling tree into patches, skid trails, or openings will reduce residual stand damage especially when used in combination with top skidding.
7. Yarding corridor change time can be greatly decreased through pre planning.
8. A balanced harvest operation will result in decreased loading and processing costs
9. Pre-work meetings can decrease operational delays
10. Merchantable volume per tree can have an effect on harvesting costs. As such the merchantable volume per tree can be increased by exploring all possible products for species being harvested.
11. Stand damage could be decreased through the use of rub structures, incentive or bonus penalty program, and/or operator education.
12. Root damage can be avoided in partial cuts by not utilizing bladed skid trails.

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