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Contents

Author
Grant Nishio
Western Region

Harvesting mountain pine beetle–killed pine while protecting the secondary structure: trials to support a partial harvesting strategy for addressing the mid-term timber supply

Abstract

In this FPInnovations–Feric Division project, we studied a series of partial harvesting trials in which the objective was to harvest all the pine trees while protecting the secondary structure in stands infested by the mountain pine beetle. The purpose of this type of treatment is to salvage the present value of the beetle-killed pine while preserving the existing secondary structure to provide a viable stand by the mid-term timber supply period (15 to 50 years from now). In this report, we provide the results from four trials in the Prince George (B.C.) Forest District using four different ground-based partial harvesting methods: a motor-manual (chainsaw) cut-to-length (CTL) method, a mechanized CTL method, a motor-manual full-tree method, and a mechanized full-tree method. Variations in pre-harvest stand attributes, harvesting equipment, and methodology resulted in differences in the total trail area, harvesting costs, and amount of secondary structure remaining undamaged in the residual stands. The results indicate that with an appropriate harvesting method and sufficient secondary structure present in the pre-harvest stand, it should be possible to harvest the mature pine trees and provide stands that will produce acceptable volumes of timber in the mid-term time period.

Keywords:

Partial harvesting, Mountain pine beetle, *Dendroctonus ponderosae*, Advance regeneration, Understory protection, Harvesting, Partial cutting systems, Harvesting methods, Cut-to-length, Motor manual method, Mechanized method, Harvesting cost, Residual stand damage, Interior British Columbia.

Introduction

The current mountain pine beetle (*Dendroctonus ponderosae*) outbreak is expected to have a significant impact on the mid-term timber supply (MTTS) in 15 to 50 years in the interior of British Columbia. In pure pine stands that lack a developed understory, the “clearcut and plant” strategy is an appropriate harvesting method. However, many other stands contain an abundant and healthy secondary structure along with the mature pine component. In British Columbia, “secondary structure” is a term becoming widely used to denote any trees that are likely to survive a subsequent mountain pine beetle attack. If the secondary structure is of sufficient size and abundance, it can become available for harvesting in 15 to 50 years (BCMOFR 2008). In many stands, if the pine is harvested while protecting the secondary structure, the post-harvest stand would qualify as a fully stocked stand with the potential to contribute harvest-able timber early enough to contribute to the MTTS. Understanding the levels of protection of the secondary structure that can be achieved during partial cutting and the associated harvesting costs will provide managers with additional tools to mitigate the impacts of the present outbreak of mountain pine beetle in the northern interior of British Columbia. In this report, we present the results from four partial-cutting trials in the Prince George (B.C.) Forest District in 2006 and 2007. The trials examined harvesting productivities and costs, and the levels of protection of the secondary structure achieved by the operation.

The single most important factor in attaining a desirable post-harvest secondary structure is likely to be the selection of a stand with appropriate pre-harvest stand attributes. Once managers identify a stand that has sufficient secondary structure to contribute to the MTTS, they must decide whether to harvest it now or leave the stand for a future harvest. If the decision is to partially harvest the stand, the treatment must be appropriate for the stand conditions. Alternatives include several different harvesting methods and equipment that can be used while protecting the secondary structure. Strategies for partial harvesting must consider the amount of healthy secondary structure present, the post-harvest windthrow hazard, and the magnitude of the insect or pathogen risk, along with a reasonable control strategy for insects or pathogens, if necessary. With this purpose in mind, Ken Hodges (British Columbia Ministry of Forests and Range) designed a decision matrix to assist managers with the site-selection process and to provide appropriate partial harvesting options (Appendix 1).

Objectives

The goals of this project were to measure the cost-effectiveness and operational feasibility of harvesting stands attacked by the mountain pine beetle while protecting the secondary structure. To do so, Feric participated in a series of partial-cutting trials with the specific objective of protecting the secondary structure to determine:

- the costs of harvesting pine trees attacked by the mountain pine beetle while protecting the secondary structure;
- the level of protection of the secondary structure that can be achieved under different stand conditions, using different combinations of harvesting machines and methodologies; and
- the factors that contribute to leaving a post-harvest stand that will be able to provide harvestable timber during the MTTS period.

Site descriptions

The trials were conducted in stands that contained a range of pre-harvest proportions of pine, stand volumes, and tree sizes (Figure 1, Table 1).

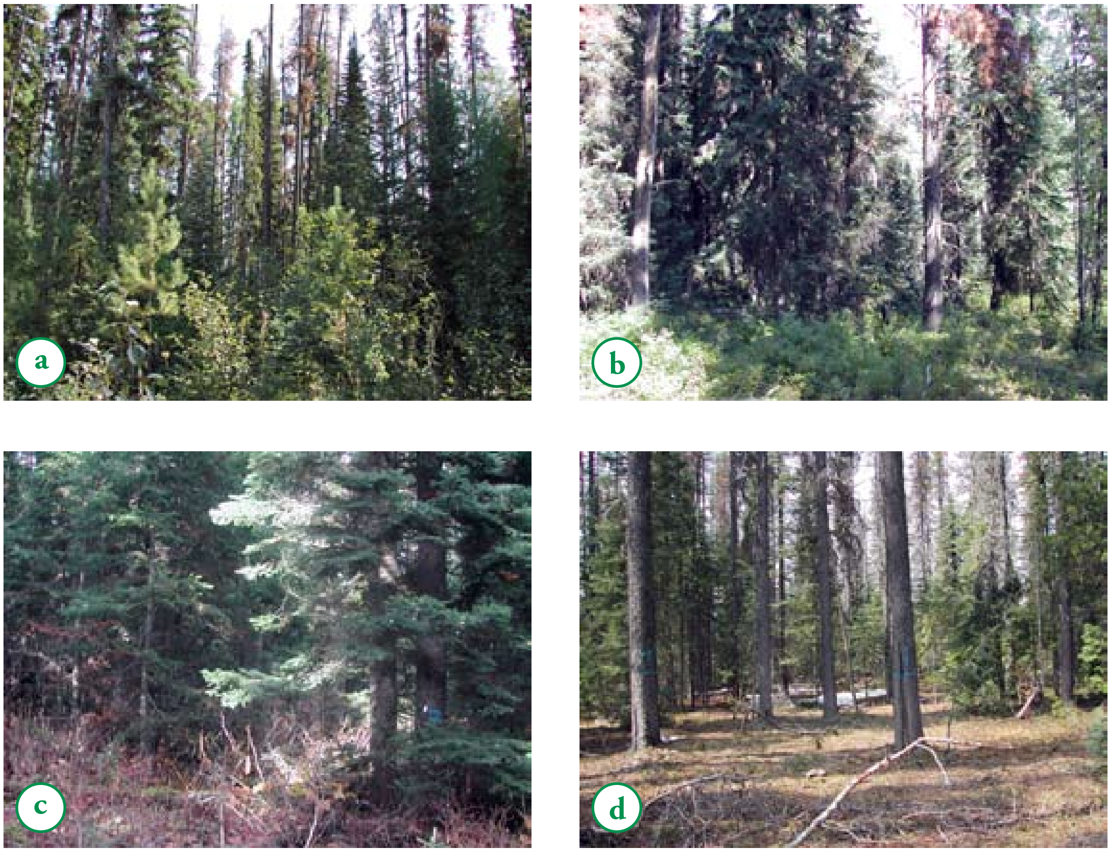


Figure 1. The pre-harvest stands: (a) Trial 1, (b) Trial 2, (c) Trial 3, (d) Trial 4.

Table 1. Site and stand descriptions

Location of the trial site	Trial 1 Wansa Forest Service Road	Trial 2 Huble Farm area	Trial 3 McEwan Lake area	Trial 4 Crystal Lake area
Total area (ha)	21.5	30.5	19.9	29.0
Pre-harvest basal area				
Pine (%)	30	42	44	78
Spruce (%)	39	35	35	13
Subalpine fir (%)	13	0	17	1
Douglas-fir (%)	0	0	1	4
Deciduous (%)	18	23	3	4
Total harvested volume (m^3)	1330	1800	4746	5369
Harvested volume per ha (m^3/ha)	62	59	238	185
Average harvested tree size (m^3)	0.7	0.5	1.6	0.4
Slope				
Range (%)	0 to 10	0 to 28	0 to 35	0 to 26
Average (%)	3	4	9	8
BEC sub-zone classification[a]	SBS wk1[b]	SBS mk1[c]	SBS wk1[b]	SBS mk1[c]

[a] The Biogeoclimatic Ecosystem Classification (BEC) system (http://www.for.gov.bc.ca/hre/becweb/index.html).
[b] SBSwk1: Sub Boreal Spruce zone, wet, cool subzone
[c] SBSmk1: Sub Boreal Spruce zone, moist, cool subzone

Pre- and post harvest stocking

The "deviation from potential" (DFP) stocking survey system developed by Martin et al. (2005) describes stocking levels observed or obtainable in partially cut stands in British Columbia. This method employs an algorithm that incorporates both the actual and the desired basal area of the overstory trees and stems per hectare of well-spaced understory trees to produce a DFP value. The DFP value represents the deviation of the partially cut stand's potential volume growth below that of a fully stocked clearcut plantation. The higher the DFP value, the lower the stocking. For example, a DFP value of 0.30 represents a potential volume growth that is 30% below that of a fully stocked clearcut plantation. The authors of the DFP method suggest classifications in which a DFP value less than 0.20 is considered to represent a "stocked" stand, whereas a DFP value greater than 0.40 represents an "open" stand, and values between 0.20 and 0.40 represent a "partially stocked" stand.

