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COMPARING SILVICULTURAL SYSTEMS IN A COASTAL MONTANE FOREST: PRODUCTIVITY AND COST OF HARVESTING OPERATIONS

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CANADA-BRITISH COLUMBIA PARTNERSHIP AGREEMENT ON FOREST RESOURCE DEVELOPMENT: FRDA II

Canada

BC

Comparing Silvicultural Systems in a Coastal Montane Forest: Productivity and Cost of Harvesting Operations

by

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EXECUTIVE SUMMARY

The *Montane Alternative Silvicultural Systems* (MASS) study is a multi-disciplinary, multi-agency project initiated both for silvicultural and social reasons. Concerns about regeneration performance in coastal montane forests, which lie between 700 and 1100 meters elevation, and public pressure to limit clearcutting in public forests prompted this research project. MacMillan Bloedel Limited, the Canadian Forest Service, and FERIC cooperated in the study, with participation by the University of Victoria and the University of British Columbia. FERIC received partial funding for its activities from the Canadian Forest Service's FRDA program and Green Plan.

Three alternative treatments representing a range of canopy removal levels were implemented in the MASS research area, located on the east coast of Vancouver Island in the Montane Moist Maritime Coastal Western Hemlock biogeoclimatic ecosystem. The three 9-ha treatments—uniform shelterwood, green tree retention, and patch cutting—were replicated three times. The study also included an old-growth and a clearcut control block. Harvesting, using the handfall/excavator forwarding technique, was completed in 1993. Post-harvest studies will continue for at least 20 years. FERIC monitored the productivity and cost of the falling and forwarding operations, and measured site disturbance and coarse woody debris for each harvesting treatment.

This trial showed that alternative harvesting treatments can be applied to old-growth forests on gentle terrain with reasonable falling and forwarding success. The combined cost of falling and forwarding were 10% higher for the patch cut ($7.88/m^3) and green tree ($7.87/m^3) treatments, and 38% higher for the shelterwood ($9.92/m^3) treatment, compared to the clearcut ($7.19/m^3). The cost of harvesting replicates within the same treatment were highly variable, due to differences in timber, terrain, and crew experience. The trial succeeded because the crew was willing to try new applications of existing skills.

The amount of downed woody biomass was generally consistent between treatments (413–477 m^3/ha); however, the distribution between decay classes was different. The shelterwood units had more material in the higher-decay classes, probably because more area was undisturbed, leaving the original woody material in place. The green-tree treatment had a higher level of solid wood because of greater breakage during falling and forwarding. To date, targets for post-harvest coarse woody debris levels have not been defined in British Columbia.

Dispersed site disturbance was roughly equal between treatments, with about 10% in the disturbed compacted category and about half of that at less than 10-cm depth. The whole soil bulk density sampling in deep tracks consistently showed an increase of approximately 10% compared to undisturbed areas. However, the densities were considered to be below the threshold for impeding root growth. The deep humus layers and the high slash loading protected the mineral soil from disturbance, and dispersed the weight of the harvesting equipment. The occupancy by roads was similar between the clearcut and the treatment area at 6.5 and 6.3% of total area.

Lower overall costs may be achieved with alternative silvicultural if free-to-grow standards can be met earlier and at less cost; however, the loss of the residual timber volume, tree marking costs, and additional supervision requirements must also be included in the equation.

Long term assessment of windthrow occurrence and regeneration success will answer some of the remaining question about the applicability of alternative silvicultural systems in the coastal montane forests of British Columbia.

ACKNOWLEDGEMENTS

This project would not have possible without cooperation and assistance by the staff of MacMillan Bloedel's Menzies Bay Division—especially the Iron River Crew—and the overall project leaders Bill Beese of MacMillan Bloedel's Land Use Planning Advisory Team and Jim Arnott of the Canadian Forest Service. Ingrid Hedin and Marv Clark of FERIC, and Shaun Berryman, formerly of FERIC, also provided valuable assistance throughout the entire project. The project was supported in part by FRDA II—Research in Sustainable Forest Development, and by the Forest Practices component of the Canadian Forest Service's Green Plan.

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1 INTRODUCTION

The Montane Alternative Silvicultural Systems (MASS) study is a multi-disciplinary, multi-agency project initiated for both silvicultural and social reasons. The study is a cooperative research project between MacMillan Bloedel Limited (MB), the Canadian Forest Service (CFS), and the Forest Engineering Research Institute of Canada (FERIC), with participation by the University of Victoria (UVic) and the University of British Columbia (UBC). The study compared uniform shelterwood, green-tree retention, patch cut, and clearcut treatments harvested by the hand-falling/excavator forwarding technique.

Concern about regeneration performance in coastal montane forests, which lie between 700 and 1100-m elevation, has been expressed by forest operators within the region, specifically MacMillan Bloedel Limited, which has 25% of its future harvest in coastal montane areas. Failure to establish regeneration and/or reduction in growth performance in these forests would have long term economic implications.[1] It has been speculated that the regeneration performance problems may be related to changes in micro-climate on larger clearcuts. However, this has not been substantiated because the ecosystem processes in montane forests are poorly understood.

Another concern is the public pressure to limit clearcutting in all public forests, especially high-elevation old-growth forests, when the practical and economic limitations of nontraditional harvesting and silvicultural practices are not clearly understood. Coastal old-growth forests are complex and often have a wide range of tree sizes and ages, with some very large diameter trees, smaller trees, advanced regeneration, and snags. The sub-projects within the MASS study were designed to address knowledge gaps in specific components of the ecosystem by comparing several silvicultural systems in an operational trial.

The MASS research area is located near Chute Creek on the east coast of Vancouver Island (Figure 1) in the Montane Moist Maritime Coastal Western Hemlock biogeoclimatic variant (CWHmm2) (Green and Klinka 1994), on MacMillan Bloedel's private forest land. This area met the project requirements of 150 ha of continuous forest land in the same biogeoclimatic zone variant and in the 700–1100-m elevation range, easy access by researchers and visitors on existing roads, and a company commitment to retain an unharvested control area (within the 150 ha) for 20 years.

The project was initiated in 1991. Funding was secured and planning was completed in 1992. Funding was provided by the Canada–British Columbia Forest Resource Development Agreement (FRDA II), Industry Canada, the Forestry Practices component of the Canadian Forest Service Green Plan, the Canadian Forest Service, MacMillan Bloedel Limited, and the Forest Engineering Research Institute of Canada. Post-harvest studies will continue for at least 20 years.

All of the MASS projects were reviewed by the overall project leaders—Beese (MB) and Arnott (CFS)—to avoid duplication and to ensure that gaps in current knowledge about montane forests were addressed. The FERIC project described in this report included monitoring all harvesting phases, surveying post-harvest woody residue, and assessing the effects of harvesting equipment on forest soils. FERIC received partial funding for its activities from the FRDA program and Green Plan. The pre-harvest layout for the 1992 clearcut block was done early in 1992 and the layout of the remainder of the area was completed during the fall of 1992 and spring of 1993. Harvesting was monitored during 1993 and post-harvest assessments were completed during 1994.

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[1] Beese, W.J. 1992. Montane Alternative Silvicultural Systems (MASS)—working plan.

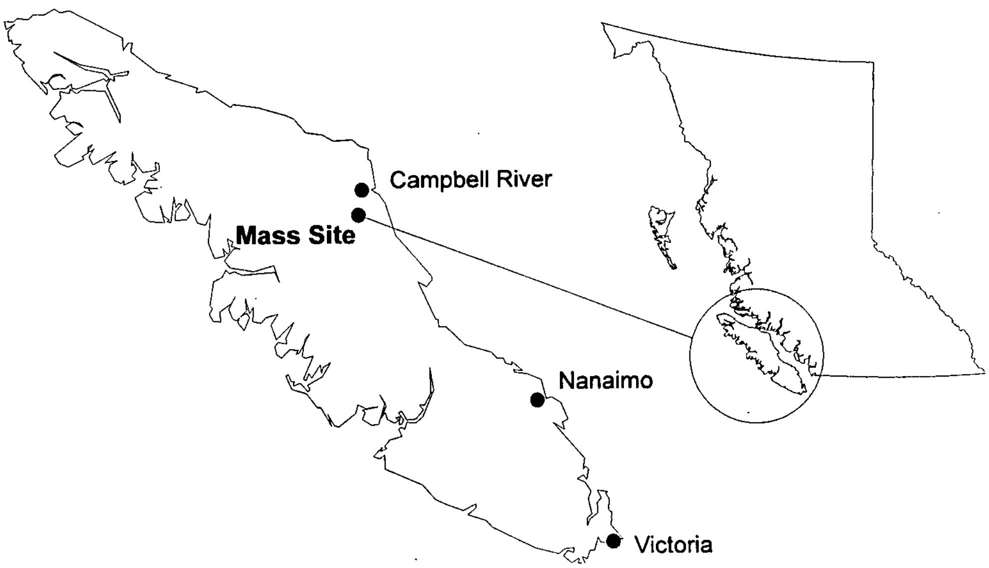

FIGURE 1. Location of the MASS site.

2 OBJECTIVES

The overall project objectives[2] were to

- quantify the impact of reduced growth and irregular stocking of high elevation forests on future harvest levels;
- investigate the biological and economic aspects of alternative silvicultural systems (specifically uniform shelterwood, green-tree retention, and patch cut) in montane coastal forests to meet regeneration, aesthetic, and wildlife objectives at the greatest economic return, without compromising worker safety; and
- develop guidelines for selecting silvicultural systems, species, and management options for montane ecosystems.

These studies will be reported by others as the results are available.

The objectives of the FERIC project are to

- determine harvesting productivity and the resulting differences in delivered wood cost, between treatments;
- measure soil disturbance and compaction levels;
- measure the volume and type of woody debris remaining on the site following harvesting;
- observe operational aspects of harvesting each of the treatments; and
- determine the forest renewal activities and costs.

The FERIC objectives are discussed in this report. The remainder of the objectives will be discussed in other FRDA reports by other researchers.

[2] Ibid.

3 SITE AND SYSTEM DESCRIPTIONS

The study design included the three treatments replicated three times (nine blocks totaling 94 ha), an old-growth control, and a conventional clearcut block harvested in both 1992 and 1993. Figure 2 shows an aerial view of the treatment areas after harvest. The three treatments, **patch cut** (PC), **shelterwood** (SW) and **green tree** (GT), were randomly assigned to the 9-ha treatment units and represent a range of canopy removal and sheltering effects. Figure 3 shows the spatial relationship of the harvesting treatments, old-growth reserve, and the clearcut controls, which all lie between 735- and 865-m in elevation.

3.1 Site Description

Site selection, ecological classification, and forest inventory were completed by MB's Woodland Services. The detailed forest cover inventory of overstory trees is shown in Table A1. Overall, the stand was composed of western hemlock *(Tsuga heterophylla)*, amabilis fir *(Abies amabilis)*, and western redcedar *(Thuja plicata)*, with a component of yellow-cedar *(Chamaecyparis nootkatensis)* and mountain hemlock *(Tsuga mertensiana)* (Figure 4). The species mix, by volume, was 40% hemlock, 30% amabilis fir, 20% redcedar, and 10% yellow-cedar. The gross volume was 1028 m^3/ha, with a net volume of 626 m^3/ha. Age sampling showed most amabilis fir trees were less than 250 years old, with some as old as 500 years while the hemlock and yellow-cedar and redcedar were 200–800 years old.[3] Many of the larger trees had a pronounced lean. There was an average of 89 snags/ha. Advanced regeneration was present in all areas, but especially in the gaps created by old-growth mortality. The amabilis fir advanced regeneration varied in age and form, with some trees older than 100 years measuring less than 3 cm in diameter.

[3] Beese, W.J. 1994. Montane Alternative Silvicultural Systems (MASS)—final progress report—year 3.

