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OPERATIONAL MANUAL FOR COMMERCIAL THINNING IN BRITISH COLUMBIA

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December 2021

In British Columbia the large-scale application of Commercial Thinning (CT) became important over the last years both as a stand tending operation, and as a method to provide the fibre needed in the interior of the province to mitigate the shortage due to large scale disturbances such as bark beetle epidemics and fire.

The Operational Manual presents the experience of FPInnovations on application of CT, and presents methods for selection of CT candidate stands, for defining prescriptions and assessing the economic operability of harvest blocks, for supervising operations, and determining the productivity and cost of machines used.

The Manual can be used by forest planners, field supervisors and machine operators in different phases of CT implementation.

Project number: 301014531

Technical Report: TR 2021 No.93

ACKNOWLEDGEMENTS

This project was financially supported by Natural Resources Canada.

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1 BACKGROUND

Commercial Thinning's (CT) are a type of partial cutting designed to guide the production of stands and trees along desirable channels and represent the most important kind of (stand) tending or intermediate cutting intervention (Smith 1996). CT aim at increasing fibre production without overlooking the other resource values provided by forests, the key principle being maintenance or enhancement of non-timber values.

The traditional objectives of CT are presented in the Guidelines for Commercial Thinning (Province of BC 1999):

- Obtain wood volume or revenue earlier than the final harvest.
- Improve the growth of residual trees.
- Improve the quality of the stand by removing dead, diseased and deformed trees.
- Capture some of the production that would otherwise be lost to mortality.
- Obtain certain species and size classes for specialty products.

In British Columbia (BC), over the past two decades, the impacts of large-scale disturbances due to bark beetle epidemics and fire have led to a fibre supply deficit, particularly in the central and northern interior of the province. Consequently, the allowable annual cut (AAC) has declined with further reductions anticipated. Fibre supply from traditional clear cuts is also constrained throughout the province to accommodate values such as wildlife habitat attributes, visual quality objectives and old growth management to name a few. Apart from its traditional objectives, commercial thinning has been identified as an opportunity to mitigate fibre shortfalls and incentives are in place to compensate for the additional costs associated with more intensive young plantation management. To facilitate this a joint government and industry committee (CT Working Group) produced a document to provide guidance on the principles of commercial thinning at the stand and landscape level including assumptions about growth and yield, timber supply and economic modelling (Province of BC 2021).

From a wider perspective, four strategies are identified by Lussier and Filipescu (2019) for the introduction of CT in regional plans as presented below:

1. Accelerate growth to reduce technical rotation age
2. Anticipate harvest
3. Allow partial harvest within constrained areas.
4. Manage the production of even-aged mixed stands.

Description of the four strategies along with details on how and where they can be applied are presented in Appendix I.

The focus of this manual is on the use of commercial thinning as a treatment to improve the vigor of young stands while generating positive cash flow from the operation. However, forest professionals cannot overlook the impact that a CT operation may have on other resource values like cultural heritage, water, forest health, windthrow, visual quality objectives (VQO), wildlife habitat, and recreation. The final section of the document also includes comments on some of the non-timber values.

The Operational Manual is designed for three types of users: 1) forest planners, to assist with selectin of CT candidate stands and quantification of the costs and benefits of commercial thinning; 2) site supervisors to implement plans for commercial thinning at the block level and; 3) operators that require simple instructions to meet the harvesting objectives. The Manual is designed to complement the Operational Guidance developed by the CT Working Group (Province of BC 2021). The Guidance is more strategic in nature and has a wide application for interior BC, whereas the Manual addresses issues at the operational level and focuses on the current commercial thinning opportunities.

2 SELECTION OF CT CANDIDATE STANDS

2.1 Defining the CT Criteria

The criteria for selecting stands suitable for CT application involve species, stand age, Site Index (SI), stand density (stems/ha), basal area (BA), and merchantable volume per hectare. Methods for determining the best time for application of CT are in general based on analysis of Mean Annual Increment (MAI) and aim at improving the stand growing conditions (i.e., reducing the stand density) at the best time to best utilize the period of maximum growth. The methodology based on MAI presents difficulties related to computation of volumes at different ages and/or the initial stand density which may be unknown. This manual applies the same principle but in a simpler form, namely: the main growth in diameter of trees follows the culmination of growth in height. Diameter and volume are highly correlated and a major growth in diameter implies a major growth in volume. The method for determining the height growth is based on Goudie (1984) and is represented in Figure 1.