In the present study, we used a slightly modified mid-term deviation from potential (MTDFP) stocking assessment to reflect our emphasis on the MTTS period. In addition, due to the high risk of attack by the mountain pine beetle, we only included non-pine trees in the DFP calculations. Unlike DFP, MTDFP only includes trees taller than 1.3 m in the calculations, since smaller trees are assumed to have no potential to contribute merchantable timber during the MTTS period. We calculated MTDFP values for each trial before and after harvesting to measure the change in stocking as a result of harvesting. We did not include severely wounded trees in the stocking assessments since their contribution to the MTTS was assumed to be compromised. Even if a tree survived a severe wound, there would be an increased risk of decay, potentially reducing the harvestable timber volume (BCMOFR 1997). Of course, post-harvest windthrow and mortality due to desiccation will remove some surviving trees from the residual stand, and estimates of these losses should be included in the projected stocking of the future stand.

Methods

Harvesting methods

The harvesting treatments in all four trials focused on protecting as much of the secondary structure as operationally feasible while harvesting all pine trees. The machine operators were instructed to create and stay on main trails and to minimize the number and length of spur trails needed to harvest the pine. The concentration of traffic in the main trails reduced the total area covered by machine travel and minimized the overall damage to the secondary structure. However, the thin duff layer and sandy soils at the Trial 4 site could only sustain a few passes by machinery without causing unacceptable soil damage. Thus, to minimize the soil disturbance that would result from concentrating traffic in the main trails, the operators in Trial 4 distributed machine traffic throughout the entire block. Trial 4 also contained a high proportion of pine dispersed throughout the stand, and consequently required many well-distributed trails throughout the block.

The harvesting methods and equipment are listed in Table 2. Trial 1 used a motor-manual cut-to-length (CTL) harvesting

Table 2. Harvesting methods and equipment

	Trial 1 (Motor-manual CTL)	Trial 2 (Motor-manual full-tree)	Trial 3 (Mechanized full-tree)	Trial 4 (Mechanized CTL)
Harvesting months	July to Aug. 2006	Aug. to Sept. 2006	Nov. 2006	July 2007
Selection of trail location	By the hand-feller	By the hand-feller	Combination of pre-harvest layout and selection by the feller-buncher operator	Selection by the feller-buncher operator
Felling equipment	Chainsaw	Chainsaw	Feller-bunchers (Timberjack 618 and 628)	Feller-bunchers (Madill 3200C and 2250, John Deere 903J)
Extraction equipment	Excavator (Komatsu PC75UU2) Forwarder (Timberjack 1210)	Cable skidders (Timberjack 540, Clark 667)	Grapple skidders (Timberjack 660)	Forwarders (Valmet 890.2, Tigercat 1765, John Deere 1710)
Processing equipment	Chainsaw at the stump	Chainsaw at the landing	Stroke delimber (Lim-mit 2300 delimber on a Link-Belt 4300 carrier)	Dangle-head processors (Hitachi 200, Caterpillar 320C), both with Waratah heads
Decking equipment	Forwarder at the landing	Skidder at the landing	Loader at the landing (Komatsu PC250)	Forwarder at roadside

method with a hand-feller, a small excavator with a modified grapple, and a forwarder. This was a one-man operation in which the worker alternately operated the chainsaw or one of the harvesting machines, as required. This meant that only one harvesting phase could be performed at a time. Trial 2 used a motor-manual full-tree harvesting method with two hand-fellers and two cable skidders. Trial 3 used a mechanized full-tree harvesting method with two feller-bunchers, two grapple skidders, one stroke delimber, and one loader. The loader was used to deck the trees from the skidders at the landings and created large and orderly log decks that facilitated efficient processing by the delimber. Trial 4 used a mechanized CTL harvesting method with two feller-bunchers, two dangle-head processors working at the stump, and two forwarders.

Data collection

We installed MultiDAT dataloggers in all harvesting equipment to monitor shift-level activities and equipment utilization for each treatment. We used handheld dataloggers to record detailed work cycle times. We ran the shift-level and detailed timing studies concurrently for all harvesting activities, with the exception of Trial 2, for which we were unable to collect the shift-level data. We used the shift-level timing information to calculate the cost per m^3 attributable to each machine in the system (Appendices 2 and 3). The contractor provided the harvested volumes, and we calculated the average harvested tree sizes from samples of standing trees and of decked logs.

We established permanent sample plots prior to harvesting in a systematic grid pattern. The plots included variable-radius (wedge prism) plots to measure overstory trees $\geq$12.5 cm in diameter at breast height (dbh), and 3.99-m-radius fixed-area circular plots using the same plot centers to measure understory trees <12.5 cm in dbh. Tree variables included species, size, stems per hectare (density), basal area, and the number of well-spaced understory trees (BCMOFR 2000). We used these variables to assess the amount of secondary structure present prior to harvesting. After harvesting, we used these same plots to determine the post-harvest stocking (Martin et al. 2005), the number of harvested non-pine trees (i.e., trees missing from the plot), and the damage to the residual trees caused by harvesting. "Severe" tree damage included gouges that penetrated into the sapwood, wounds that girdled more than one-third of the stem's circumference, or wounds on a supporting root within 1 m of the stem. "Moderate" tree damage included any damage that did not meet the minimum criteria for severe damage. The parameters for moderate and severe damage to the overstory trees were directly comparable to the "acceptable" and "not acceptable" classifications, respectively, defined in BCMOFR (1997) for stands with a scheduled re-entry within 20 years. We excluded severely damaged trees from the post-harvest stocking assessments. We included the percentages of lost or missing understory stems to assess the level of damage done to the secondary structure during the harvesting treatment and the residual stand's potential contribution to the MTTS.

We used the MTDFP method for our stocking assessments. Measurements before and after harvesting provided the pre- and post-harvest stocking, as well as the change in stocking values resulting from the treatments. We recorded the trail length, width, and location, and the extent of exposed mineral soil on trails, for all main trails and the in-block road in Trial 4 using GPS mapping and systematic trail measurements, as described later in this section.

Trail mapping

For the purposes of this study, we defined trails as any area where a harvesting machine had traveled and caused a noticeable and contiguous change in the forest floor (excluding landings). Main trails and "ghost trails" (Sambo 1999, Meek 2001) were both included in this description. This broad definition provided a measure of the total area directly affected by machine travel. For the most part, areas between trails were essentially machine-free zones. Since machine travel required removal of all overstory and understory trees from a trail, we assumed that an increase in the total trail area would result in a higher loss of secondary structure. We have presented the measurements of trail and in-block road areas as the proportion of the block's net ground area covered by the trails and road. The net ground area is only the harvested area of the block and does not include any non-harvested areas (e.g. retention patches). With an average boom reach of 10 m for the feller-bunchers, all trees should be accessible within a 20-m trail edge to trail edge inter-trail spacing (i.e., twice the boom's reach). In comparison, a hand-feller could potentially accommodate an inter-trail spacing of up to twice the tree length, or even greater with the use of cable skidders to winch felled trees to the extraction trail. Nevertheless, the trail layout efficiency measure that we used was standardized to an inter-trail spacing of 20 metres.

We mapped the trails after the completion of harvesting by traversing all trails with a handheld GPS unit (Garmin GPSMAP-76C). GPS data was interpreted and digitized into maps. Sources of error that affect the potential accuracy are inherent in the level of GPS technology used in this study (Garmin 2008). Average error is 2 m and 95% of the errors are less than 4.4 m (Mehaffey et al. 2009) It is possible that some of these errors affected the mapped locations of the trails, but the since the GPS points are relative to themselves there would be little impact on the inter-trail distances or the general visual layout of the trail mapping.

Results

Stocking assessments

Table 3 presents the pre- and post-harvest MTDFP summaries. The pre-harvest stands in Trials 1, 2, and 3 began with stocked MTDFP classifications. Careful harvesting in Trial 1 protected almost all of the secondary structure, resulting in a post-harvest stocked stand (Figure 2a). Harvesting in Trial 2 also produced a stocked stand (Figure 2b). Trial 3 produced a stand with a MTDFP partially stocked classification. In fact, the Prince George Forest District accepted a maximum DFP value of 0.28 for Trial 3 which meant it was classified as stocked. Further, when saplings less than 1.3 m in height were included in the post-harvest calculations, Trial 3 easily met the criteria for a stocked classification (Figure 2c). Before harvesting, Trial 4 was classified as partially stocked, but harvesting resulted in the loss of most of the original non-pine overstory and understory, resulting in an open stand under both the MTDFP and the DFP classifications (Figure 2d).

Trail coverage and site disturbance

The four sites differed considerably in the proportion and distribution of pine, trail occupancy (Table 4), and trail layout efficiency (Figures 3 to 6). The pre-harvest stand in Trial 1 contained a 30% pine component, and the operator created narrow trails (3.5-m average width), using 3.3% of the block area for trails. This system used a careful hand-feller, a small excavator, and a forwarder to access all of the pine trees while minimizing the total trail area. The

Table 3. MTDFP values for mid-term stocking

Trial	MTDFP values[a]		
	Pre-harvest	Post-harvest	Change
1	0.09	0.10	0.01
2	0.07	0.20	0.13
3	0.07	0.30	0.23
4	0.40	0.79	0.39

[a] MTDFP classifications: <0.20 = stocked, 0.21 to 0.40 = partially stocked, $\geq$0.41 = open.

Figure 2. The post-harvest stands: (a) Trial 1, (b) Trial 2, (c) Trial 3, and (d) Trial 4.