The terrain was even to hummocky, with slopes of 0–30% (average 14%), and low-to-moderate brush and a low-to-moderate number of obstacles. The most common obstacles to machine travel were windfalls and small swampy patches. The predominant soils were classified as Orthic and Gleyed Ferro-Humic Podsols.[4] The Pre-Harvest Silviculture Prescription (PHSP) rated the site sensitivity as low for the clearcut blocks, and medium for the alternate treatment blocks. The hazard for mass-wasting was low. The medium-to-fine textured soils (loam, silt loam to occasionally clay loam) and moderately well drained to imperfectly drained conditions created a moderate-to-high sensitivity to compaction.[5]

3.2 Treatment Description

The three alternative treatments represent a range of canopy removal levels. Some advanced regeneration was expected to survive from each of the treatments, with the highest level of survival expected in the shelterwood treatment.

The objective of the patch cut treatment was to protect the regeneration against snow, wind, and temperature extremes, and to distribute harvesting over a longer period to increase aesthetic and wildlife habitat values.[6] Each patch cut unit was divided into sub units, with 50% of the area harvested in small, clear-felled patches of 1.5–2 ha. Each of the patches was rectangular in shape, and had rounded corners at the intersections to increase windthrow resistance. The opening size was designed to be small enough to receive some protection from climatic extremes, to provide wildlife habitat, and to allow some natural regeneration from seed fall. However, planting

[4] Senyk, J.P and D. Craigdallie, 1994. Long term soil and forest productivity—progress report.

[5] J.P. Senyk, 1995. Long term soil and forest productivity —progress report.

[6] W.J. Beese, 1995. Montane Alternative Silvicultural Systems (MASS) project establishment report.

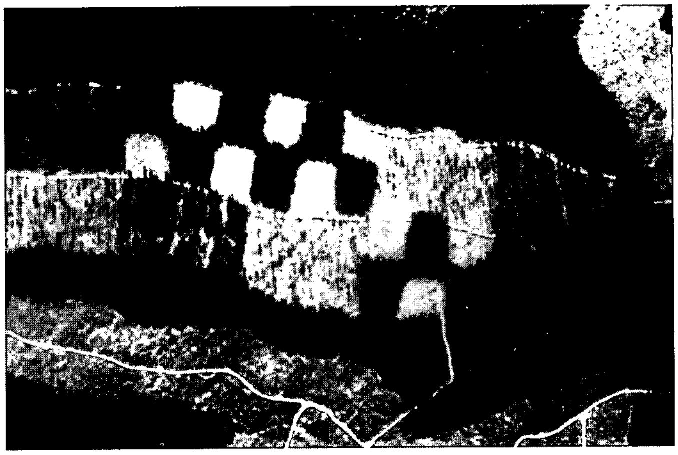

FIGURE 2. Aerial view of MASS alternative treatment blocks.

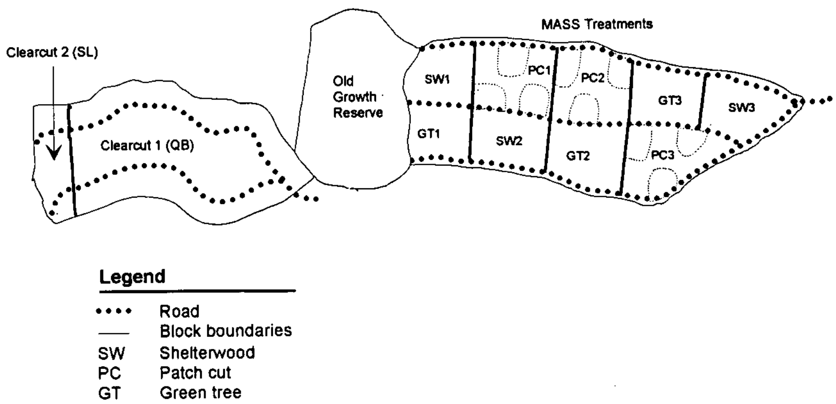

FIGURE 3. Map of the MASS area showing the clearcut and old-growth controls.

FIGURE 4. Pre-harvest stand.

was planned to supplement natural regeneration. The unharvested units will be left until the new forest becomes large enough to shelter the next regeneration.

The goal of the uniform shelterwood treatment was "to protect regeneration against snow, wind and temperature extremes, and to enhance the structural diversity of future stands for wildlife and aesthetic values."[7] About 70% of the basal area was removed, resulting in approximately 150 trees/ha retained out of the original 530 trees/ha (Figure 5). Generally, the residual trees were in the size class and species distribution of the original stand; however, high-value redcedar and yellow-cedar trees were removed to make the treatment as economically viable as possible. Traditionally, shelterwoods are harvested in two or three entries. However, it is uncertain if the remaining trees can be harvested economically without damaging the regeneration. Therefore, the decision for final removal will be made when the regeneration has reached sufficient size. The shelterwood treatment will be regenerated using advanced regeneration, natural regeneration, and infill planting where required.

The green-tree treatments used in this study, also known as *clearcut with reserves*, retained uniformly spaced residuals. The goal was "to leave reserve trees in a small (9 ha) clearcut to enhance the structural diversity of future stands for wildlife and aesthetic values."[8] However, this treatment was not intended to be a seed-tree silvicultural system, because with units of this size hemlock will usually seed-in from the surrounding area. Planting will be used to supplement natural regeneration in order to obtain the desired species, and to establish the stand before brush competition becomes a problem. Advanced regeneration will also form a component of the new stand. Leave-trees were selected to represent the pre-harvest size and species composition, with preference given to trees that were likely to be windfirm, and to lower-value trees that were not genetically inferior. Because all snags had to be felled to meet Workers' Compensation Board (WCB) regulations, some of the standing live trees (about 5 trees/ha) will be made into snags if enough natural recruitment does not occur. The residual trees will remain until the next rotation.

3.3 Equipment Description

A primary operational objective was to utilize existing company equipment wherever possible. Ground-based equipment, excavator forwarding to roadside, or excavator forwarding to within super-snorkel reach is normally used in this terrain and was also used in the study.

Specifications for the forwarding equipment are given in Table A5. Excavator 1, a Thunderbird 1146 equipped for excavator forwarding, was the primary forwarder in all treatments. Excavators 2 and 3 (Cypress/Chapman 1825) were used for forwarding and loading. A KMC 2500 AG tracked grapple/line skidder was used in the shelterwood treatment to forward excavator-decked wood to roadside, and, to a limited extent, in some of the other treatments for forwarding and clean-up. The tracked skidder was leased for the project to ensure all treatments were harvested in a single season. The super-snorkel, was only used in the first clearcut (1992) block.

[7] Ibid.
[8] Ibid.

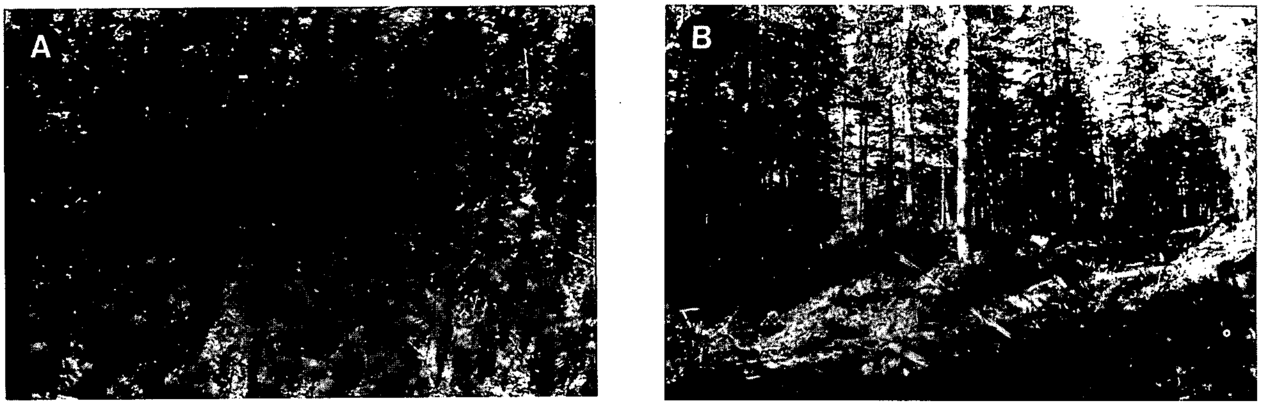

FIGURE 5. Shelterwood treatment.

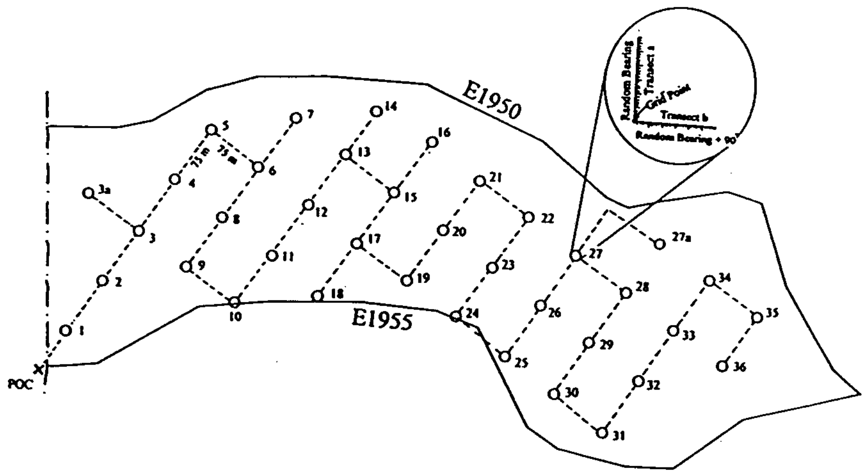

FIGURE 6. Grid and site disturbance layout for Clearcut 1.

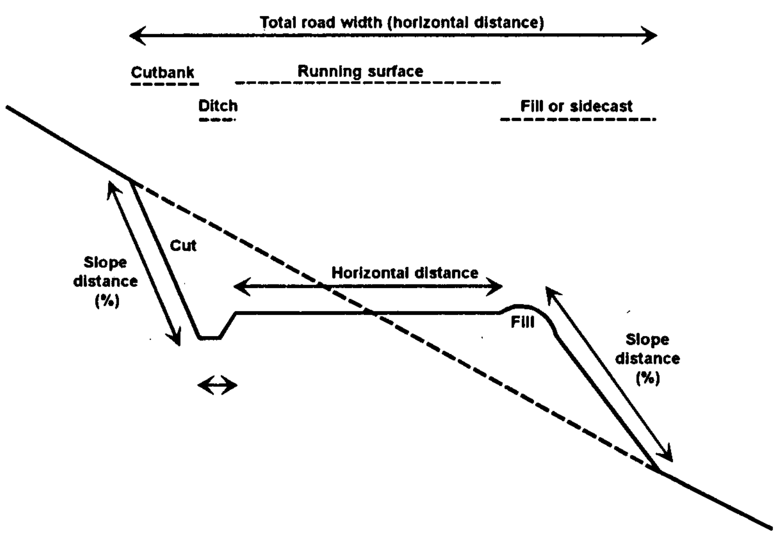

FIGURE 7. Haul road cross-section measurement.

4 STUDY METHODS

An overall objective of all of the research projects was to collect information in a manner that would allow coordination and cross reference between studies. Whenever possible, all measurement locations were referenced to the overall MASS research grid.

4.1 Site disturbance Studies

The site disturbance sampling was systematic from a randomized start. Site disturbance was measured on transects radiating from fixed grid points, before and after harvesting, as described by Curran and Thompson (1991). Two 30-m transects were established at each grid point, one on a random bearing and the second at right angles to the first. An example from the Clearcut 1 block is shown in Figure 6. Because the patch cut treatments had a smaller harvested area than the others, four transects per grid point were used to obtain enough sampling points. Point observations were made at 1-m intervals along the transects; the surface material (humus or mineral), disturbance class (undisturbed, compacted, gouged or mounded), depth of disturbance (in centimeters measured from the undisturbed surface), and probable cause of disturbance were recorded for each sample point. The pre-harvest survey was used to classify the site terrain and to check for any pre-harvest site disturbance from prior activities, such as logging or mining, or from natural occurrences, such as blowdown, landslides, or meandering streams. Pre- and post-harvest site disturbance measurements were made from a 75- x 75-m grid for the 1992 clearcut block (Figure 6), and from a 60- x 60-m grid (alternate research grid points) in the other treatments. Observations were summarized as a percentage of the total observations by type and depth class.