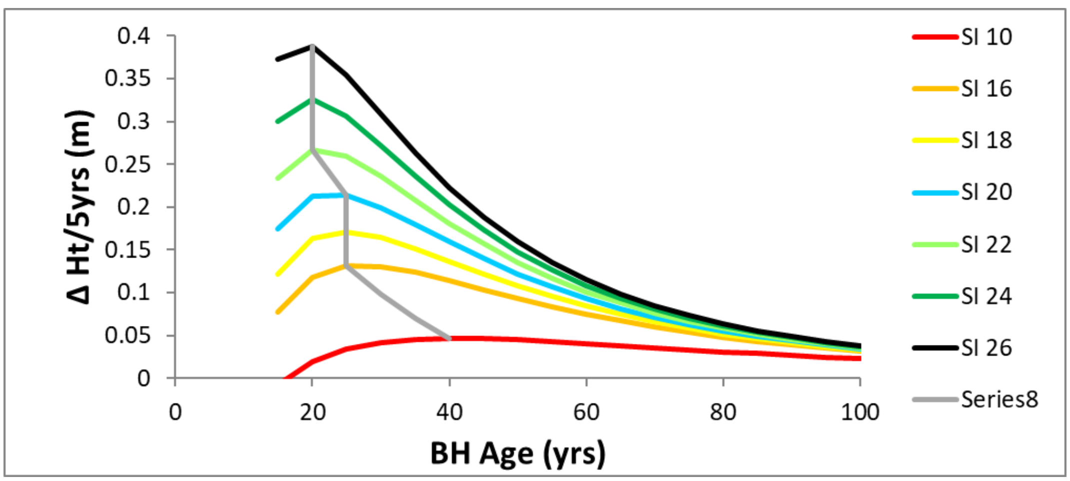


Figure 1. Culmination of relative height growth for lodgepole pine at different SI.

The coordinates in Figure 1 are breast height (BH) age in years, and the difference in the rate of height growth between successive 5-year periods. Combining the results presented in Table 1 and the number of years to reach breast height (years to breast height – YBH) the optimal (i.e., minimum) thinning age for stands is presented in Table 1.

Table 1. Optimal thinning age for lodgepole pine by SI.

SI	10	12	14	16	18	20	22	24	26
YBH	10	9	9	8	8	8	8	7	7
Optimal thin age	50	44	39	33	33	33	28	27	27

For the most common species in interior BC, the minimum ages for application of CT determined with this methodology are presented in Table 2.

Table 2. Minimum thinning ages for species in interior BC

Minimum age for CT by Species and SI									
Species\SI	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**
At	40	39	34	34	28	28	28	28	28
Bl	43	41	39	33	31	30	29	28	23
Fd	44	42	41	40	35	34	33	33	33
Pl	50	44	39	33	33	33	28	27	27
Lw	92	81	70	64	53	48	42	37	32
Sx	100	83	72	66	55	55	49	44	43

As highlighted in Table 2, for stands with SI equal to 18 the minimum age for balsam is 31 years, for lodgepole pine 33, and for spruce 55. Forest planners can adjust these ages based on their experience and knowledge of local conditions. Based on the minimum thinning age a period can be defined for application of CT, e.g.: if we consider a 10-year window, pine stands between 33 and 43 years can be identified as good CT candidates.

For SI there seem to be a general agreement (Province of BC 2021) that stands with a SI above 16 (or even 18) are good candidates for CT. For the other stand attributes (density, BA, volume/ha) minimum requirements are in general determined by local knowledge of stand and sites conditions. For example, in interior BC a minimum BA of 20 m^2/ha for the residual stand is recommended.

In BC, the site and stand attributes needed for CT stand selection are available through the Vegetation Resources Inventory (VRI) in a Geographic Information System (GIS) format. However, Province of BC (2021) mentions that VRI was designed to be a strategic management unit level inventory and is not always reliable at the stand level. Based on an examination of completed CT operations, VRI appears useful for age and density but not for basal area or volume. The Provincial Site Productivity Layer (PSPL) is recommended to address SI rather than VRI's SI value.

2.2 Procedure for Stand Selection

The selection of CT candidate stands needs to combine the spatial description and associated attributes of stands in GIS format, and local knowledge of the operating area, e.g.: existing roads and bridges, distances to mills, grouping of stands that can minimize machine movement. The following procedure is proposed:

1. Select stands by attribute in GIS based on species, SI, age, stand density, BA. Site conditions should be also considered, e.g., slope should be analyzed in conjunction with harvesting machines available.
2. Further refine the list based on accessibility (roads to build/maintain), distance to mills, grouping of stands.
3. Field reconnaissance to confirm validity and accuracy of GIS data. This can include quick prism plots based on a simplified procedure: using calipers instead of diameter tapes, and the ‘one in one out’ procedure for trees. FPInnovations developed a simple spreadsheet that can be used on a phone to determine main stand attributes (density and BA) for each plot and from all the plots located in a stand. This step will produce a (shorter) list of stands where detailed inventory should be obtained.
4. Other field observations based on experience and knowledge of local stands may help with stand selection. For example, the most recent 10-year radial increment and the height/DBH ratio are indicators of CT timeliness, and percent live crown (which represents the ratio of crown height to total tree height) is considered an indicator of the vigor and potential growth response the stand may have after CT operations.
5. For the stands selected in the previous step a detailed inventory is needed to assess their economic operability. This may already exist based on new Lidar-based methods. Otherwise, if an inventory is not available or is not of sufficient accuracy, new field data should be collected using traditional methods (prism plots).
6. Processing of field data, definition of CT prescription, and economic operability analysis can be done with the methods and tools described in this manual.

The selection criteria should also include considerations for broader assessment of Management Units (Timber Supply Areas, Tree Farm Licenses, Community Forest Agreements) to develop landscape level multi-year spatially sequenced CT harvest plans to support contractor investment in equipment and training resources. Other criteria for stand selection and management in CT operations using stand density management diagrams (SDMD) are described in Farnden (1996). Also, the CT Working Group developed a Stand Level Decision Key for Commercial Thinning Opportunity (Province of BC 2021).

3 PLANNING CT OPERATIONS AT THE BLOCK LEVEL

The planning phase aims at defining the CT prescription at the block level and assessing the economic operability of stands. The main steps in the CT planning process are:

1. Pre-harvest assessment of the stand.
2. Selection of harvesting system: evaluation of machinery available, of experience of operators and first-line supervisors.
3. Definition of CT prescription and block layout which comprises selection of trail width, trail spacing, and tree selection criteria.
4. Economic operability analysis.
5. Assessment of the impact of CT over the entire life of the stand.

Thinnings can be applied in different forms. The planning process presented in this Operational Manual is based on row/trail thinning (Smith 1996) and is described in conjunction with the analysis methods implemented in the Partial Cutting Simulator (PCSim). PCSim is a model developed by FPInnovations for designing prescriptions and assessing the economic feasibility of CT operations.

Planning is presented in this document from the fibre production perspective. This version of the Operational Manual does not include details on non-timber values. The remainder of this section describes each phase of the planning process.

3.1 Pre-harvest Assessment of the Stand

The pre-harvest assessment aims at obtaining good info on species existing in the block, distribution of trees by DBH, total and merchantable volume, and state of health of the stand (presence of pathogens and their influence on volume and value loss). In many areas of BC enhanced forest inventory (EFI) is available and may include all the stand attributes needed for a pre-harvest assessment. Otherwise, a stand inventory (timber cruising) is needed. The main attributes to be collected for each tree are species, DBH, total height, and information on its health, which can come in the format of standard cruise data or customized/simplified cruise. Essentially, in the field inventory we need to collect the stand and tree metrics to be used in the prescription definition and assessment of economic operability.

The pre-harvest assessment needs to account for the limitations of mechanized harvesting, namely that the machine operator can see only the bottom 6 – 7 m. of the stem. For this reason, a quality class system with three classes is introduced, as presented in Table 3.

Table 3. The classification system for tree quality

Classification	Description	Examples
Q1	Future crop tree with no visible defects in the lower 6m	No defects
Q2	Tree with a major defect on 1 or 2 of the 4 faces in the lower 6 m. 50% risk of non-detection	Crack Fungi Sap Holes Scar
Q3	Tree with a major defect on 3 or 4 of the 4 faces in the lower 6m. Always detectable	Fork Crook Leaning Unwanted species Small diameters

Alternatively, the tree quality classes can be presented in relation to percentage circumference of tree where damage indicators exits, i.e.: Q2 have between 25 and 50% of tree circumference with a major defect in the bottom 6 – 7 m, and Q3 have more than 50% of the tree circumference with a major defect in bottom part. Examples of Q1 – Q3 trees are presented in the Figure 2.