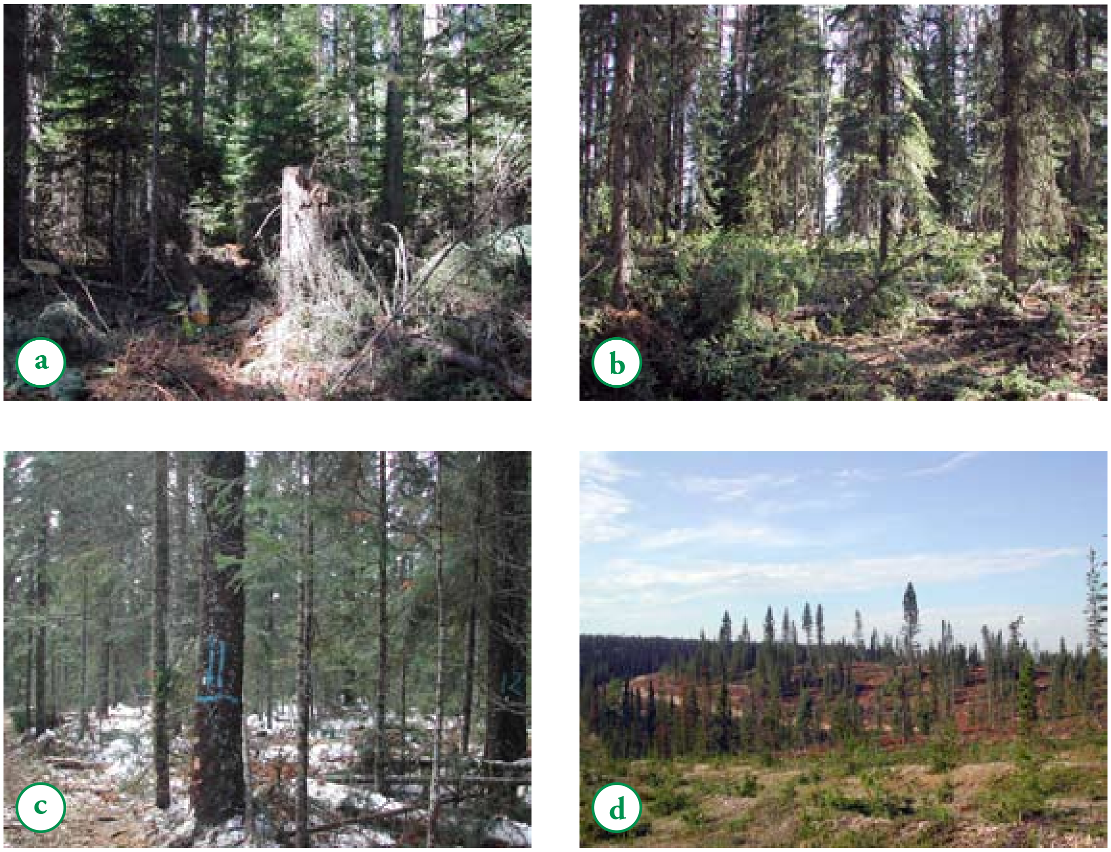


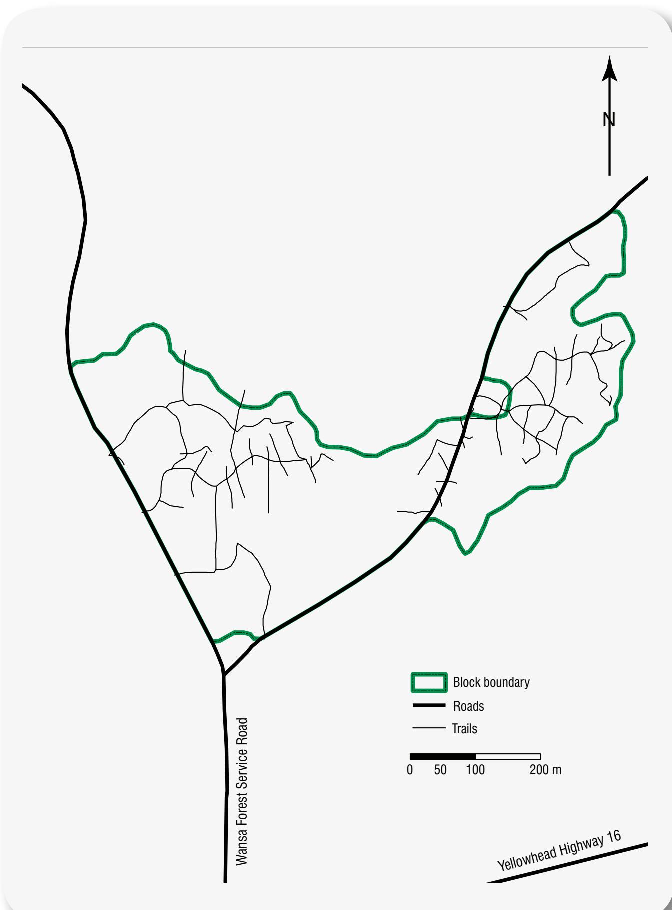
Table 4. Trail areas and mineral soil disturbance in the trails	Trial 1	Trial 2	Trial 3	Trial 4
Average trail width (m)	3.5	4.4	4.7	5.2
Average road width (m)	0	0	0	7.7
Total trail length (m)	2000	4744	7735	15 263
Total road length (m)	0	0	0	1986
Total trail area (ha)	0.7	2.1	3.6	7.9
Total road area (ha)	0	0	0	1.5
Total harvested block area (ha)	21.5	30.5	19.9	25.9
Coverage of site by trails (%) = [(Trail area + Road area) / Block area] x 100	3.3	6.9	18.3	36.5
Exposed mineral soil in trails (%)	16.2	4.6	2.6	3.9
Exposed mineral soil in block (%) = [((Trail area x % exposed mineral soil in trails) + Road area) / Block area] x 100	0.53	0.32	0.47	7.1
Harvested volume (m^3/ha)	61.9	59.0	238.5	207.3
Harvested volume per length of trail (m^3/m)	0.7	0.4	0.6	0.4

forwarder trails were positioned so as to avoid key areas of secondary structure. This was possible because the forwarder was able to manoeuvre around the non-pine leave trees and areas with a significant understory. In Trial 2, the hand-feller plus cable skidder system created 4.4-m-wide trails, resulting in 6.9% coverage of the block by trails to access the 42% pine component. Trial 3 was a fully mechanized system with feller-bunchers and grapple skidders. With an average trail width of 4.7 m, 18.3% of the block was required for trails to access the 44% pine component. Skidding full trees in Trials 2 and 3 required a relatively straight trail layout, resulting in some non-pine trees being harvested during trail construction. Trial 4, a fully mechanized CTL system, combined an in-block loop road with an extensive network of secondary machine trails, with an average trail width of 5.2 m, and a block road with an average width of 7.7 m. The combined total (roads and trails) covered 36.5% of the net block area (Table 4) to access the 78% pine component. Since the pine component in Trial 4 was uniformly distributed throughout most of the block and the fragility of the soil required dispersal rather than concentration of traffic, the trail and road coverage was extensive (Figure 6), and harvesting of much of the non-pine overstory was unavoidable.

Trial 1 contained the lowest proportion of pine and produced the lowest coverage of the site by trails. However, since traffic

Figure 3. (*left*) Trail layout in Trial 1. The total trail length was 2000 m in a net harvested area of 21.5 ha.

Figure 4. (*right*) Trail layout in Trial 2. The total trail length was 4744 m in a net block area of 30.5 ha.



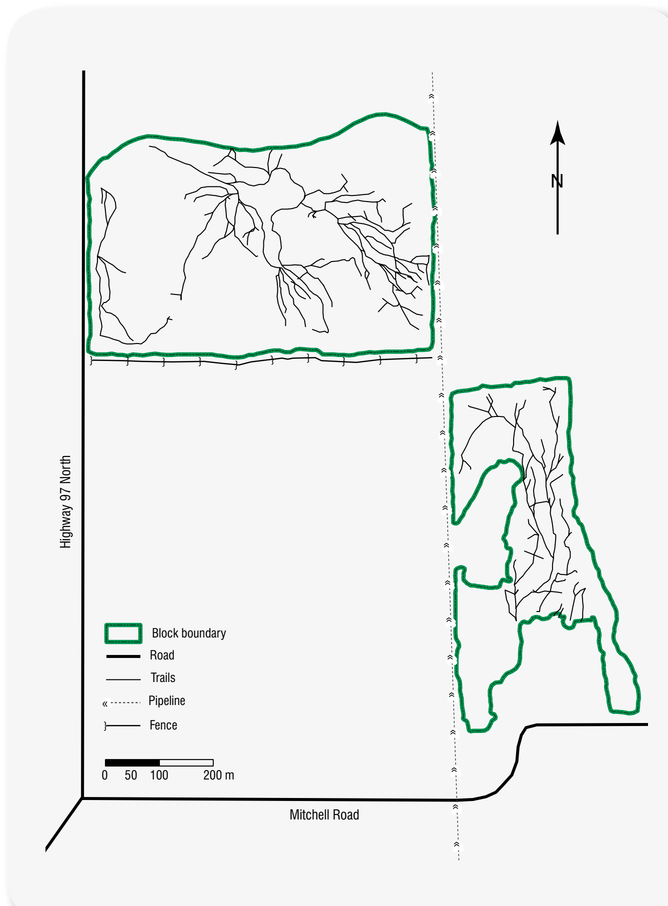


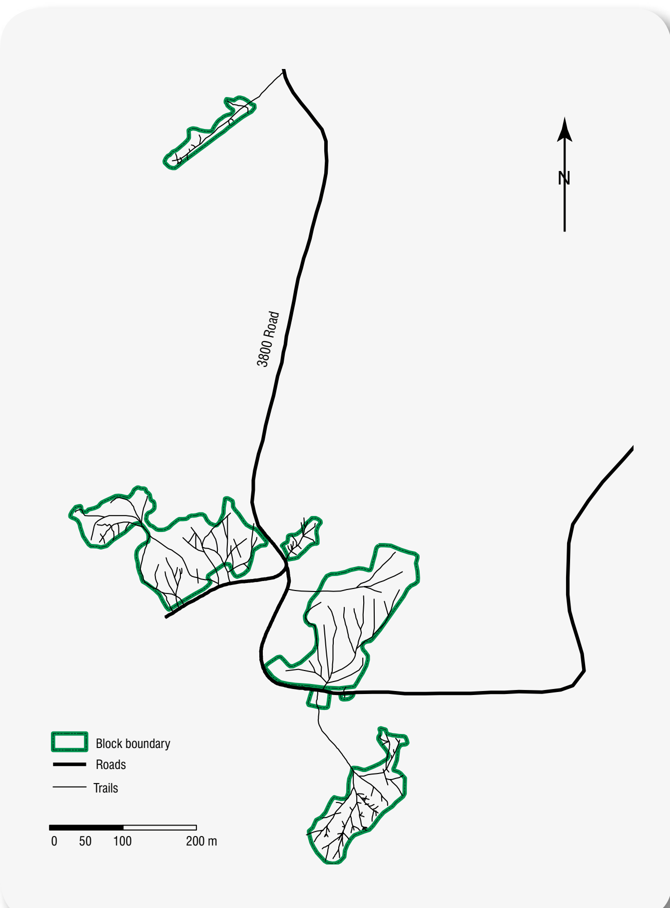
Figure 5. (*left*) Trail layout in Trial 3. The total trail length was 7735 m in a net block area of 19.9 ha. Trails outside of the harvested areas were not included in the calculations.