Site disturbance from roads and landings was measured using the traverse method. The total length of road was divided by the sample size (10) to determine the spacing for cross-section measurement points. This sample size met both the Interior and Coastal guidelines for sample intensity (Curran and Thompson 1991, B.C. Ministry of Forests 1992). At each of these points, a cross section was measured from the top of the road cut to the toe of fill slope. Measurements included cut slope and distance, width of ditch, width of running surface, and width of side cast (fill) (Figure 7). These measurements also correspond to those required by the *Coastal Pre-Harvest Silvicultural Prescription Procedures* (B.C. Ministry of Forests 1992). Landings and turnouts were traversed. The area occupied by roads and landings was calculated and presented as a percentage of the total harvested area.

4.2 Soil Bulk Density

Between two and four sites near each grid point were prepared by removing the humus layers and creating small-diameter holes to accommodate the probe of a Campbell Pacific MC-1DR direct-readout, single-probe, moisture/density gauge (densiometer). The densiometer measures bulk density and moisture content in place, and calculates the dry total soil bulk density used in comparisons of bulk densities. The densiometer reads the density between the four probe depths (20, 15, 10, and 5 cm) and the surface. Sites for pre-harvest readings were selected to represent the average terrain of each grid-point site. Post-harvest studies measured paired undisturbed and disturbed areas (Figure 8). Soil samples for coarse-fraction analysis were not collected because intensive soil analysis was conducted by the CFS.

4.3 Woody Debris Assessment

Downed coarse woody debris is recognized as an important part of the forest ecosystem. The woody debris functions as a moisture reservoir, has a role in nutrient cycling, and provides site stability and small-mammal habitat (Maser *et al.* 1984, Maser and Trappe

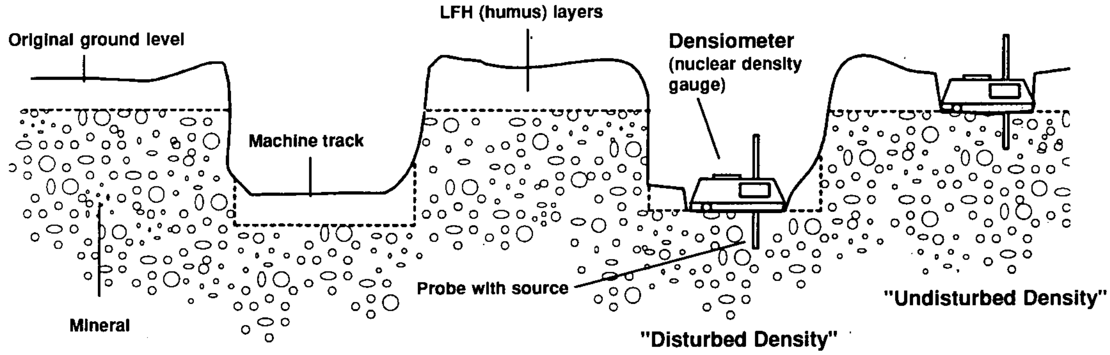

FIGURE 8. Post-harvest total soil bulk density measurement.

FIGURE 9. Measurement of woody debris.

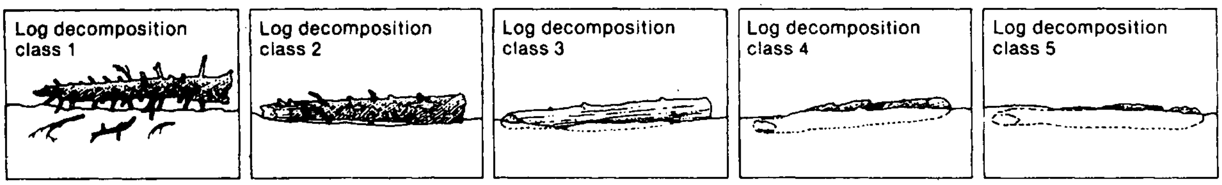

FIGURE 10. Decay classes of down woody material.

1984, Graham *et al.* 1990, Hopwood 1991). No current targets exist for post-harvest residual woody debris for British Columbia. The goal of the FERIC woody debris measurement and classification was to document the levels as part of the overall post-harvest site description.

The volume and type of woody debris left on the site after harvesting were measured with a modified line intersect method as described by Sutherland (1986). Except for the patch cut treatments, two 20-m transects radiating from each of the FERIC grid points (alternate research grid points) were established at right angles at the bearings used for the site disturbance measurements. Four transects were used for the patch cut treatments to obtain adequate sampling in the 1.5–2-ha openings. The end of each transect was marked with a labeled reference stake. Each transect was further subdivided into 2-m quadrats. Pieces of woody debris with diameters of 1–5 cm were counted for each quadrat. The maximum depth of slash greater than 1 cm in diameter was measured inside a 15-cm radius cylinder at the center of each quadrat. The diameters of larger pieces (greater than 5 cm) were measured at their intersection with the line (Figure 9), and the decay class for each piece was recorded as described by Hopwood (1991) (Figure 10). Material that exceeded the **class 5** decomposition was also measured; these logs had become part of the humus layer of the soil and were classified as **class 5+**. The lengths of pieces greater than 5 cm in diameter were recorded on alternate transects as well.

Volumes, in cubic meters per hectare, were calculated using Sutherland's (1986) procedure, according to basic theory described by Van Wagner and Wilson (1968 and 1976). Slash depths were averaged for all quadrats.

4.4 Detailed Timing

Detailed timing is the continuous timing of a process, separating it into individual cycle-time elements. At the request of the crew, no detailed timing of falling activities was carried out. Falling in a partially cut old-growth stand is hazardous, and placing fallers under additional stress by timing them continuously was not judged wise or necessary. However, the forwarding equipment was timed on each treatment unit, including the 1993 clearcut block. This allowed comparison, between treatment blocks, of specific wood-handling (forwarding) operational elements.

4.5 Shift-level Monitoring

Productive and nonproductive times were collected from daily time cards provided by the company and summarized into total machine and worker hours. Delays that were not specific to a treatment were pro-rated over all the treatments. Delays that were specific to the research nature of the trial, such as delays caused by visitors or management activities, were excluded from the analysis.

4.6 Costing

Costing is based on the actual time spent by machines and workers (scheduled machine/person hours less delays for management or research activities), and on FERIC's standard costing procedure (Cottell *et al.* 1976). Operating costs per hour were calculated using dealer-supplied replacement values for equipment, current interest at the time of the study, 1993 IWA wages, and projected repair and maintenance costs (Table A10).

5 RESULTS

5.1 Harvesting

The falling phase was monitored using company time cards and through weekly meetings with the fallers. The forwarding was also monitored with the company time cards and with detailed timing.

5.1.1 Falling

A summary of falling time, cost, and productivity, by treatment, is presented in Table 1, while Tables A6–A10 present this information in more detail, by treatment and replicate. The hours used for costing are the productive hours plus pro-rated delays. The pro-rated delays include call-out time (allowance for days when it is too windy to fall), on-site safety meetings, faller training, accident reviews, moving time, and light duty. More detail on the costing assumptions are contained in Tables A2 and A3. The falling costs for the alternative treatments ranged from $3.65/m^3 for green tree to $4.35/m^3 for shelterwood, compared to $3.74/m^3 for one clearcut. The results show considerable variation between replicates due to differences in severity and direction of tree lean, number and size of obstacles, steepness and evenness of terrain, and number of snags.

The customary practice of maintaining visual contact between fallers was not possible in most of the treatments, especially the shelterwood treatment. Typically, only one faller would work in each patch cut, and one or more fallers would work in green-tree and shelterwood treatments (Figure 11). The fallers used radios with collar microphones (and in some cases earmuff speakers) to regularly check with their partner in compliance with WCB check-in requirements. One lost-time falling accident did occur in a shelterwood treatment, caused by a falling branch.

5.1.2 Forwarding

Forwarding hours and cost by treatment are presented in Table 1 and Tables A6–A10. The cost and productivity summaries include all fallers and all forwarding equipment. In some treatments, several pieces of equipment were used to take a log from the stump to roadside. In the shelterwood treatments, the logs were forwarded by one of the three excavators to the corridors, and then forwarded by the tracked skidder to roadside. Logs in Clearcut 1 were forwarded by the excavators to within reach of the super-snorkel. Details on the utilization of each piece of equipment are shown in Tables A6–A10.

Costs were calculated using FERIC's standard methods (Cottell *et al.* 1976). The assumptions are shown in Table A10. Overall, the least costly forwarding was the clearcut treatment at $3.45/m^3, followed by the patch cut at $3.59/m^3, the green tree at $4.22/m^3, and the shelterwood at $5.57/m^3. Using the clearcut cost as the base, the patch cut cost was 4% higher, the green tree was 22% higher, and the shelterwood was 61% higher. When individual treatment units are examined, the lowest forwarding costs were Green tree 1 at $2.86/m^3, Clearcut 2 at $3.22/m^3, and Patch cut 3 and Clearcut 1 at $3.49/m^3. The data show the lowest forwarding cost in replicates with Excavator 1 (Figure 12) as the primary machine. Excavator 1 was the newest machine, had the operator with the most experience in excavator forwarding, and was the machine with the most suitable specifications (Table A5). For excavator forwarding, the most important machine specifications were high ground clearance, long boom reach, and adequate power.

The combined falling and forwarding costs at roadside were 10% higher than the clearcut base for the patch cut and green tree treatments, and 38% higher for the shelterwood.

FIGURE 11. Wedging during falling.

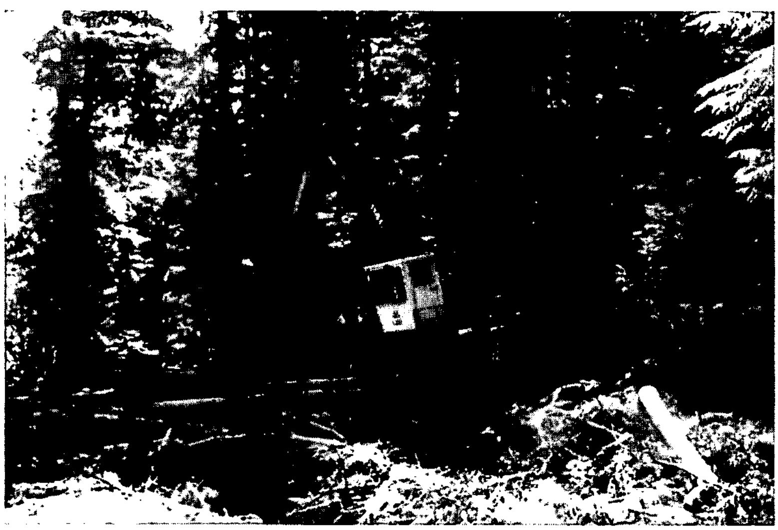

FIGURE 12. Excavator 1 forwarding in shelterwood.

5.1.3 Detailed timing

Detailed timing results for the primary forwarder (Excavator 1) are shown in Table 2. Generally, the cycle time increases with the number of leave-trees, while the production in pieces per productive machine hour decreases.

Excavator 1 used a "serpentine" forwarding pattern (Figures 13 and 14) in all treatments except for the shelterwood units. In this pattern, the excavator travels to the timber face or split line that is furthest from and parallel to the road. Forwarding begins by moving the excavator in a path parallel to the haul road and decking all logs at right angles to the haul road. At the end of the block, the excavator turns to a new path, parallel to the first, and decks all new logs and then swings the previous log deck to the new deck. In theory, each pass with Excavator 1 will move the log deck 63 m closer to the road. This pass distance is the sum of twice the excavator reach (14.6 m) plus twice the average log length (17 m). However, in Clearcut 2 the actual distance per pass was 29 m, while in the patch cuts and green tree units it was 27 and 23 m, respectively. The limitations were primarily due to terrain, swampy pockets and large stumps, and the variability of log size. The large logs were beyond the lifting capacity of the excavator at full extension, and the small, short logs could not be moved long distances per pass. By comparison, Andersson and Jukes (1995) measured 50 m between decks in even terrain with more-uniform second-growth log sizes.