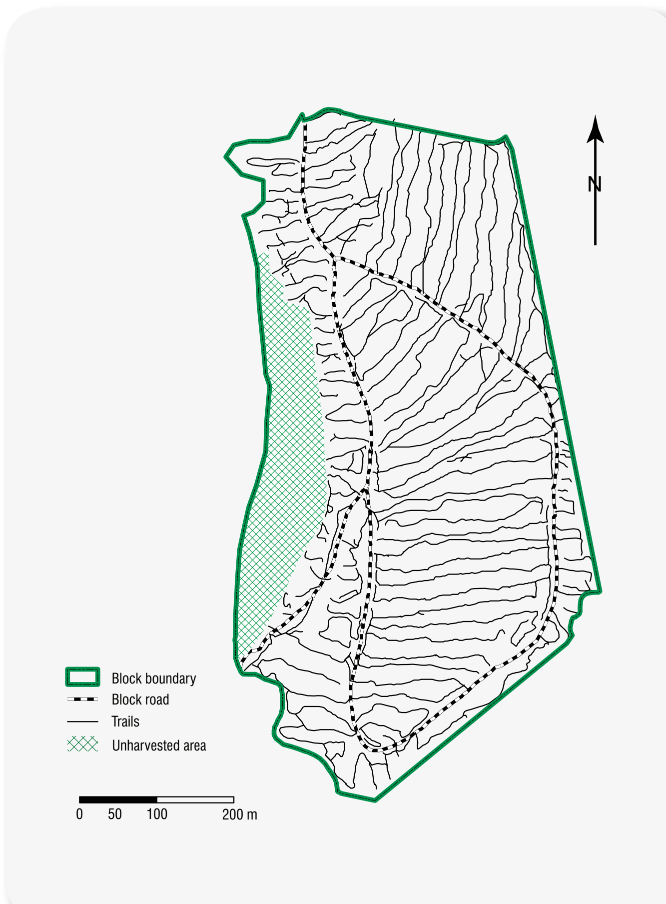
Figure 6. (*right*) Trail and road layout in Trial 4. The total trail length was 15 263 m and the total length of in-block road was 1986 m in a net block area of 25.9 ha.

in Trial 1 was concentrated on a few main trails, this resulted in the highest level of exposed mineral soil as a proportion of trail area (16.2%). Trial 2 contained a 12% higher proportion of pine than in Trial 1, but produced more than twice the coverage of the site by trails. The trail layout in Trial 3 was efficient, but the stand contained a higher proportion of pine than in the two hand-feller trials and used a fully mechanized harvesting system, resulting in a higher overall coverage of the site by trails. However, Trial 3 had the lowest level of exposed mineral soil as a proportion of trail area (2.6%). The stand in Trial 4 contained the highest proportion of pine and had a thin duff layer and sandy soils that required dispersal of traffic, resulting in the highest coverage of the site by the trails and in-block road. Since Trial 4 contained a relatively homogeneous trail layout, the inter-trail spacing for the entire block was calculated to average about 15 m (Figure 6). Trial 4 had a 3.9% level of exposed mineral soil within the trail area and 100% within the road area. The totals for exposed mineral soil as a proportion of block area ranged from 0.32 to 7.1% (Table 4). Most of the 7.1% block proportion of exposed mineral soil in Trial 4 resulted from the in-block road.

Harvesting productivity and costs

Table 5 summarizes the ownership and operating costs for the harvesting machines, and Appendix 2 presents details of these





costs. Table 6 summarizes the combined harvesting costs for the four trials, and Appendix 3 presents details of these costs. We calculated the harvesting costs as the combined scheduled machine hour (SMH) costs from stump to landing, excluding equipment transportation, log hauling, planning costs, and other overhead. Shift-level data for Trial 2 were not available and are not included in Table 5. Total volume harvested, and scheduled machine hours for Trial 2 were provided by the contractor (Table 6).

Table 7 summarizes the results of the detailed cycle timing studies. The hand-feller cycle times for Trial 1 included tree processing times because the worker also delimbed and bucked the trees at the stump. The feller-buncher's times per tree in Trial 3 were more than four times as long as those in Trial 4. However, the mean tree volume in Trial 3 was four times that of the trees in Trial 4, resulting in a similar productivity per m^3. The mean tree size in Trial 1 was 0.7 m^3/tree, versus values of 0.5 m^3/tree in Trial 2, 1.6 m^3/tree in Trial 3, and 0.4 m^3/tree in Trial 4. Trial 1 used two main landings whereas Trial 4 used roadside landings along the length of the in-block loop road. This meant that the average forwarder extraction distance in Trial 1 (approximately 200 m) was about twice the average extraction distance in Trial 4 (approximately 100 m), resulting in almost double the forwarder cycle time per m^3 in Trial 1 (Table 7).

Table 5. Ownership and operating costs for the equipment used in trials 1, 3, and 4

	Trial 1			Trial 3				Trial 4		
	Forwarder	Small excavator	Hand-feller	Feller-buncher	Skidder	Delimber	Loader	Feller-buncher	Forwarder	Processor
Ownership cost ($/ SMH)	37.40	14.15	4.00	52.56	30.32	43.46	53.57	52.06	49.63	46.33
Operating cost ($/ SMH)	95.92	69.54	50.85	119.87	89.98	95.69	123.08	135.19	103.98	101.68
Total machine cost ($/ SMH)	133.32	83.69	54.85	172.43	120.30	139.15	176.65	187.25	153.61	148.01

Table 6. Harvesting costs

	Trial 1	Trial 2	Trial 3	Trial 4
Total volume harvested (m^3)	1330	1800	4746	5369
PMH Harvesting cost ($/$m^3$)	14.85	na	12.43	11.50
SMH Harvesting cost ($/$m^3$)	20.70	16.33	16.39	13.60

Table 7. Harvesting machine cycle times per unit volume[a]				
	Cycle times (min/m³)			
	Trial 1	Trial 2	Trial 3	Trial 4
Harvesting activity				
Hand-feller (felling, delimbing, and bucking)	6.3	–	–	–
Hand-feller (felling)	–	0.6	–	–
Hand-feller (delimbing and topping)	–	0.7	–	–
Feller-buncher (felling)	–	–	0.9	1.0
Excavator (hoe forwarding)	2.0	–	–	–
Forwarder (forwarding CTL logs)	3.5	–	–	1.9
Skidder (skidding full trees)	–	2.2	2.1	–
Processor (processing full trees)	–	–	0.8	1.9
Loader (assisting skidders and delimber at the landing)	–	–	0.2	–

[a] The totals of the detailed machine cycle times are taken from relatively short time studies and therefore do not include some sources of non-productive time (e.g., travel time, extended delays, breakdowns) that are included in shift-level time measurements.

Harvesting damage

Figure 7 presents our measurements of post-harvest tree damage and of understory loss as a proportion of the original non-pine secondary structure that was present before harvesting. Damage to both the overstory and the understory progressively increased from Trial 1 to Trial 4. With the exception of Trial 1, the number of non-pine overstory trees harvested was directly related to the proportion of the site covered by trails. The trails in Trial 1 covered only 3.3% of the site, and virtually no non-pine species were harvested because this operator was able to position trails to avoid desirable leave trees and to protect these stems during harvesting. The proportion of the site covered by trails in Trial 2 was 6.9%. Post-harvest measurements indicated that 11% of the original non-pine trees were harvested, suggesting that approximately 4% of the non-pine trees were not on trails and may have been harvested unnecessarily. However, some non-pine trees may have been felled to provide access to pine trees and others may have been felled for safety reasons. The proportion of the site covered by trails in Trial 3 was 18.3%, which coincides approximately with the 20% of the non-pine trees that were harvested. The total combined trail and road area for Trial 4 amounted to 36.5% of the block's area, which coincides with 37% of the non-pine trees that were harvested. Due to the extensive network of trails and roads in Trial 4, almost all sample plots included some portion of ground covered by a trail or road.

In Trial 1, where the harvesting costs were highest, the harvesting damage to the overstory and understory and the proportion of the non-pine trees that was harvested were lowest (Figure 7). Conversely, in Trial 4, where the harvesting costs were lowest, the harvesting damage to the overstory and understory and the amount of non-pine that was harvested were highest. Furthermore, the proportion of the site covered by trails was lowest in Trial 1 and highest in Trial 4 (Appendix 4). Again, we assumed that the higher number of shorter low-use secondary trails in Trial 4 allowed more efficient access and shorter travel times than with the use of fewer longer high-use main trails (with short spurs), with less efficient access and longer travel times. We found the same general trend in Trials 2 and 3. Even though the stand attributes (e.g., piece size, harvested volumes) and the combinations of harvesting equipment differed between the trials, these results suggest that the increased effort required to protect a greater amount of secondary structure (e.g., careful harvesting techniques, increased travel time/m³ on fewer trails) increased the harvesting costs. Appendix 5 summarizes the harvesting results in a table of pre-and post-harvest stand attributes.

Post-harvest survival of the residual stand

Compared to the mean value for the last 10 years, the maximum wind speeds in the Prince George area were higher than normal in 2006 and normal in 2007 (Environment Canada 2008). Compared to the mean monthly summer precipitation (June to August) for the last 10 years, rainfall was lower in both 2006 and 2007 (Environment Canada 2008). This means that at the time of the post-harvest survival study measurements in July and August 2008, the residual stands had been exposed to at least one complete seasonal cycle (two in Trials 1 and 2) of winter followed by summer conditions that were typical of the local average or drier. To indicate the post-harvest mortality, Figure 8 presents mortality indicators as a proportion of the residual stand density that was present immediately after harvesting. The standing dead overstory trees ranged from 0.5 to 16.7%, wind-thrown overstory trees ranged from 0.6 to 38.6%, and post-harvest understory mortality ranged from 8.1 to 30.1%.

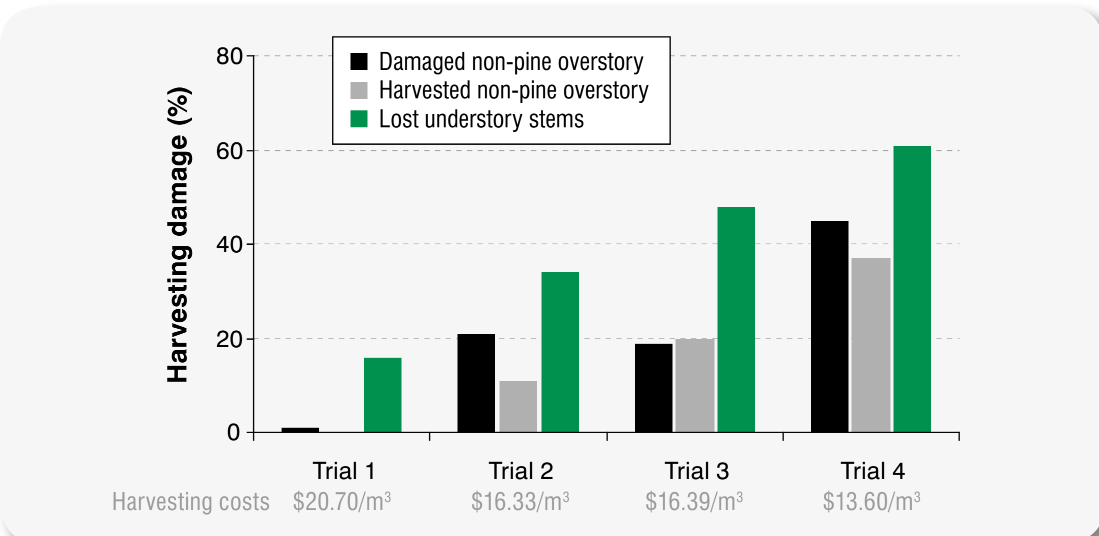


Figure 7. The relationship between harvesting damage and SMH harvesting costs.

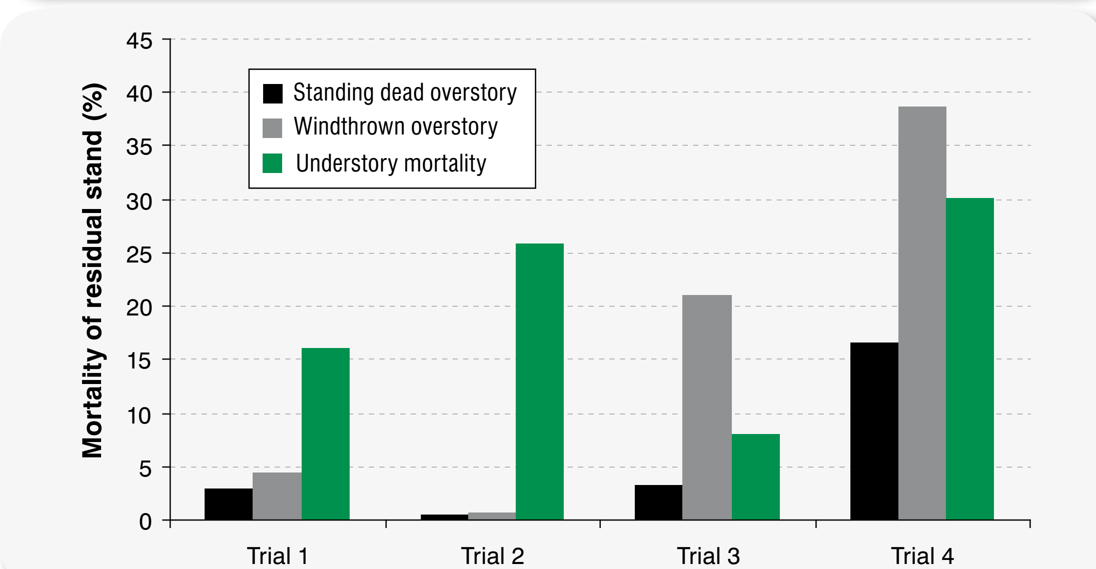


Figure 8. Mortality and windthrow in the residual stand 1 to 2 years after harvesting.

Discussion

Creating a post-harvest stand with the potential to contribute to the MTTS requires protection of the secondary structure that was present before harvesting. However, regardless of how carefully partial harvesting is done, there will inevitably be some damage and subsequent loss of potential crop trees. There will also be some post-harvest mortality as a result of exposure (e.g., windthrow and desiccation). These losses must be estimated so they can be included in the pre-harvest assessment of the suitability of a stand attacked by mountain pine beetle for partial harvesting treatments. If high levels of secondary structure are found, but projected damage levels are unacceptable, it may be better to defer harvesting. If there is insufficient secondary structure present before harvesting, there will not be a viable opportunity to perform partial harvesting that will create a harvestable stand within the mid-term time period, so standard practices (clearcutting followed by planting) would be more appropriate.

All trials in the present study employed experienced operators, but operator experience with partial harvesting in Trial 4 was not as recent as that for the operators in Trials 1, 2, and 3. More importantly, all the equipment operators in Trials 1, 2, and 3 were highly motivated to protect secondary structure and were encouraged to do so by the contractor. The contractor and operators in Trial 4 attempted to protect as much secondary structure as possible, but maintaining a high level of productivity was a priority. Also, the requirement to travel over a large proportion of the block inevitably led to more damage to residuals. Assessments of worker motivation were based on personal observations, conversations with the equipment operators, and the general objectives of the contractor. Operation of the feller-bunchers in Trial 3 required extra effort because of the large, heavy trees (an average of 1.6 m^3/tree) and the added challenge of protecting the abundant secondary structure (both overstory and understory) in a stand with a 56% non-pine component. The high individual tree volumes in Trial 3 mitigated the productivity loss that resulted from the extra handling time per tree. On the other hand, the feller-buncher operators in Trial 4 had shorter travel times between trees and easily handled the smaller trees. Also, less effort was devoted to protecting the surrounding secondary structure, since the pre-harvest stand only contained a 22% non-pine component and very little understory.

The hand-felling phase in Trials 1 and 2 resulted in very little damage to the surrounding trees or understory. In Trial 1, trees were limbed and bucked before they were placed on the trails. This minimized damage related to the extraction phase. However, in Trial 2, trees were not limbed at the stump, and the presence of large branches resulted in damage to residual trees and the understory when the cable skidder winched the trees to the trail. One of the most important factors related to the loss of secondary structure in all four trials was the total coverage of the site by trails. Virtually all of the overstory and understory is removed from a trail, so minimizing the total area of trails is important to reduce the overall loss of secondary structure. Factors that influence the number of trails in a block include the density, distribution, and size of pine in the stand, the type of harvesting equipment used, and the efficiency of the pre-harvest trail layout. In addition, soil characteristics may require a higher density of trails (as in Trial 4) to protect vulnerable soils that cannot withstand repeated heavy traffic. Since trail width is determined by the size and design of the harvesting machines, and since the main trails must be sufficiently long to access all of the pine trees, the only way to minimize the overall trail area is to reduce the total number of trails by spacing them as far apart as possible. Often, local features of the site such as steep slopes, wet patches or rocky outcrops determine the trail locations, but this was not an issue that would have appreciably affected inter-trail spacing in any of the study blocks.

There was little exposed mineral soil found in any of the four harvested areas. Exposed mineral soil was only found in the trails (and in the block road in Trial 4). The level of mineral soil exposure in the trails is related to the type of equipment and how much machine traffic the trail sustains. Soil disturbance is also affected by soil type and ground conditions during the harvesting season. None of the trials were done during the winter season, when frozen ground would likely have reduced soil disturbance (Henderson 2001).

For protection of the secondary structure, the trail layout in Trial 1 was very efficient, with few trails spaced less than 20 m apart (Figure 3). The trail layout in Trial 2 was relatively less efficient, resulting in a number of trails with an inter-trail spacing of less than 20 m (Figure 4). The large, heavy trees in Trial 3 required the feller-bunchers to move close to the trees during felling, and this reduced the inter-trail spacing requirement. Nevertheless, the trail layout in Trial 3 was very efficient with few trails having an inter-trail spacing of less than 20 m (Figure 5). Trial 4 had the least-efficient trail layout, and also contained a loop road within the block (Figure 6). The average inter-trail spacing of approximately 15 m in Trial 4 produced about 1.3 ha more trail area than would have been produced by a 20-m spacing in the 25.9-ha block. This means that an additional 5% of the ground area and related secondary structure could potentially have been protected by increasing the trail spacing. The loop road added an additional 1.5 ha of ground area (Figure 6) that could have been reduced if secondary structure protection was a higher priority.