In the shelterwood treatments, Excavator 1 used a different forwarding pattern, which was a modification of the "up-and-down" (Figure 14) method described by Andersson and Jukes (1995). The excavator traveled from the clear-felled corridor, between the standing trees, and piled the logs within reach until it had advanced to the split line between corridors. The operator then reversed and forwarded the piles to the corridor for forwarding to roadside by the tracked skidder.

Excavators 2 and 3 used the serpentine pattern in the green-tree blocks and the patch cuts, and the up-and-down pattern in Clearcut 2 and the shelterwoods.

The tracked skidder worked primarily in the shelterwood units, with some work in one green-tree unit and two patch cut units. The detailed timing results for the tracked skidder are shown in Table 3. The patch cut forwarding was used for operator training, and was therefore not detailed timed. In the shelterwood units, the tracked skidder forwarded the logs decked by the excavator on the corridors to roadside. In the green-tree block, the skidder forwarded logs, skidding from the stump to roadside with some orienting of log butts, by Excavator 1 to facilitate grappling. Detailed timing of forwarding in the green tree treatment was done primarily in nonaligned wood and showed an increase of almost three times in position and grapple. However, the operator was less experienced during the green-tree forwarding than during the shelterwood. An example of a strategy, used later in the study, was the use of the winch/chokers to correct for any log misalignment and to allow the turn to be winched up steeper grades and across swampy areas. In addition to forwarding in the three treatments, the tracked skidder also acted as a clean-up machine in all treatments by retrieving logs missed by the excavator.

Comparisons of machine cost and productivity are difficult to make because of differences in pieces per cycle (Tables 2 and 3), forwarding distance per cycle, and machine cost per hour (Table A10). Figure 15 is a graphical comparison of treatment cost (from detailed timing) for three of the forwarding machines. The cost comparison basis is the cost to forward one piece (log) one meter. The lowest cost was in the clearcut treatment, using the primary excavator. Except with the tracked skidder, productivity decreased and cost increased as the level of removal decreased. The tracked skidder's production was the lowest in the green-tree treatment because most of the logs were not aligned to the direction of skidding, as they were on the shelterwood treatment corridors.

TABLE 1. Productivity and cost summary

		Shelterwood	Green tree	Patch cut	Clearcut
Area	(ha)	27.5	27.3	17.1	69.1
Volume	Total (m^3)	14 503	18 425	11 175	45 360
Piece size	Average (m^3)	1.25	1.12	1.12	1.15
Falling	Time[a] (hr)	1 069	1 138	807	2 868
	Productivity (m^3/hr)	13.6	16.2	13.8	15.8
	Cost ($/hr)	59.14	59.14	59.14	59.14
	Cost ($/$m^3$)	4.35	3.65	4.29	3.74
Forwarding	Time[b](hr)	646	569	292	1 001
	Productivity (m^3/hr)	22.4	32.4	38.3	45.3
	Cost[c]$/hr)	125.00	136.58	137.40	156.20
	Cost ($/$m^3$)	5.57	4.22	3.59	3.45
Total at roadside	Cost ($/$m^3$)	9.92	7.87	7.88	7.19

[a] including pro-rated delays
[b] including pro-rated delays, all machines
[c] Tables A6–A10 provide additional cost and assumption details

TABLE 2. Detailed timing of excavators 1 and 2—summary by treatment

	Excavator 1				Excavator 2	
Time functions	Shelter-wood (min)	Green tree (min)	Patch cut (min)	Clearcut (min)	Green tree (min)	Clearcut (min)
Average time/cycle						
Move	0.15	0.08	0.03	0.03	0.04	0.05
Swing empty	0.10	0.10	0.09	0.10	0.11	0.09
Position and grapple	0.10	0.11	0.11	0.08	0.10	0.08
Bunch/pull from deck	0.04	0.04	0.05	0.06	0.08	0.01
Swing loaded	0.15	0.16	0.15	0.17	0.17	0.14
Deck	0.22	0.20	0.20	0.17	0.24	0.14
Productive	0.76	0.69	0.63	0.61	0.74	0.51
Delay	0.04	0.15	0.07	0.04	0.05	0.06
Total	0.80	0.84	0.70	0.65	0.79	0.57
Average pieces/cycle	1.63	1.52	2.07	2.02	1.39	1.54
Production (pieces/PMH)[a]	129	132	197	199	113	181

[a] Productive machine h.our

FIGURE 13. Excavator 1 using serpentine forwarding pattern in patch cut.

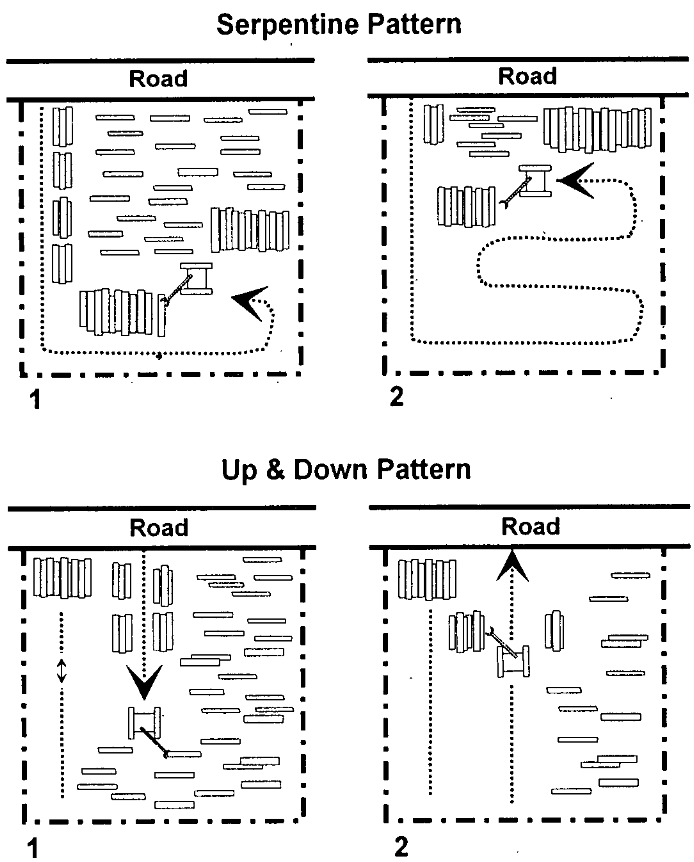

FIGURE 14. Serpentine and up-and-down forwarding patterns.

5.2 Site Disturbance and Compaction

5.2.1 Pre-harvest site surveys

Pre-harvest site conditions are summarized by treatment in Table 4, and by replicate in Table A11. No pre-harvest disturbance was found in sampling. The *undisturbed mineral soil* was exposed mineral soil resulting from windfall and intermittent streams. (A large swamp in Clearcut 1 (QB) was not sampled.) The windfall category included woody debris with root attached. Coarse woody debris is summarized, by decay class, in Table 5 and in Figure 10. Most areas of the forest floor, including woody debris in Classes 3 and higher, were covered with a thick layer of moss.

5.2.2 Post-harvest surveys

The post-harvest site survey is summarized in Tables 6 and 7, with additional detail in Tables A12 and A13. More than 75% of the sample points were undisturbed, and this proportion was relatively consistent between treatments. The primary cause of disturbance was from machine tracks, followed by stumping and log gouges. The machine tracks caused both compaction (of humus and/or mineral soil) and soil displacement (mounding) (Figure 16). All depth measurements were in comparison to the surrounding undisturbed ground level, and not to the depth of compression into mineral soil. The depth of humus soil layers, the hummocky nature of the site, and the thick root mat in the humus layers made measurement of depth of impression into mineral soil impossible within the limits of this project. In addition to soil displacement, compression of the humus material also provided depth. Given the low mass-wasting hazard, the disturbance was probably not significant; in fact, the gouged and deposit areas are preferred planting areas. *Disturbed humus* and *mineral compacted* are shown by area and depth in Table 7. Selected areas that met the company's criteria for rehabilitation were treated the year following harvest, and are shown as *Rehabilitated (in block)* in Table 6. Cost and productivity of the rehabilitation was monitored, and has been reported in a separate publication (Phillips 1995).

Disturbance from roads and landings are summarized in Tables 8 and 9. All of the road area is included for the clearcut block, and one-half of the upper and lower roads in the alternative treatment area are used (Curran and Thompson 1991, B.C. Ministry of Forests 1992) because the upper and lower roads can be used to access adjacent old-growth timber in the future. The occupancy of roads was 6.5% in the clearcuts and 6.3% in the MASS site. The calculations do not include rehabilitated pits and landings in the clearcut blocks, which represent approximately 0.5%. In Clearcut 1, small logs were bundled to reduce transportation cost. This required a landing, which was rehabilitated after harvest. The road calculations include the road sidecast, as required by the *Pre-harvest Silviculture Prescription Guidelines* (in effect during the study), even though these sidecast piles were primarily mineral soil, and were planted after harvest. The new *Forest Practices Code Guidebook for Soil Conservation* (B.C. Ministry of Forests 1995) procedures will delete plantable sidecast from roads, and would reduce permanent access structures (roads) to 4.3% for the clearcuts, and 3.5% for the alternative treatment area. An effort was made, especially on the MASS site, to build minimum-width roads, and to minimize turnout size. With use, and as a result of road maintenance activities, these roads widened slightly. The data presented here are for the post-harvest final width.

5.2.3 Pre-harvest soil density

Pre-harvest total soil bulk densities are summarized in Table 10. There was no correlation between depth of humus and bulk density, or between grid-point location and bulk density. To characterize the area, samples representing the range of conditions near each sample point were measured *in situ*. The humus (LFH) layers were usually much thinner on hummocks than the surrounding area; the average depth was 22 cm with the minimum 2 cm and the maximum 75 cm. (In fact, some

TABLE 3. Detailed timing of tracked skidder

Time Functions	Shelterwood (min)	Green tree (min)
Travel empty	0.88	0.84
Position	0.54	1.94
Grapple	0.76	1.73
Accumulate load	0.15	0.11
Travel loaded	0.96	0.74
Deck/forward on road	1.97	1.27
Productive	5.26	6.63
Delay	0.58	0.23
Total	5.84	6.86
Pieces/cycle	1.88	2.00
Average skidding/forwarding distance (m)	94.8	42.7

TABLE 4. Pre-harvest soil surface conditon summary for all treatments

	Disturbance			
Treatment	**Shelterwood (%)**	**Green tree (%)**	**Patch cut (%)**	**Clearcut (1 & 2) (%)**
Undisturbed	100.0	100.0	100.0	100.0
Moss/litter	74.2	81.0	81.6	81.7
Woody debris	14.9	11.1	6.9	10.9
Windfall	3.0	2.8	6.0	4.0
Rock	0.0	0.0	0.0	0.3
Stump	2.2	2.6	0.5	1.8
Stream	0.3	0.8	1.8	0.0
Mineral soil	0.6	0.4	0.7	0.2
Tree	2.6	1.3	0.4	1.1
Seepage site	0.9	0.0	0.6	0.0
Swamp	1.3	0.0	1.5	0.0
Disturbed	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0

TABLE 5. Pre-harvest downed woody debris, by decay class and treatment

	Treatment							
	Shelterwood		Green tree		Patch cut		Clearcut 2 (SL)	
Decay class	Average diameter (cm)	Percent of total samples[a] (%)	Average diameter (cm)	Percent of total samples[a] (%)	Average diameter (cm)	Percent of total samples[a] (%)	Average diameter (cm)	Percent of total samples[a] (%)
Class 1[b]	15.6	0.6	32.5	0.5	31.8	0.5	32.8	1.0
Class 2[b]	29.4	1.0	40.8	0.6	33.5	0.8	35.4	1.2
Class 3[b]	42.2	3.5	40.2	2.1	52.1	1.8	36.7	3.7
Class 4[b]	69.1	3.7	64.7	4.1	53.8	3.8	34.9	3.1
Class 5[b]	49.1	5.7	49.4	4.4	42.2	4.2	38.3	5.7
Class 5+	50.6	3.4	40.4	2.2	49.0	1.8	46.7	4.2
Total		17.9		13.9		12.9		18.9

[a] Percentage of total samples is the total of windfall and woody debris proportions in Table 4.
[b] See Figure 10 for pictoral description of decay classes

TABLE 6. Post-harvest soil surface condition

	Treatments							
	Shelterwood		Green tree		Patch cut		Clearcut	
Disturbance	% of total area	Average depth (cm)	% of total area	Average depth (cm)	% of total area	Average depth (cm)	% of total area	Average depth (cm)
Undisturbed	79.4		75.6		79.3		80.4	
Disturbed	20.6		24.4		20.7		19.6	
Humus-compacted	7.7	-12	8.9	-11	8.9	-15	9.1	-13
Mineral-compacted	0.4	-20	1.1	-24	1.0	-30	1.1	-18
Other (noncompacted)[a]	7.6		12.4		10.7		7.5	
Rehabilitated (in block)	4.9		2.0		0.1		1.9	

[a] mounds, gouges and deposits

TABLE 7. Post-harvest disturbance, by depth class—disturbed humus-compacted and mineral-compacted only

Depth Class (cm)	Shelterwood % of total area	Green tree % of total area	Patch cut % of total area	Clearcut % of total area
greater than -36	0.2	0.2	0.5	0.2
-31 to -35	0.1	0.1	0.1	0.1
-26 to -30	0.2	0.4	1.1	0.6
-21 to -25	0.5	0.5	0.5	0.4
-16 to -20	1.0	1.1	1.5	1.4
-11 to -15	1.6	1.3	2.1	2.4
-6 to -10	2.2	3.2	2.2	3.1
0 to -5	2.3	3.2	1.9	2.0
Total	8.1	10.0	9.9	10.2

TABLE 8. Area occupied by roads and landings—clearcut blocks

Disturbance cause	Average width (m)	Area(ha)	Percentage of total area(%)
Landings		0.0[a]	0.0[a]
Pull-outs		0.1	0.2
Roads:			
Cutbank	1.3	0.4	0.5
Ditch	1.9	0.6	0.8
Running surface	6.6	1.9	2.8
Sidecast	5.3	1.5	2.2
Total roads	15.1	4.4	6.3
Total all sources		4.5	6.5
Total clearcut area		69.1	100.0
Rehabilitated area:			
Pit/quarry		0.2	
Spur road		0.1	
Pulp-bundling landing		0.1	
Pull-out		0.0	
Total rehabilitated area		0.4	

[a] All landings were rehabilitated.

TABLE 9. Area occupied by roads—alternative treatment areas combined

Disturbance cause	Average width (m)	Area(ha)	Percentage of total area(%)
Landings		n/a	
Pull-outs		0.1	0.1
Roads:			
Cutbank	0.9	0.3	0.3
Ditch	2.6	0.9	1.0
Runing surface	5.2	1.9	2.0
Sidecast	7.4	2.6	2.8
Total roads	16.1	5.7	6.1
Total all sources		5.8	6.3
Total treatment area		93.9	100.00

TABLE 10. Pre-harvest total soil bulk density summary (g/cm^3)

	Sampling depth			
Treatment	0–20 cm	0–15 cm	0–10 cm	0–5 cm
Summary by Treatment				
Shelterwood	0.98	0.91	0.85	0.73
Green tree	0.96	0.91	0.86	0.76
Patch cut	0.94	0.90	0.85	0.73
Clearcut	0.98	0.93	0.90	0.80
Summary by Replicate				
Shelterwood 1	0.92	0.86	0.80	0.69
Shelterwood 2	0.96	0.89	0.84	0.73
Shelterwood 3	1.07	1.01	0.94	0.80
Green tree 1	0.96	0.91	0.85	0.75
Green tree 2	0.97	0.94	0.89	0.80
Green tree 3	0.94	0.89	0.84	0.75
Patch cut 1	0.86	0.85	0.79	0.68
Patch cut 2	0.97	0.91	0.86	0.75
Patch cut 3	0.99	0.95	0.89	0.76
Clearcut 1 (QB)	0.93	0.89	0.87	0.77
Clearcut 2 (SL)	1.03	0.98	0.93	0.83

humus layers were probably greater than 1 m, but measurement was not possible with the sampling procedure used.) In the deep humus areas, most of the rooting was confined to these layers. Evidence of fire, a charcoal layer at the mineral/humus interface, was noted at about 10% of the grid points. Table A14 details the humus depth information. The pre-harvest and undisturbed post-harvest measurements have been combined to increase the sample size.

5.2.4 Post-harvest soil density

Post-harvest total soil bulk densities are shown in Table 11, with more detail in Table A15. The *disturbed* densities were measured only in machine tracks because density gauge and shovel sampling in log gouges and stumping disturbance in the Clearcut 1 revealed no measurable compaction. Machine tracks also represented the largest proportion of disturbance. For each treatment and depth, the soil bulk density was greater for the disturbed samples than for the undisturbed. No relationship between the machine track depth and the change in bulk density (between disturbed and undisturbed) was observed. In general, the change in bulk density increased with increasing forest removal levels (from shelterwood to clearcut).

5.3 Woody Debris

The results of the post-harvest woody debris survey are shown in Tables 12 and 13, and in Tables A16 and A17. The volumes, per hectare, of all decay and size classes are relatively consistent between treatments, except that the patch cut treatments are 20% lower than the others. Only dispersed woody material volumes are shown. Roadside areas with accumulations of slash were site-prepared. A weighted average of the woody waste from the site-prepared area and the dispersed debris was 413 m^3/ha for the patch cut treatment, which was 10% lower than for the other treatments.

The volume of large (greater than 5-cm diameter) sound wood (Class 1) is 16–31% of the total large wood. The remainder of the large wood varies in decay level (Table 13). The pre-harvest cruise data shows that net volumes were 60% of gross volumes and were similar between treatments and Clearcut 2, except for the green-tree treatment, which was 70% (Table A1). The amount of large, broken, sound wood is similar for the clearcut and patch cut treatments, but is 25% lower in the shelterwood treatments and 80% higher in the green-tree treatments (Table A17). Breakage from falling and forwarding could not be separated in the post-harvest surveys.

5.4 Regeneration

No operational planting costs were obtained because natural regeneration was the method designated in the PHSP, with planting only if necessary. Therefore, planting will be carried out in the fall of 1995 or 1996 if there is insufficient stocking of desired species from natural regeneration. A central core in each of the treatments was designated for research planting that will explore shade tolerance, nutrient needs, and competition issues.[9, 10] In addition, the bio-assay for the soil compaction project has required planting on some of the machine tracks and adjacent undisturbed areas.[11] In an additional study by the division, a strip around the central research core was planted to monitor the growth potential of yellow-cedar and Douglas-fir (*Pseudotsuga menziesii*). Douglas-fir is not normally a recommended species for the montane ecosystem because of the high potential for snow damage (Figure 17); however, there is historical evidence that Douglas-fir grew on this site, and that the growth increment on nearby plantations is good.

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9 Dunsworth, B.G. and J.T. Arnott, 1992. Growth limitations of regenerating montane conifers in field environments. *In* Montane Alternative Silvicultural Systems—working plan.

10 Mitchell, A.K. and J.T. Arnott. 1992. Growth limitations of regenerating montane conifers in controlled environments *In* Montane Alternative Silvicultural Systems—working plan.

11 Senyk, J.P. and D. Craigdallie, 1992. Long-term soil and forest productivity impacts of silvicultural trials at Iron River (FC-IRM-18) *In* Montane Alternative Silvicultural Systems—working plan

TABLE 11. Post-harvest total soil bulk density summary (g/cm^3)—summary by treatment

	Sampling depth							
Treatment	**0–20 cm undisturbed**	**0–20 cm disturbed**	**0–15 cm undisturbed**	**0–15 cm disturbed**	**0–10 cm undisturbed**	**0–10 cm disturbed**	**0–5 cm undisturbed**	**0–5 cm disturbed**
Shelterwood	1.01	1.07	0.96	1.02	0.89	0.97	0.78	0.87
Green tree	1.01	1.13	0.95	1.08	0.91	1.02	0.82	0.93
Patch cut	1.02	1.13	0.96	1.08	0.91	1.05	0.84	0.93
Clearcut	1.03	1.18	0.99	1.12	0.95	1.08	0.84	0.98

TABLE 12. Volume of post-harvest downed woody debris, by type and treatment (m^3/ha)

Size class (diameter in cm)	Shelterwood	Green tree	Patch cut	Clearcut
1–5	11	15	13	14
greater than 5	438	417	368	463
Total	449	432	380	477

TABLE 13. Volume of post-harvest large (greater than 5-cm diameter) woody debris, by decay class (m^3/ha)

	Shelterwood	Green tree	Patch cut	Clearcut
Class 1[a]	69	132	88	136
Class 2[a]	51	77	97	87
Class 3[a]	61	73	72	77
Class 4[a]	88	49	48	51
Class 5[a]	108	52	44	105
Class 5+	61	34	19	7
Total	438	417	368	463

[a] See Figure 10 for pictoral descriptions of decay classes.

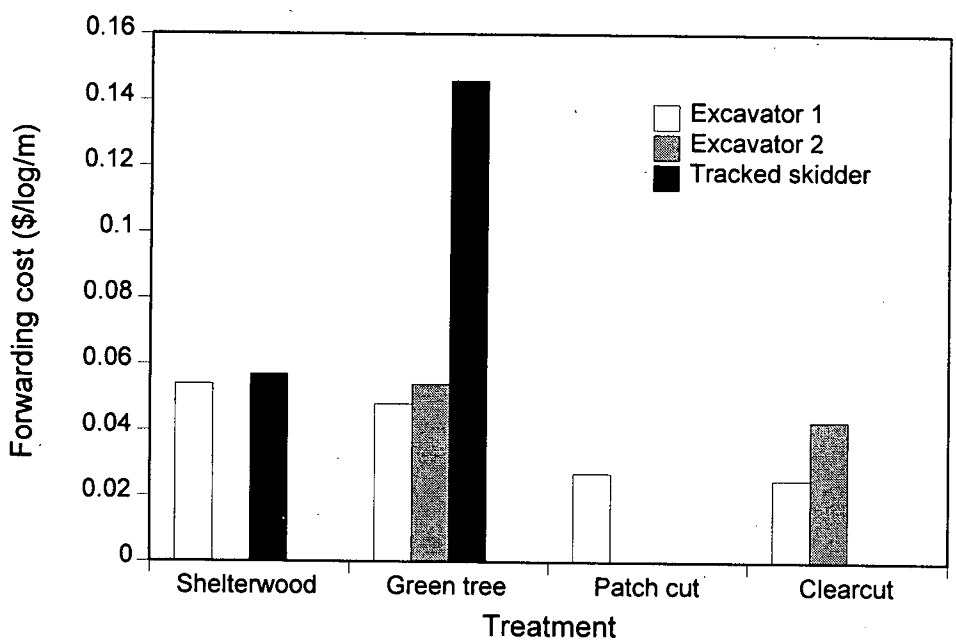

FIGURE 15. Comparison of Forwarding Cost.

FIGURE 16. Single-pass machine track.