Two of the greatest concerns following partial harvesting are the risks of mortality from overstory windthrow and understory desiccation. Trial 1 had the highest level of basal area retention (i.e., the lowest level of post-harvest exposure) and experienced the lowest levels of overstory windthrow and standing dead trees, and the second-lowest understory mortality (2 years after the harvest). Trial 4 had the lowest basal area retention (i.e., the highest level of post-harvest exposure) and experienced the highest levels in all three mortality categories. Trial 4 also had sandy, well-drained soils that likely contributed to water stress aggravated by the lower than normal precipitation in 2006 and 2007. Trial 2 had a moderate to low level of post-harvest exposure, resulting in a low level of standing dead trees and windthrow, but for some reason experienced a high level of understory mortality (possibly due to increased competition with understory vegetation). Trial 3 had a relatively moderate basal area retention (i.e., a moderate level of exposure), leading to low levels of standing dead non-pine trees and understory mortality and a moderate level of windthrow. These results may also be related to the relatively wetter soils in Trial 3, which would have mitigated mortality caused by desiccation but could have increased the windthrow risk.

Even though the four trials employed different harvesting systems in different stands, our results suggest a general trend in which the magnitude of the harvesting damage is inversely related to the harvesting cost (Figure 7). Since our results supported the assumption that an increase in the effort required to protect secondary structure would increase costs, this relationship seems logical. For example, Trial 1 used small equipment and a very careful methodology suitable for harvesting a stand with a small component of pine and a high protection objective, whereas Trial 4 used larger equipment with a modified clearcut style of harvesting in a stand with a large component of pine and a high production objective. In this study, we determined the harvesting costs, degree of secondary structure protection achieved, and factors that contribute to leaving a desirable residual stand by means of four individual case studies, and the results should thus represent illustrative explanations rather than general trends with broad application. Several additional trials will be needed, in a variety of representative stand types, to provide results that are meaningful across the study area.

A decision matrix for managing secondary structure

Ken Hodges of the British Columbia Ministry of Forests and Range (BCMOFR) created a decision-key matrix to determine whether a stand has an adequate secondary structure to contribute to the MTTS and to provide general harvesting suggestions. This matrix acknowledges that a clearcut-and-plant strategy may be more appropriate for stands with insufficient secondary structure. The matrix incorporates results from the present Feric study and input from a variety of other sources, including the Canadian Forest Service, University of Northern British Columbia, BCMOFR, and the forest industry (forest companies, contractors, and field crews). Ecosystems are unique and complex, so the matrix was designed to be used as a decision-support guide that focuses on many aspects of managing secondary structure and on subsequent harvesting strategies. The decision matrix is provided both as a detailed complete version and as a one-page flowchart (Appendix 1) that captures the essence of the main document. Both versions are available from the BCMOFR Web site (http://www.library.for.gov.bc.ca/ipac20/ipac.jsp?index=BIB&term=108142).

Conclusions

The results of this study indicate that pine can be selectively removed from a stand attacked by the mountain pine beetle while protecting the secondary structure. However, in order to leave an adequately stocked post-harvest stand, the pre-harvest stand must have sufficient secondary structure to allow for losses resulting from the construction of trails and from windthrow and exposure of the residual stand. Further, the objective to protect secondary structure must be the key element in the harvesting plan and this must be clearly explained to all workers. Our results suggested that harvesting costs were inversely related to the level of harvesting damage in the four study trials. This relationship was highlighted in Trial 1, where the labour-intensive work of delimbing and bucking trees at the stump lowered productivity, but was one of the key elements responsible for the high level of protection of the secondary structure that the worker achieved. Minimizing the total trail area will reduce the loss of secondary structure by reducing the proportion of the site covered by trails. An approximate calculation using 5-m-wide trails at a 20-m inter-trail spacing (25 m centerline to centerline spacing) will produce 0.2 ha of trail area per hectare of harvested area. This means there would be an estimated 20% loss of overstory and understory trees resulting from the trails. If the stand has a low density of pine or pine that is concentrated in patches, it may be possible to space the trails farther apart, resulting in a lower loss of secondary structure.

Harvesting damage is also affected by the choice of equipment and the harvesting methodology. For example, the winching of full-length trees to the trails damaged the secondary structure in Trial 2, and processing and sorting trees at the stump in Trial 4 increased understory damage and tree loss. In addition to selecting an appropriate combination of equipment and methodology, both the contractors and their machine operators must clearly understand the harvesting objectives. The operators should be experienced and skilful at this type of harvesting method, and must be highly motivated to accomplish the protection objectives for the secondary structure.

Managers must balance the decision to harvest a stand between its future potential to provide a suitably stocked post-harvest stand and its present potential to be economically viable. Nevertheless, repeated partial harvesting treatments of the type described in this report will inevitably refine the methodology and improve operator skills, making it possible to more effectively protect the secondary structure and subsequently lower total harvesting costs. However, it is important to note, if there is inadequate recognition for the true value of secondary structure there will be little motivation to protect it. In this regard, government needs to develop a system that can classify non-merchantable secondary structure with an appropriate and measurable monetary value so licensees can receive a suitable credit for their protection efforts.

Implementation

The following recommendations should improve the efficiency and productivity of a partial harvesting treatment in stands damaged by the mountain pine beetle, in which the objective is cost-effective protection of the secondary structure:

- Survey the candidate blocks to ensure that the secondary structure is sufficient to produce a fully stocked post-harvest stand after accounting for the expected harvesting damage and post-harvest mortality.
- Estimate the proportion of the site that must be covered by trails to access the pine component, and use this as an indication of the proportion of mature non-pine trees that will be removed during harvesting. For example, an estimated 20% loss of overstory and understory trees should be included in calculations of the post-harvest stocking requirements for a 20-m inter-trail spacing. There will also be additional losses due to harvesting damage.
- Incorporate a comprehensive pre-harvest strategy to guide the harvest planning, such as the decision matrix for managing secondary structure (Appendix 1).
- Select harvesting equipment that is suitable for the site and stand conditions. For example, larger feller-bunchers may require slightly wider trails than smaller machines, but can control the fall of large trees more effectively, thereby reducing damage to the residual secondary structure. Also, cable skidders can damage the secondary structure during winching to the trail, particularly if the trees are not delimbed at the stump, but may allow greater inter-trail spacing, possibly reducing overall losses of the non-pine overstory trees.
- Position trails efficiently so as to minimize the total coverage of the site by trails.
- Clearly communicate the objectives of the partial harvesting treatment to the contractor and the machine operators.
- Ensure that the operators are sufficiently skilled to accomplish the harvesting objectives and are highly motivated to achieve them.

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Appendix 1.
Decision matrix for managing secondary structure

by Ken Hodges, RPF

The strategy of managing a stand's secondary structure is not a new concept, but given predicted shortfalls ("fall down") in the timber supply, it has become an increasingly prudent and wise option that should be considered. Not only is there the potential for a future timber harvest, but there are also additional biological benefits such as:

- the creation or preservation of coarse woody debris,
- improved biodiversity, wildlife habitat, and forest health,
- social benefits in the form of future employment and community stability,
- economic considerations in terms of the recovery of otherwise non-recoverable losses, revenues for the Crown, and disposable incomes for communities, and
- global benefits such as carbon sequestration and earlier harvesting of dead and dying trees, thereby allowing prompt actions to ensure future crops.

The main focus for managing secondary structure is to help offset the expected shortfall in the annual allowable cut within the mid-term timber supply (MTTS) period. The shortfall is predicted to occur in 5 to 15 years, and could last up to 70 years from the present. One strategy that can offset the MTTS shortfall would be to protect growing trees that have the potential to contribute harvestable timber during the mid-term time period. These trees, which form the stand's secondary structure, include any tree (typically non-pine species and juvenile pine) that is likely to survive a mountain pine beetle attack in stands damaged by infestations of the beetle. Secondary structure that can contribute to the MTTS should ideally be able to outgrow a plantation within the mid-term time period; if not, a clearcut and plant strategy may be the best option.

The first step in effectively managing secondary structure is to recognize the need for it to contribute to the near-future timber supply. Strategic action must then be taken to manage any block proposed for harvesting that contains a certain threshold level of secondary structure (i.e., enough secondary structure to provide reasonable confidence that these trees will mature into an economically viable harvestable stand). The process starts with planning of harvesting in priority areas, followed by field surveys and data collection. The key factors in assessing the stand management alternatives are the pre-harvest species composition, forest health factors, windthrow hazard, overall stand structure, stem distribution, and stem densities. The post-harvest secondary structure should provide sufficient volume (numbers and sizes of trees) to out-produce a plantation within the MTTS period. The pre- and post-harvest numbers used within the secondary-structure decision matrix presented in this appendix follow the current British Columbia stocking standards for mature trees with a certain minimum volume per tree. The larger trees (saplings, poles, and mature trees) have the greatest influence on the mid-term timber supply. Growth models indicate that these trees will outgrow a plantation and thus, will more effectively address the MTTS needs. Note that the Forest Practices and Practices Regulation amendment (July 2008) on protecting secondary structure takes a conservative approach that requires an ecologically acceptable understory of 700 well-spaced stems per hectare that are $\geq$ 6 m tall, or 900 well-spaced stems per hectare that are $\geq$ 4 m tall.