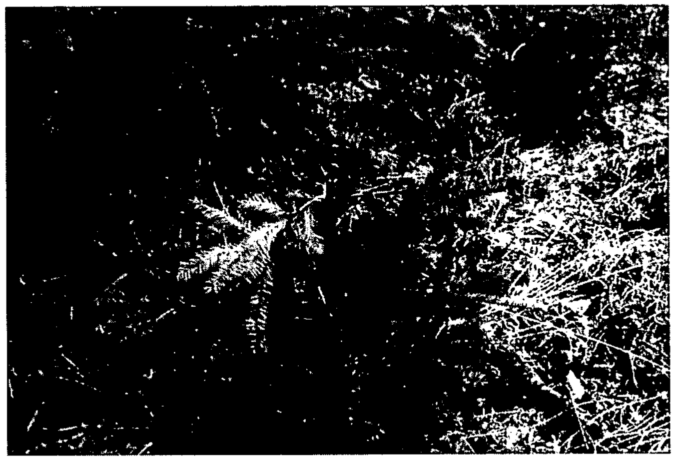

FIGURE 17. Douglas-fir with snow damage

Very little advanced regeneration was undamaged after harvesting in the patch cut and clearcut treatments. A higher percentage survived in the green-tree and shelterwood—especially near leave-trees. Post-harvest surveys by MB's Woodland Services have documented the exact distribution, and these will be published in a report on that component of the study. Age sampling of amabilis fir advanced regeneration found two age classes of 60–160 years with diameter less than 2 cm and less than 60 years with diameter up to 5 cm.[12] Age sampling of old-growth trees shows that some have a very dense core, indicating that they may have developed from released advanced regeneration several hundred years ago. Permanent sample plots through all the treatments will be monitored to determine the long-term growth of all trees, including advanced regeneration.[13]

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[12] W.J. Beese, 1993. Montane Alternative Silvicultural Systems (MASS)—progress report

[13] N.J. Smith, 1992. Yield implications of alternative silvicultural systems and advance amabilis-fir regeneration problems in montane forests *In* Montane Alternative Silvicultural Systems—working plan.

6 DISCUSSION

Much of the success of this trial was related to project planning and coordination. The crew accepted the rationale of the objectives, and, in most cases, accepted the challenge and tried to find solutions to operational problems. Throughout the study, the researchers communicated with the crew and answered questions as they arose.

6.1 Patch Cut

The patch cuts were essentially small clearcuts, and initially the falling and forwarding were not expected to be challenging. However, the inconsistent lean of the stand, especially the larger trees, and the number and depth of small swampy areas made harvesting difficult, and did not allow the fallers to open and maintain a normal falling face. The patch areas were too small for two fallers to work safely, so radios were used to maintain safety check-in procedures. The patch cuts were the first areas to be felled and forwarded. The forwarding did not pose problems, except for the small swampy patches that were often camouflaged by the felled timber. The excavator operators checked the softness of the ground with the heel of the boom and used puncheon (slash used to increase machine flotation during forwarding) where necessary. The falling pattern did not greatly affect the excavator forwarding productivity; however, when small stems were crossed, the breakage was high. Considerable reduction in excavator forwarding productivity would have been required to ensure no breakage. Much of the advanced regeneration that was preserved in falling was destroyed in forwarding.

The performance of the tracked skidder was greatly affected by falling pattern because it did not have the potential to reach for pieces, and had to maneuver to the end of each piece. The manufacturer suggested that a swing grapple would be more versatile in future trials. However, with experience, the operator learned to use the winch for large logs, for logs that were not correctly aligned, or where the terrain made it difficult to access logs. The use of the winch/choker with the grapple for large logs prevented log loss during skidding, and allowed log release and winching on steep trails. The use of the winch for logs that were not aligned and for logs on swampy patches reduced site disturbance and increased productivity.

6.2 Green Tree

Falling in the green-tree treatment was more difficult than in a conventional clearcut. Initially, tree marking had not fully accounted for the lean of the larger trees, and some leave-trees were in the falling path of large-diameter trees. In these cases, and in cases with special safety considerations, the fallers substituted a harvest tree for a leave-tree. Leaving smaller trees standing was very difficult; unlike the larger leave-trees, even brushing the small-diameter trees with the top of a larger felled tree resulted in damage or complete knock-down. After viewing the forwarding of the first green-tree unit, the fallers changed to a practice of leaving patches of advanced regeneration, especially close to leave-trees.

Forwarding the green-tree treatment required more skill than in the clearcut. Initially, forwarding damaged some of the leave-trees, but, with more experience and on-site discussion of the project objectives among the crew, fewer trees were damaged. Decking logs in the green-tree and the shelterwood blocks presented problems because the shallow roots of the residual trees were easily damaged when piling occurred too close to them. The presence of the trees also reduced the options for machine travel. To produce a potentially windfirm stand, trees on higher ground were chosen, requiring more use of puncheon during forwarding. The serpentine pattern was generally the most efficient, but the up-and-down pattern enabled the excavator to be at roadside for truck loading more frequently. The up-and-down pattern was also used by one excavator to combine both forwarding and truck loading.

6.3 Shelterwood

The shelterwood treatment was the greatest challenge for the fallers. Falling the large-diameter, high-value trees without breakage and without damaging leave-trees was difficult. Groups of leave-trees were the easiest to avoid. As in the green-tree treatment, some of the initial marking did not take into account the falling direction of the larger trees. After feedback from the fallers working in the first replicate, the tree marking in the remaining replicates took this factor into account. The fallers considered that the shelterwood falling was the most hazardous. The techniques required were comparable to continually opening a road right-of-way. The one lost-time accident in the shelterwood block resulted when a limb falling from a residual tree struck a faller.

Initially, long log lengths were cut to increase productivity—especially in the shelter-woods. However, long logs were more prone to breakage, and soon short log lengths were chosen, both for ease of forwarding and to reduce breakage. The wood on the corridors was forwarded before the falling between the corridors was completed to reduce stems falling across each other with subsequent breakage of high-value logs.

In order to reduce their visual impact, the corridors were not located in one continuous strip between the roads. Falling a short machine trail, parallel to the haul roads and between two staggered halves of one corridor, improved the forwarding efficiency. As with the other treatments, during the layout of the shelterwood corridors leave-trees were left on higher, better-drained sites to reduce the risk of windthrow. The forwarding corridors tended to be on lower, wetter sites, and the forwarding operator puncheoned these corridors to reduce site damage. Some leave-trees outside of the corridors were removed during forwarding to accommodate the size of the excavator. The forwarding corridors varied from 15 to 20 m in width at the completion of forwarding. This width was barely adequate for the equipment, especially close to the road where large log decks were made, often very close to residual trees. More loading during forwarding would have helped reduce the size of log decks.

6.4 Post-harvest Surveys

The amount of downed woody biomass was reasonably consistent between treatments; however, the distribution between decay classes was different. The shelterwood had more material in the higher decay classes, probably because more area was undisturbed with the original woody material in place. The green-tree treatment had a higher level of solid **class 1** wood remaining. Increased breakage during falling and forwarding was the primary cause. No current targets exist for post-harvest coarse woody debris levels in British Columbia; however, the MASS levels are about three times those suggested as minimum levels (Hopwood 1991) from one US Forest Service ranger district.

Site disturbance was roughly equal between treatments, with about 10% in the disturbed compacted category and about half of that in the less than 10-cm depth class. The whole soil bulk density sampling in deep tracks consistently showed an increase of approx-imately 10%, compared to undisturbed areas. However, the density was considered to be below the threshold for impeding roots (Heilman 1981, Lousier 1990). The deep humus layers and the high slash loading helped protect the mineral soil by dispersing the weight of the harvesting equipment.

7 CONCLUSIONS

This multi-agency, multi-disciplinary research project was prompted by forest operators' concerns about regeneration performance in coastal montane forests, and by public pressure to limit clearcutting in all public forests when the practical and economic limitations of such restrictions are not clearly understood. The study was a cooperative project between MacMillan Bloedel Limited, the Canadian Forest Service, and FERIC, with participation by the University of Victoria and the University of British Columbia.

Harvesting of the three alternative treatments—shelterwood, green-tree retention, and patch cut—was completed in 1993 and then compared to a conventional clearcut block on MacMillan Bloedel's private forest land. Post-harvest studies will continue in the alternative treatments, the clearcut, and an old-growth reserve for at least 20 years.

This trial showed that alternative harvesting systems can be applied to old-growth forests in gentle terrain with reasonable falling and forwarding success. The combined cost of falling and forwarding were 10% higher for the patch cut and green-tree treatments, and were 38% higher for the shelterwood treatment, compared to the clearcut base. The cost of harvesting replicates within the same treatment were very variable because of differences in timber, terrain, and crew experience. The trial succeeded because the crew was willing to try a new application of existing skills.

The success of the application of alternative silvicultural systems to coastal montane areas will be measured by the amount of windthrow that occurs over time, and by regeneration performance. There is potential for windthrow in each of the treatments. It may be possible to achieve lower overall costs through the application of silvicultural systems if free-to-grow standards can be met earlier and at less cost; however, the loss of the residual timber volume, tree marking costs, and additional supervision requirements must also be included in the equation. Long-term assessment of windthrow and regeneration success will answer some of the remaining question about the applicability of alternative silvicultural systems in these stands.

8 RECOMMENDATIONS

- Include the crew in the planning and the layout processes.
- Select leave-trees that are likely to be windfirm.
- Tree marking should recognize the practicalities of falling and forwarding.
- Consider layout and protective structures to protect leave-tree stems and roots and advanced regeneration during harvest.
- Forwarding corridors in a shelterwood should not be continuous, and should be staggered with machine access trails connecting the halves.
- Clump leave-trees in shelterwood treatments to maintain productivity with minimal damage.
- Avoid large log decks by loading during harvesting.

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APPENDIX

TABLE A1. MASS Forest cover inventory—overstory trees by block (after Beese 1995)

Block	Stand composition[a]	Volume: Gross merchantable (m³/ha)	Volume: Total net (m³/ha)	Basal area (m²/ha)	Tree density (trees/ha)[b]
Green tree 1	B5H4C1	1 056	675	71	461
Green tree 2	H5B2C2Y1	911	736	91	751
Green tree 3	H4C4B1Y1	1 159	757	94	568
Patch cut 1	B5H3C2	947	583	71	496
Patch cut 2	B4H3C3	1 031	618	82	489
Patch cut 3	C4H4B1Y1	1 048	573	83	525
Shelterwood 1	H5B4C1	937	592	69	401
Shelterwood 2	B5H3C2	1 021	499	72	604
Shelterwood 3	C4H2B2C1	975	562	78	493
Alternative treatment area	**H4B3C2**	**1 028**	**626**	**78**	**528**
Clearcut[c]	B6H4	1 092	661	74	508
Old growth	H4B4C2	990	549	71	431

[a] For example, H5B2C2Y1 = Western hemlock, 50%; Amabilis fir, 20%; Western red cedar, 20%; Yellow-cedar, 10%—based on total net volume.

[b] Does not include snags

[c] Average for 56 ha clearcut, harvested in 1992.