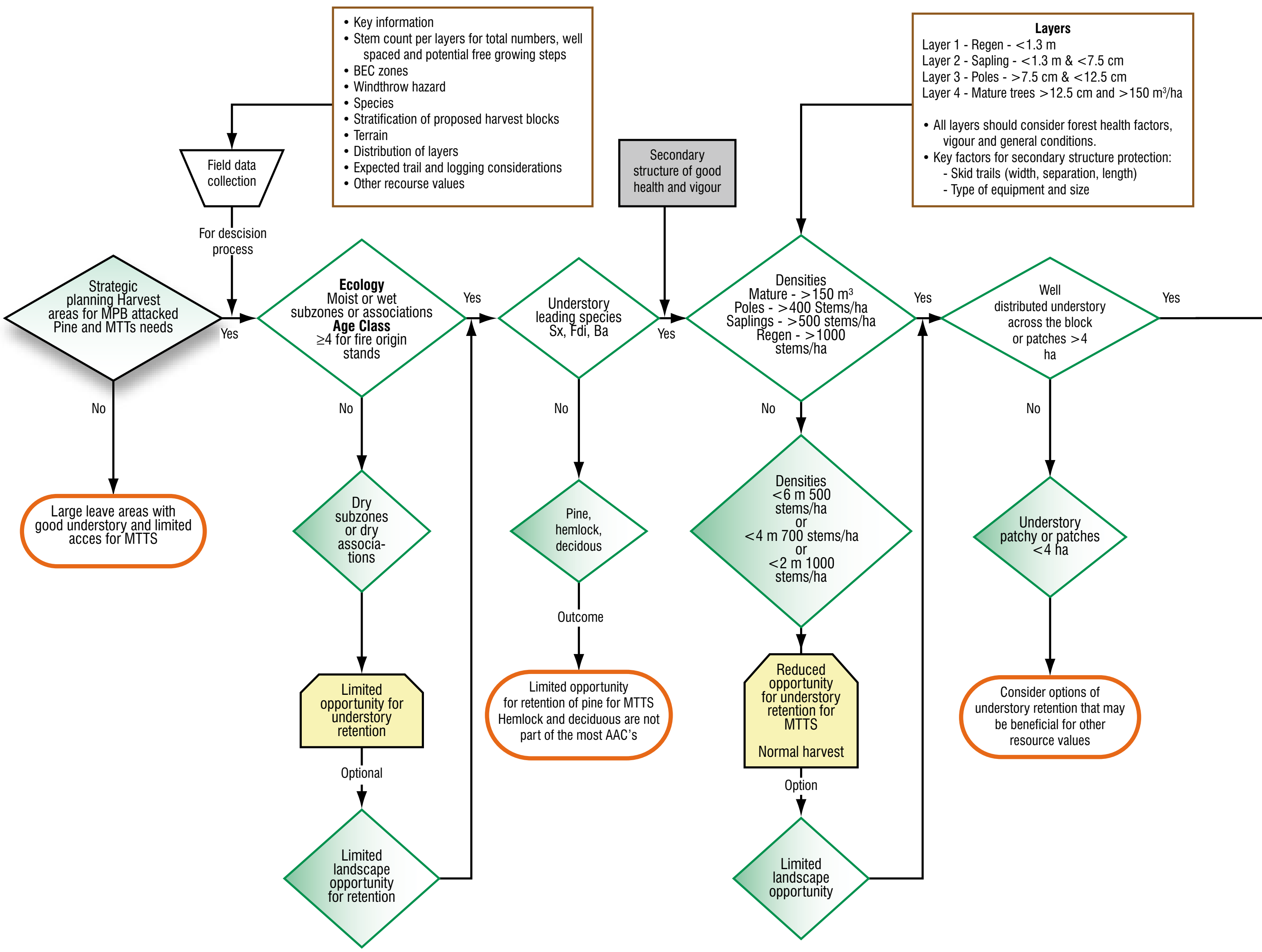
Once the information has been gathered and assessed, managers can then choose one of the following four strategies:

- Option one is no harvesting. This option may be based on several factors, including strategic decisions (e.g., timber access, current market conditions, harvest timing, etc.), the need to preserve other resource values, the fact that a stand is one of the few areas with sufficient understory within the operating area, or a high percentage of non-pine species present within the stand.
- Harvest option two represents stand structure conditions for which partial harvesting while protecting the non-pine overstory is a reasonable option. The benefit of this option is that it will have a positive impact on the early part of the MTTS period, will release mature and understory trees, and will protect against exposure of the understory. Note that the retention level of the non-pine overstory may be more than 50% and >150 m^3/ha of mature volume.
- Harvest option three is directed at stands where partial harvesting is not practical due to the low levels (<50%) of non-pine species, which would result in a post-harvest stand environment with significant windthrow risk and would produce a stand that is unlikely to contribute to the MTTS. The focus then shifts to managing the understory for non-MTTS purposes, with some protection of the overstory. Note that the trees retained may be a mixture of pine and non-pine species.

- Harvest option four is used where the understory is distributed throughout the block in patches less than 5 ha in size. In this option, several factors should be considered prior to harvesting. These may include the proportions of mature pine and non-pine species (% species mixture), and strategic planning considerations. Harvesting options include protection of understory or overstory patches, protection of mature non-pine trees for a later harvest within the MTTS period, or partial harvesting of dead pine trees while protecting both the understory for inclusion in the MTTS and the non-pine overstory for other values. If pine accounts for less than 50% of the trees in the stand, it will be necessary to determine whether logging is economically feasible.

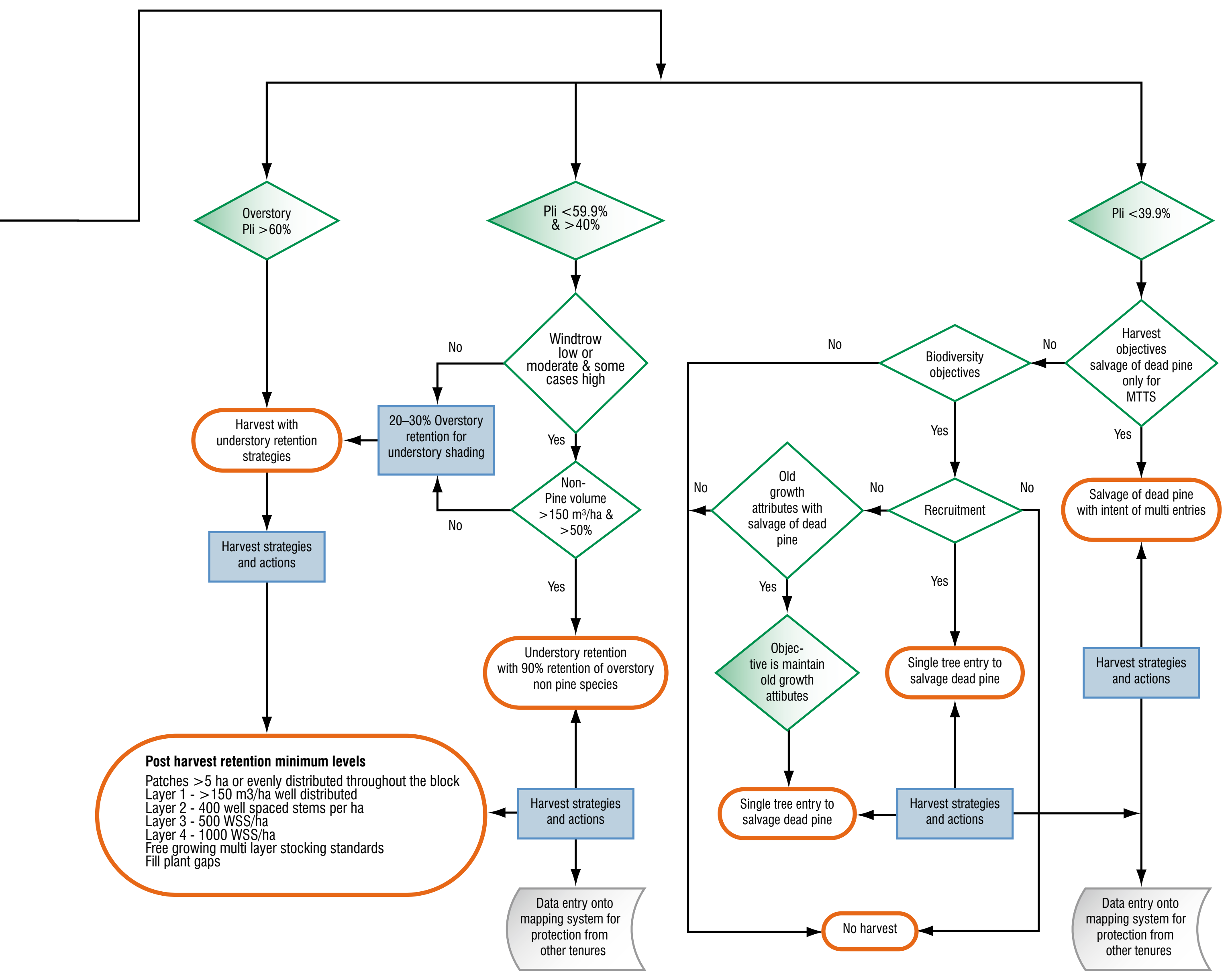
For successful management of a secondary structure program, all of these steps must be completed, including data collection, developing an

Understory retention and partial harvest decision matrix (short form)



understanding of the secondary structure, layout of the harvesting operation (e.g., trail locations, treatment unit boundaries, leave areas, etc.), and equipment selection. However, the key factor in the success of managing secondary structure is that the equipment operators and all other stakeholders are passionate about the process. As operators become more experienced with partial harvesting and understory protection, their efficiency will increase, management strategies will improve, and costs will decrease. The attached flowchart summarizes the decision process involved in managing secondary structure Figure 1-1. A complete version of the decision matrix for managing secondary structure is available on the British Columbia Ministry of Forests and Range Web site: <http://www.library.for.gov.bc.ca/ipac20/ipac.jsp?index=BIB&term=108142>.

Figure 1-1. Secondary structure management flowchart created by Ken Hodges, RPF.



Appendix 2.
Machine costs ($/scheduled machine hour (SMH))[a]

	Trial 1		Trial 3				Trial 4		
	Forwarder	Small excavator	Feller-buncher	Skidder	Delimber	Loader	Feller-buncher	Forwarder	Processor
Total purchase price (P) $	370 000	140 000	520 000	300 000	430 000	530 000	515 000	491 000	458 333
Expected life in hours (H)[b]	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000
Expected life in years (Y) = (H/SMHY)	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
Scheduled machine hours/year (h)[c]	1 620	1 620	1 620	1 620	1 620	1 620	1 620	1 620	1 620
Salvage value as % of P (s) %	25	25	25	25	25	25	25	25	25
Interest rate (Int) %	7	7	7	7	7	7	7	7	7
Insurance rate (Ins) %	3	3	3	3	3	3	3	3	3
Salvage value (S) = P(s/100)] $	92 500	35 000	130 000	75 000	107 500	132 500	128 750	122 750	114 583
Average investment (AVI) = (P+S)/2 $	231 250	87 500	325 000	187 500	268 750	331 250	321 875	306 875	286 458
Loss in resale value = (P-S)/H $/h	23.13	8.75	32.50	18.75	26.88	33.13	32.19	30.69	28.65
Interest = ([Int/100]xAVI)/h $/h	9.99	3.78	14.04	8.10	11.61	14.31	13.91	13.26	12.38
Insurance = ([Ins/100]xAVI)/h $/h	4.28	1.62	6.02	3.47	4.98	6.13	5.96	5.68	5.30
Total ownership costs (OW) $/h	**37.40**	**14.15**	**52.56**	**30.32**	**43.46**	**53.57**	**52.06**	**49.63**	**46.33**
Fuel consumption (F) L/h	25.0	15.0	32.5	25.0	20.0	35.0	45.0	25.0	25.0
Fuel cost (fc), $/L	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Lube & oil as a % of fuel (fp), %	15	15	15	15	15	15	15	15	15
Annual tire consumption (t) no.	1	0	0	1	0	0	0	1	0
Tire replacement cost (tc) $	3 200	0	0	2 500	0	0	0	3 200	0
Track and undercarriage replacement cost (Tc) $	0	12 000	25 000	0	28 000	30 000	16 000	0	16 000
Track and undercarriage life (Th) h	0	6 000	6 000	0	4 500	4 500	4 000	0	4 000
Lifetime repair and maintenance cost as a % of purchase price (Mc)[b] %	80	80	80	80	80	80	80	80	80
Lifetime repair and maintenance (Rp) = (PxMc/100) $	296 000	112 000	416 000	240 000	344 000	424 000	412 000	392 800	366 667
Shift length (sl) h	9	9	9	9	9	9	9	9	9
Total wages (W) $/h	26.42	27.53	28.02	25.83	24.91	25.83	28.02	26.42	24.91
Wage benefit loading (WBL) %	35	35	35	35	35	35	35	35	35
Fuel cost (F*fc) = (Fxfc) $/h	27.50	16.50	35.75	27.50	22.00	38.50	49.50	27.50	27.50
Lube & oil ((fp/100))x((F*fc)) $/h	4.13	2.48	5.36	4.13	3.30	5.78	7.43	4.13	4.13
Tire cost = (txtc)/h $/h	1.98	0.00	0.00	1.54	0.00	0.00	0.00	1.98	0.00
Track and undercarriage cost = Tc/Th $/h	0.00	2.00	4.17	0.00	6.22	6.67	4.00	0.00	4.00
Repair and maintenance cost = Rp/H $/h	24.67	9.33	34.67	20.00	28.67	35.33	34.33	32.73	30.56
Wages and benefits = W (1+WBL/100) $/h	35.67	37.17	37.83	34.87	33.63	34.87	37.83	35.67	33.63
Prorated overtime = (0.5xW)x (sl-8)x((1+WBL/100) /sl) $	1.98	2.06	2.10	1.94	1.87	1.94	2.10	1.98	1.87
Total operating costs (OP) $/h	**95.92**	**69.54**	**119.87**	**89.98**	**95.69**	**123.08**	**135.19**	**103.98**	**101.68**
Total ownership and operating costs (OW+OP) $/h	**133.32**	**83.69**	**172.43**	**120.30**	**139.15**	**176.65**	**187.25**	**153.61**	**148.01**

[a] These costs are calculated using Feric's standard costing methodology and do not include supervision, profit, overhead, or transportation of equipment or logs. These are not the actual costs incurred by the contractor. Shift-level timing data for Trial 2 was not available.

[b] Actual machine costs may differ due to variations in life expectancy (H) and lifetime repair and maintenance costs (Mc) between the machines. In these costing caculations, we standardized these variables for all machines. Life expectancy (H) is the number of machine hours when "the majority of owners trade in that type of machine" (Sinclair, 1986).

[c] We estimated the number of SMH per year (1620 h) as 9 hours per day, 5 days per week, and 4 weeks per month, for 9 months.

Appendix 3.
Productivity and costing summary

	Trial 1			Trial 2	Trial 3				Trial 4		
	Forwarder	Excavator	Hand-feller	All machines	Feller-buncher	Grapple skidder	Stroke delimber	Loader	Feller-buncher	Forwarder	Processor
PMH[a] (hours)	41	88	126	-	150	133	85	30	49	154	195
SMH[b] (hours)	180	270	126	-	207	180	90	45	64	173	233
NPMH (hours)[c] = SMH - PMH	139	182	0	-	-	-	-	-	-	-	-
Utilization (%) = PMH/SMH	23	33	100	-	72	74	94	67	78	89	84
Harvested volume (m^3)	1 330	1 330	1 330	1 800	4 746	4 746	4 746	4 746	5 369	5 369	5 369
Ownership cost (OW) $/SMH	37.40	14.15	4.00	-	52.56	30.32	43.46	53.57	52.06	49.63	46.33
Operating cost (OP) $/SMH	95.92	69.54	50.85[d]	-	119.87	89.98	95.69	123.08	135.19	103.98	101.68
PMH machine cost[d] ($/$m^3$)	4.11	5.54	5.20	-	5.45	3.37	2.49	1.12	1.71	4.41	5.38
NPMH machine cost[e] ($/$m^3$)	3.91	1.94	0	-	-	-	-	-	-	-	-
SMH machine cost ($/$m^3$)	8.02[f]	7.48[f]	5.20[g]	-	7.52[h]	4.56[h]	2.64[h]	1.67[h]	2.23[h]	4.95[h]	6.42[h]
Total PMH machine cost ($/$m^3$)	**14.85**			**-**	**12.43**				**11.50**		
Total SMH machine cost ($/$m^3$)	**20.70**			**16.33[i]**	**16.39**				**13.60**		

[a] PMH = productive machine hours (machine working or traveling + delays <15 minutes).

[b] SMH (scheduled machine hours) is calculated as the combined total hours in the scheduled work days for the machine from the start of harvesting to the finish. Since not all of the machines were required to be present on the site for the same amount of time, a scheduled work day was considered any day when the machine was required for work.

[c] NPMH (non-productive machine hours) represents the time a machine is available during a workday, but cannot work because an operator is not available (this calculation was only used in Trial 1).

[d] PMH machine costs = Ownership costs + operating costs multiplied by PMH divided by harvested volumes = (OW+OP) x PMH / harvested volume.

[e] NPMH machine costs = Ownership costs multiplied by NPMH divided by harvested volume = (OW x NPMH) / Harvested volume. A separate harvesting cost calculation was employed to account for the ownership cost of the harvesting machines when they remained idle for long periods on the site during their non-productive machine hours (NPMH). This calculation was only used in Trial 1.

[f] SMH machine costs for Trials 3 and 4 used ownership + operating cost multiplied by SMH divided by harvested volume: [(OW+OP) x SMH] / Harvested volume.

[g] SMH machine costs for Trial 1 included separate ownership costs for the lengthy periods when the machines were not working (NPMH machine costs) plus ownership + operating costs for machine operating times (PMH machine costs): SMH machine costs = NPMH machine costs + PMH machine costs

[h] Hand-feller operating cost (OP) per hour = wage + (WBL/100 x wage) = $37.67 + (0.35 x 37.67) = $50.85 / hr

[i] Total machine cost for Trial 2 was provided by the contractor and did not employ the FERIC costing methodology. In Trial 2, costs per m^3 were calculated by simply dividing the contractor-estimated “stump to landing” costs ($29 400) by the harvested volume (1800 m^3).

Appendix 4. Harvesting damage and costs/m³

	Trial 1	Trial 2	Trial 3	Trial 4
Undamaged non-pine overstory as a proportion of the pre-harvest non-pine stems (%)	99	68	61	18
Moderately damaged non-pine overstory as a proportion of the pre-harvest non-pine stems (%)	0	5	7	19
Severely damaged non-pine overstory as a proportion of the pre-harvest non-pine stems (%)	1	16	12	26
Harvested non-pine overstory as a proportion of the pre-harvest non-pine stems (%)	0	11	20	37
Lost or damaged understory as a proportion of the pre-harvest stems (%)	16	34	48	61
Proportion of harvested area covered by trail area (%)	3.3	6.9	18.3	36.5
Harvesting cost ($/m^3)	20.70	16.33	16.39	13.60
Harvesting damage is proportional to the amount of secondary structure stems that were present before harvesting.				

Appendix 5. Summary of the pre-and post-harvest stand

	Trial 1	Trial 2	Trial 3	Trial 4
Pre-harvest pine overstory[a] basal area (m^2/ha)	not available	13.0	19.2	20.2
Post-harvest pine overstory[a] basal area (m^2/ha)	not available	0.4	0	0
Pre-harvest non-pine overstory[a] basal area (m^2/ha)	16.8	12.1	22.9	3.2
Post-harvest non-pine overstory[a] basal area (m^2/ha)	16.8	8.0	7.1	0.5
Pre-harvest well-spaced understory[b] trees (stems/ha)	970	1070	585	572
Post-harvest well-spaced non-pine understory[b] trees (stems/ha)	918	600	429	168
Pre-harvest MTDFP value	0.09	0.07	0.07	0.40
Post-harvest MTDFP value	0.10	0.24	0.30	0.79

[a] Overstory = trees $\geq$ 12.5 cm dbh
[b] Understory = trees < 12.5 cm dbh

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Find us Online!
www.feric.ca

Eastern Region
580 boul. St-Jean
Pointe-Claire, QC, H9R 3J9
☎ (514) 694–1140
(514) 694–4351
admin@mtl.feric.ca

Western Region
2601 East Mall
Vancouver, BC, V6T 1Z4
☎ (604) 228–1555
(604) 228–0999
admin@vcr.feric.ca

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