TABLE A2. Shift-level falling delays, by treatment (all times in hours)

	Call out	Light duty	Mechanical	Move between areas	Safety	Training	Total of all delays to pro-rate[a]	Mangement/ Organization	Research	Total of research and management delays
Green tree 1		1.5			6.0		7.5	0.5		0.5
Green tree 2					16.0		16.0		2.5	2.5
Green tree 3					8.0		8.0			
Patch cut 1	8.0		1.0	2.0	2.5	1.0	14.5	0.5	1.0	1.5
Patch cut 2	4.0		0.5		2.5	1.5	8.5		2.0	2.0
Patch cut 3					12.0	0.5	12.5		2.0	2.0
Shelterwood 1		1.5		1.0	13.5		16.0		1.0	1.0
Shelterwood 2					14.0		14.0	10.5	5.8	16.3
Shelterwood 3				1.5	4.0		5.5			
Clearcut 2	4.0	6.5			2.5		13.0			
Total	16.0	9.5	1.5	4.5	81.0	3.0	115.5	11.5	14.3	25.8

[a] Pro-rate delay factor = (delays to pro-rate)/(total productive hours) = (115.5)/(3 406.8) = 0.03 hours of delay/productive hour

TABLE A3. Costing assumptions (for fallers)

Daily rate	$260.88
Wage benefit loading (%)	37
Wages and benefits	$357.41
Chainsaw & supplies	$27.00
Total cost/day	$384.41
Working hours/day	6.5

TABLE A4. Shift-level forwarding delays, by treatment (all times in hours)

Machine	Treatment	Pro-rated* mechanical (in-shift)	Service	Move	Total delays for costing	Personal	Other	Total delays not in costing
Excavator 1	Green tree 1	7.0	3.0	4.0	14.0	0.5		0.5
	Green tree 2	5.7	3.5	2.0	11.2			
	Green tree 3	0.7	4.5	2.0	7.2			
	Patch cut 1	5.2	4.0	2.0	11.2			
	Patch cut 2	5.2	4.5	2.0	11.7			
	Patch cut 3	1.4	3.5	2.0	6.9			
	Shelterwood 1	6.2	3.5	2.0	11.7			
	Shelterwood 2	4.8	3.0	4.0	11.8	0.5		0.5
	Shelterwood 3	3.5	5.0	2.0	10.5			
	Clearcut 2	5.0	5.5	2.0	12.5			
		*pro-rate factor = 0.07 hr mechanical/productive hr						
Excavator 2	Green tree 1	0.2	0.5		0.7			
	Green tree 2	0.7	0.5		1.2			
	Green tree 3							
	Patch cut 1							
	Patch cut 2							
	Patch cut 3	0.8	1.5	3.0	5.3	1.0	2.0	3.0
	Shelterwood 1							
	Shelterwood 2							
	Shelterwood 3	0.0		0.5	0.5			
	Clearcut 2	0.1	0.5	2.0	2.6			
		*pro-rate factor = 0.02 hr mechanical/productive hr						
Excavator 3	Green tree 1							
	Green tree 2	0.7	0.5	4.0	5.2	1.0	1.0	2.0
	Green tree 3	2.6	4.5	17.6	24.7	2.0	1.0	3.0
	Patch cut 1							
	Patch cut 2							
	Patch cut 3	0.5	0.5	3.0	4.0	1.0	3.5	4.5
	Shelterwood 1	0.4	1.0	3.5	4.9		3.0	3.0
	Shelterwood 2	0.3		1.3	1.6			
	Shelterwood 3	0.2		1.3	1.5	2.0		2.0
	Clearcut 2							
		*pro-rate factor = 0.02 hr mechanicnal/productive hr						
Tracked skidder	Green tree 1							
	Green tree 2	7.9	1.0	0.8	9.7	1.0	2.5	3.5
	Green tree 3							
	Patch cut 1	1.9			1.9			
	Patch cut 2							
	Patch cut 3	0.1			0.1			
	Shelterwood 1	8.2			8.2	1.0	2.0	3.0
	Shelterwood 2	8.8			8.8	6.5	1.5	8.0
	Shelterwood 3	10.0	0.5		10.5	2.0	0.5	2.5
	Clearcut 2							
		*pro-rate factor = 0.08 hr mechanical/productive hr						

TABLE A5. Equipment specifications

Excavator 1 (Primary Forwarder)	
Thunderbird 1146	
Machine type	Hydraulic excavator with grapple
Reach	14.6 m
Weight	63 400kg
Engine	Cummins L10 - 235 kw
Ground clearance	0.84 m
Machine width	4.1 m
Foot print length	4.3 m
Track width	0.81 m
Excavator 2	
Cypress 1825 C	
Machine type	Hydraulic excavator with grapple
Reach	13.4 m
Weight	65 800 kg
Engine	Cummins - 261 kw
Ground clearance	0.61 m
Machine width	4.3 m
Foot print length	4.5 m
Track width	0.82 m
Excavator 3	
Chapman 1825	
Machine type	Hydraulic excavator with grapple
Reach	13.4 m
Weight	60 800 kg
Engine	GM - 268 kw
Ground clearance	0.57 m
Machine width	4.3 m
Foot print length	4.8 m
Track width	0.76 m
Flexible tracked skidder	
KMC 2500AG (arch grapple)	
Machine type	Tracked skidder with grapple and chokers
Weight	15 200 kg
Engine	Detroit - 149 kw
Ground clearance	0.48 m
Machine width	2.6 m
Foot print length	2.9 m
Track width	0.56 m

TABLE A6. Productivity and cost summary—shelterwood

Shelterwood treatments only	SW1	SW2	SW3	All SW
Area (ha)	9.4	9.5	8.7	27.5
Volume				
Sawlogs & peeler logs (m^3)	4 635	4 397	4 024	13 056
Pulp (m^3)	761	395	291	1 447
Total (m^3)	5 396	4 792	4 315	14 503
Piece size				
Sawlogs & peeler logs (m^3)	1.61	1.52	1.59	1.57
Pulp (m^3)	0.44	0.45	0.41	0.44
Total (m^3)[a]	1.17	1.27	1.33	1.25
Falling				
Productive time (hr)	359.5	358.3	316.5	1 034.3
Productive time+prorated delays (hr)	371.7	370.4	327.2	1 069.3
Productivity (m^3/h)	14.5	12.9	13.2	13.6
Cost ($/hr)	59.14	59.14	59.14	59.14
Cost ($/$m^3$)	4.07	4.57	4.48	4.36
Forwarding				
Excavator 1				
Productive time (prime function) (hr)	90.0	69.3	50.8	210.1
Productive time+prorated delays (h)	103.5	80.1	60.8	244.5
Cost ($/hr)	137.95	137.95	137.95	137.95
Total cost ($)	14 278	11 050	8 387	33 715
Excavator 2				
Productive time (prime function) (hr)			0.5	0.5
Productive time+prorated delays (hr)			1.0	1.0
Cost ($/hr)			145.44	145.44
Total cost ($)			145.44	145.44
Excavator 3				
Productive time (prime function) (hr)	20.0	16.5	13.3	49.8
Productive time+prorated delays (hr)	22.4	16.8	13.5	52.7
Cost ($/hr)	145.44	145.44	145.44	145.44
Total cost ($)	3 258	2 443	1 963	7 665
Tracked Skidder				
Productive time (prime function) (h)	97.3	104.0	118.5	319.8
Productive time+prorated delays (h)	105.5	112.8	129.0	347.4
Cost ($/hr)	112.95	112.95	112.95	112.95
Total cost ($)	11 916	12 741	14 571	39 228
Total forwarding cost ($)	29 452	26 234	25 067	80 753
Total forwading cost ($/$m^3$)	5.46	5.47	5.81	5.57

[a] Weighted-average piece size

TABLE A7. Productivity and cost summary—green tree

Green tree treatments only	GT1	GT2	GT3	All GT
Area (ha)	8.6	9.7	9.0	27.3
Volume				
Sawlogs & peeler logs (m^3)	5 217	5 579	5 366	16 162
Pulp (m^3)	787	852	624	2 263
Total (m^3)	6 004	6 431	5 990	18 425
Piece size				
Sawlogs & peeler logs (m^3)	1.56	1.52	1.38	1.48
Pulp (m^3)	0.48	0.39	0.38	0.41
Total (m^3)[a]	1.20	1.10	1.08	1.12
Falling				
Productive time (hr)	315.0	339.0	447.0	1 101
Productive time+prorated delays (hr)	325.7	350.5	462.2	1 138.4
Productivity (m^3/hr)	18.4	18.3	13.0	16.2
Cost ($/hr)	59.14	59.14	59.14	59.14
Cost ($/$m^3$)	3.21	3.22	4.55	3.65
Forwarding				
Excavator 1				
Productive time (prime function) (hr)	101.8	82.0	10.0	193.8
Productive time+prorated delays (hr)	115.8	95.7	12.0	223.5
Cost ($/hr)	137.95	137.95	137.95	137.95
Total cost ($)	15 975	13 202	1 655	30 832
Excavator 2				
Productive time (prime function) (hr)	7.5	30.3		37.8
Productive time+prorated delays (hr)	8.4	32.4		40.8
Cost ($/hr)	145.44	145.44		145.44
Total cost ($)	1 222	4 712		5 934
Excavator 3				
Productive time (prime function) (hr)		41.0	147.5	188.5
Productive time+prorated delays (hr)		46.2	155.6	201.9
Cost ($/hr)		145.44	145.44	145.44
Total cost ($)		6 719	22 630	29 350
Tracked Skidder				
Productive time (prime function) (hr)		93.0		93.0
Productive time+prorated delays (hr)		102.7		102.7
Cost ($/hr)		112.95		112.95
Total cost ($)		11 600		11 600
Total forwarding cost ($)	17 196	36 233	23 286	77 716
Total forwarding cost ($/$m^3$)	2.86	5.63	4.05	4.22

[a] Weighted-average piece size

TABLE A8. Productivity and cost summary—patch cut

Patch cut treatments only	PC1	PC2	PC3	All PC
Area				
Harvested area	5.9	5.4	5.7	17.1
Treatment harvested (%)	51	50	53	52
Volume				
Sawlogs & peeler logs (m^3)	3 620	2 940	3 450	10 010
Pulp (m^3)	443	370	352	1165
Total (m^3)	4 063	3 310	3 802	11 175
Piece size				
Sawlogs & peeler logs (m^3)	1.59	1.43	1.31	1.44
Pulp (m^3)	0.41	0.32	0.43	0.38
Total (m^3)[a]	1.22	1.03	1.10	1.12
Falling				
Productive time (hr)	297.5	208.0	275.0	780.5
Productive time+prorated delays (hr)	307.6	215.1	284.3	807
Productivity (m^3/hr)	13.2	15.4	13.4	13.8
Cost ($/hr)	59.14	59.14	59.14	59.14
Total cost ($/$m^3$)	4.48	3.84	4.41	4.29
Forwarding				
Excavator 1				
Productive time (prime function) (hr)	75.3	75.8	20.0	171.1
Productive time+prorated delays (hr)	85.0	88.3	23.4	196.7
Cost ($/hr)	137.95	137.95	137.95	137.95
Total cost ($)	11 726	12 181	3 228	27 135
Excavator 2				
Prosuctive time (prime function) (hr)			32.5	32.5
Productive time+prorated delays (hr)			38.7	38.7
Cost ($/hr)			145.44	145.44
Total cost ($)			5 629	5 629
Excavator 3				
Productive time (prime function) (hr)			29.0	29.0
Productive time+prorated delays (hr)			30.0	30.0
Cost ($/hr)			145.44	145.44
Total cost ($)			4 363	4 363
Tracked Skidder				
Productive time(prime function) (hr)	23.0		1.5	24.5
Productive time+prorated delays (hr)	24.9		1.6	26.5
Cost ($/hr)	112.95		112.95	112.95
Total cost ($)	2 812		181	2 993
Total forwarding cost ($)	14 538	12 181	13 400	40 120
Total forwarding cost ($/$m^3$)	3.58	3.68	3.52	3.59

[a] Weighted-average piece size

TABLE A9. Productivity and cost summary—clearcut

Clearcut control only	Clearcut 1 (QB)	Clearcut 2 (SL)	All Clearcut
Area (ha)	58.5	10.6	69.1
Volume			
Sawlogs & peeler logs (m^3)	33 366	5 807	39 173
Pulp (m^3)	5 196	991	6 187
Total (m^3)	38 562	6 798	45 360
Piece size			
Sawlogs & peeler logs (m^3)	1.33	1.51	1.68
Pulp (m^3)	0.39	0.39	0.39
Total (m^3)[a]	1.17	1.07	1.15
Falling			
Producitve time (hr)	2 227.8	491.0	2 718.8
Productive time+prorated delays (hr)	2 360.1	507.7	2 867.8
Productivity (m^3/hr)	16.3	13.4	15.8
Cost ($/hr)	59.14	59.14	59.14
Cost ($/$m^3$)	3.63	4.41	3.74
Forwarding			
Excavator 1			
Productive time (prime function) (hr)	404.9	72.2	477.1
Productive time+prorated delays (hr)	437.9	84.7	522.6
Cost ($/hr)	137.95	137.95	137.95
Total cost ($)	60 408	11 684	72 093
Excavator 2			
Productive time (prime function) (hr)	180.0	61.0	241.0
Productive time+prorated delays (hr)	200.5	70.1	270.6
Cost ($/hr)	145.44	145.44	145.44
Total cost ($)	29 161	10 195	39 356
Excavator 3			
Productive time (prime function) (hr)	21.0		21.0
Productive time+prorated delays (hr)	21.0		21.0
Cost ($/hr)	145.44		145.44
Total cost ($)	3 054	3 054	
Super-snorkel			
Productive time (prime function) (hr)	165.2		165.2
Productive time+prorated delays (hr)	187.0		187
Cost ($/hr)	223.82		223.82
Total cost ($)	41 854	41 854	
Total forwarding cost ($)	134 478	21 880	156 357
Total forwarding cost ($/m3)	3.49	3.22	3.45

[a] Weighted-average piece size

TABLE A10. Machine costs

Machine Costs	Cypress 1825C hydraulic loader	Madill O75 super snorkel	Thunderbird 1146 hydraulic loader	KMC 2500 track skidder	Cypress 7230 cable loader
Ownership Costs					
Total purchase price (P) $	650 000	950 000	600 000	284 000	883 000
Expected life (Y) yr	10	10	10	5	12
Expected life (H) h	14 400	14 400	14 400	8 000	17 280
Scheduled hours per year (h)=(H/Y) h	1 440	1 440	1 440	1 600	1 440
Salvage value as % of P (s)%	30	20	30	20	30
Interest rate (Int) %	5.5	5.5	5.5	5.5	5.5
Insurance rate (Ins) %	1.5	1.5	1.5	1.5	1.5
Salvage value (S)=(P*s/100) $	195 000	190 000	180 000	56 800	264 900
Average investment (AVI)=((P+S)/2) $	422 500	570 000	390 000	170 400	573 950
Loss in resale value ((P-S)/H $/h	31.60	52.78	29.17	28.40	35.77
Interest ((Int*AVI)/h) $/h	16.14	21.77	14.90	5.86	21.92
Insurance ((Ins*AVI)/h) $/h	4.40	5.94	4.06	1.60	5.98
Total ownership costs (OW) $/h	52.14	80.49	48.13	35.86	63.67
Operating Costs					
Wire rope (wc) $		6 000			6 000
Wire rope life (wh) h		1 440			1 440
Fuel consumption (F) L/h	37	37	37	12	37
Fuel (fc) $/L	0.42	0.42	0.42	0.42	0.42
Lube and oil as % of Fuel (fp) %	10	10	10	10	10
Track and undercarriage replacement (Tc) $	32 000	19 392	32 000	146 580	14 544
Track and undercarriage life (Th) h	8 000	16 000	8 000	8 000	16 000
Annual repair and maintenance (Rp) $	61 800	92 461	56 800	28 650	71 871
Shift length (sl) h	8	8	8	8	8
Wages $/h					
Operator	21.38	22.57	21.38	20.23	21.97
Second Loader		18.78			18.78
Total wages (W) $/h	21.38	41.35	21.38	20.23	40.75
Wage benefit loading (WBL) %	37	37	37	37	37
Wire rope (wc/wh) $/h		4.17			4.17
Fuel (F*fc) $/h	15.54	15.54	15.54	5.04	15.54
Lube and oil ((fp/100)*(F*fc)) $/h	1.55	1.55	1.55	8.10	1.55
Track and undercarriage (Tc/Th) $/h	4.00	1.21	4.00	18.32	0.91
Repair and maintenance (Rp/h) $/h	42.92	64.21	39.44	17.91	49.91
Wages and benefits (W*(1+WBL/100)) $/h	29.29	56.65	29.29	27.72	55.83
Total operating costs (OP) $/h	93.30	143.33	89.83	77.09	127.91
Total Ownership and Operating Costs (OW+OP) $/h	145.44	223.82	137.95	112.95	191.58

* These costs are based on FERIC's standard costing methodology for determining machine ownership costs. These costs do not include supervison, profit and overhead, crew transportation, nor costs related to lost productivity of one day or more. The costs are not the actual costs of the company studied.

- Purchase price is based on distrubutor quoted prices for new equipment.
- Annual repair and maintenance costs were estimated by dividing the purchase price (P) by the expected life (Y).
- Wages are derived from the coastal I.W.A, wage scale for June 15, 1993.
- KMC anual costs for repair and maintenance were provided by the equipment supplier.

TABLE A11. Pre-harvest soil surface condition disturbance summary

	Treatment										
	Shelterwood			Green tree			Patch cut			Clearcut	
Disturbance	**1 (%)**	**2 (%)**	**3 (%)**	**1 (%)**	**2 (%)**	**3 (%)**	**1 (%)**	**2 (%)**	**3 (%)**	**1(QB) %**	**2 (SL) %**
Undisturbed	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Moss/litter	79.6	68.0	74.0	82.2	77.5	83.2	81.4	80.5	82.7	91.3	72.7
Windfall	2.5	4.1	2.5	2.6	2.5	3.1	2.5	3.8	11.2	2.1	5.7
Woody debris	12.1	18.0	15.3	10.2	15.1	8.1	9.0	7.8	4.1	5.0	16.4
Rock	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.6	0.1
Stump	2.5	1.9	2.3	2.4	2.8	2.7	0.2	0.2	1.1	0.1	3.3
Stream	0.3	0.5	0.2	1.0	0.9	0.4	2.9	2.7	0.0	0.0	0.1
Mineral	0.4	1.0	0.2	0.3	0.5	0.4	1.6	0.0	0.4	0.5	0.0
Tree	2.6	2.7	2.4	1.3	0.7	1.9	0.6	0.2	0.5	0.4	1.7
Seepage	0.0	1.5	1.3	0.0	0.0	0.0	1.8	0.0	0.0	0.0	0.0
Swamp	0.0	2.3	1.8	0.0	0.0	0.0	0.0	4.8	0.0	0.0	0.0

TABLE A12. Post-harvest soil surface condition

	Treatments							
	Shelterwood		Green tree		Patch cut		Clearcut	
Condition	**total (%)**	**Average depth (cm)[a]**	**total (%)**	**Average depth(cm)[a]**	**total (%)**	**Average depth (cm)[a]**	**total(%)**	**Average depth (cm)[a]**
Undisturbed	79.4		75.5		79.3		80.4	
Disturbed	20.6		24.4		20.7		19.6	
Organic-compacted	7.7	-12	8.9	-11	9.0	-15	9.1	-13
Organic-mounded	2.1	12	3.0	12	1.5	10	1.6	11
Organic-gouged	2.0	-11	3.8	-11	4.0	-13	1.6	-13
Organic-deposit	2.8	22	3.4	26	3.9	27	1.5	25
Mineral soil-compacted	0.4	-20	1.0	-24	1.0	-30	1.1	-18
Mineral soil-mounded	0.0		0.1	63	0.1	17	0.5	18
Mineral soil-gouged	0.2	-16	0.7	-19	0.5	-29	1.3	-16
Mineral soil-deposit	0.5	17	1.5	14	0.6	18	1.1	21
Mineral soil-rehabilitated	2.3		0.9		0.1		0.9	
Organic-rehabilitated	2.6		1.1		0.0		0.9	
Total	100.0		100.0		100.0		100.0	

[a] Depth is measured form original ground surface level.

TABLE A13. Post-harvest site-disturbance, by cause

	Treatment			
	Shelterwood total samples (%)	Green tree total samples (%)	Patch cut total samples (%)	Clearcut total samples (%)
Cause:				
Excavator track	7	12	9	12
KMC track	3	1	2	0
Excavator and KMC	1	0	2	0
Forwarding corridor	1	0	0	0
Log gouge	2	4	4	3
Stumping	2	5	4	3
Ditching	0	0	0	
Unknown	0	0	0	
Rehabilitation	5	2	0	2
Total	21	24	21	20

TABLE A14. Depth of organic (LFH) soil layers (undisturbed humus)

Treatment	Average (cm)	Minimum (cm)	Maximum (cm)	Standard deviation (cm)
Shelterwood 1	22	2	65	12
Shelterwood 2	26	2	62	14
Shelterwood 3	21	6	59	11
All shelterwood	23	2	65	13
Green tree 1	24	3	75	14
Green tree 2	24	4	75	14
Green tree 3	29	6	73	13
All green tree	26	3	75	14
Patchcut 1	28	9	50	11
Patchcut 2	27	7	68	12
Patchcut 3	26	8	75	12
All patchcut	27	7	75	12
Clearcut QB	16	2	51	11
Clearcut SL	14	3	51	10
All clearcut	15	2	51	11
All treatments	23	2	75	13

TABLE A15. Post-harvest total soil bulk density summary (g/cm^3)

	Sampling depth							
Treatment	0–20 cm undisturbed	0–20 cm disturbed	0–15 cm undisturbed	0–15 cm disturbed	0–10 cm undisturbed	0–10 cm disturbed	0–5 cm undisturbed	0–5 cm disturbed
Shelterwood 1	0.97	1.03	0.94	0.99	0.87	0.94	0.74	0.86
Shelterwood 2	1.02	1.06	0.95	1.00	0.90	0.94	0.78	0.84
Shelterwood 3	1.05	1.16	0.98	1.10	0.90	1.05	0.83	0.94
Green tree 1	1.04	1.08	0.97	1.02	0.93	0.97	0.81	0.86
Green tree 2	1.01	1.18	0.96	1.12	0.92	1.09	0.83	1.04
Green tree 3	0.97	1.17	0.93	1.14	0.88	1.06	0.82	0.95
Patch cut 1	1.02	0.99	0.96	0.94	0.91	0.90	0.81	0.79
Patch cut 2	1.08	1.11	0.97	1.09	0.95	1.06	0.88	0.95
Patch cut 3	0.97	1.40	0.93	1.35	0.86	1.32	0.84	1.19
Clearcut 1 (QB)	1.03	1.15	0.98	1.10	0.94	1.06	0.83	0.96
Clearcut 2 (SL)	1.06	1.19	1.02	1.14	0.98	1.10	0.86	1.01

TABLE A16. Length and diameter of large[a] post-harvest woody debris, by decay class[b]

	Shelterwood		Green tree		Patch cut		Clearcut	
	Average diameter (cm)	Average length (m)	Average diameter (cm)	Average length (m)	Average diameter (cm)	Average length (m)	Average diameter (cm)	Average length (m)
Class 1[b]	13	4.5	13	3.0	12	2.6	13	2.8
Class 2[b]	18	2.5	19	2.2	18	2.4	18	2.3
Class 3[b]	22	3.0	22	2.8	21	2.1	23	2.5
Class 4[b]	26	3.6	24	2.1	24	2.9	25	2.0
Class 5[b]	36	5.1	38	4.2	35	3.2	36	2.6
Class 5+	48	4.2	44	3.3	52	3.3		
Average of all classes	20	4.0	17	2.8	16	2.5	17	2.6

[a] Greater than 5 cm in any dimension.
[b] See Figure 10 for pictoral descripiton of decay classes.

TABLE A17. Volume of large[a] class 1[b] post harvest woody debris, by type (m^3/ha)

Breakage	Shelterwood (m^3/ha)	Green tree (m^3/ha)	Patch cut (m^3/ha)	Clearcut (SL only) (m^3/ha)
Round logs	27	66	33	43
Chunks and slabs	11	28	15	10
Total breakage	38	94	48	53
Merchantable	21	27	24	17
Nonmerchantable	10	8	12	13
Bark	1	2	3	4
(Windfall)	(16)	(8)	(0)	(0)
All (except windfall)	70	131	87	87

[a] Greater than 5 cm in any dimension.
[b] See Figure 10 for pictoral descripiton of decay classes.