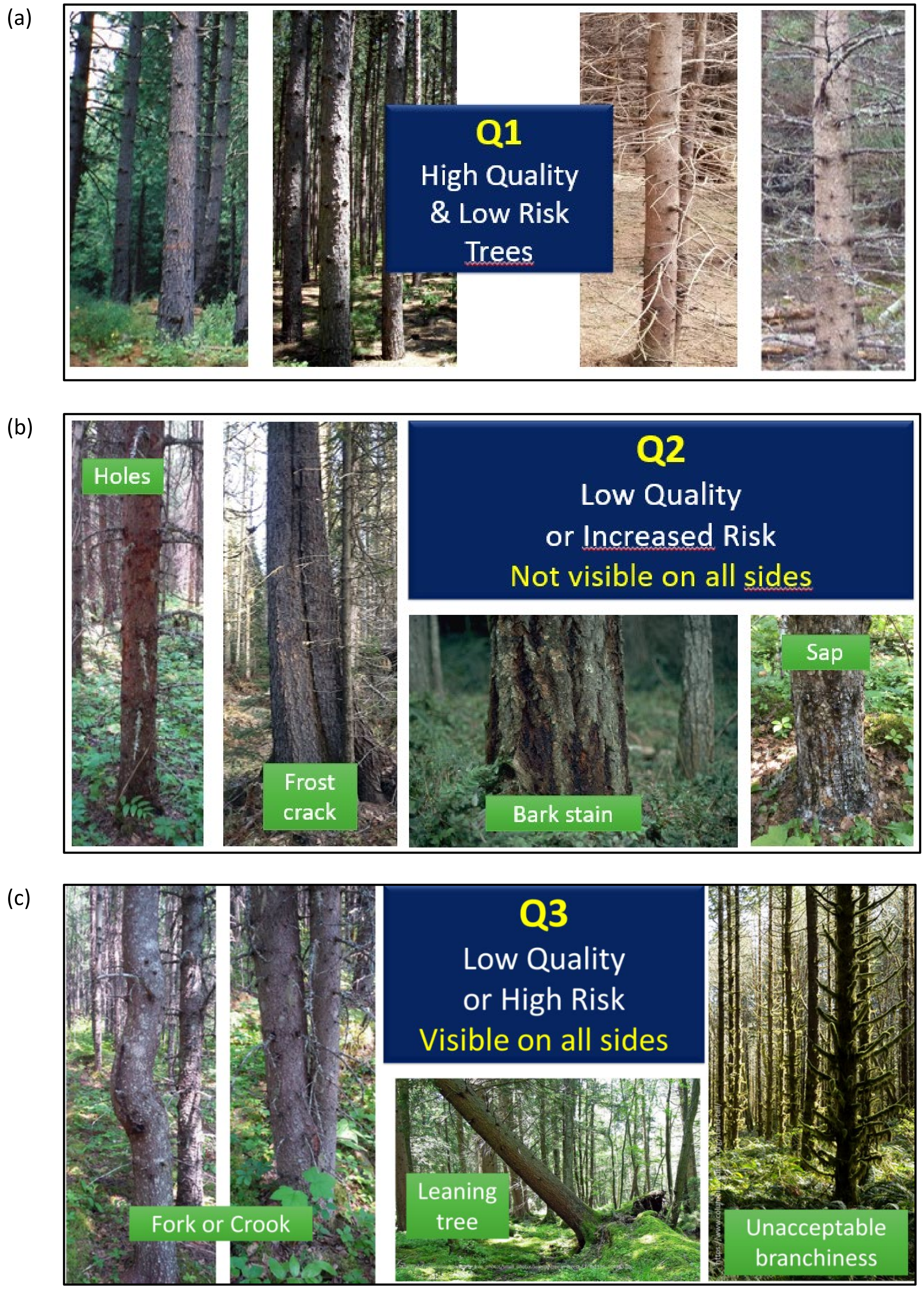


Figure 2. Examples of Quality 1 (a), Quality 2 (b), and Quality 3 (c) trees.

A fourth quality class (Q4) can also be used to describe vampire/wolf trees. These are trees which in general have no defects but may be of a species that is not desired, or due to their large size are detrimental to adjacent trees. Other attributes that may be collected in the field inventory are:

- Crown opening: from 0 – 100% in 25% classes; 0% - completely suppressed, 100% - completely open. This indicator is meant to measure the influence of the prescription and quantify the overall opening of the stand before and after the operation.
- Crown class using the known classification: D – dominant, C – codominant, I – intermediate, and S – suppressed. This can be used in an intensive CT operation in which an individual selection of trees is conducted.

3.2 Selection of Harvesting System: Evaluation of Machinery Available, Experience of Operators and First-line Supervisors

Harvesting systems applied in CT operations are described in Meek (2000) and consist of: (i) harvester, forwarder; (ii) feller-buncher, skidder, processor; (iii) less commonly, a feller-buncher can be used for establishing the trails followed by a harvester and forwarder. Also, very seldom manual felling using full tree or cut-to-length systems was used in combination with skidding or forwarding, and processing for full trees.

Selection of the harvesting system is first influenced by the equipment available. The harvesting system is usually selected in connection with the prescription and stand and site attributes. Large machines are expensive and difficult to maneuver in small spaces, small machines may be inefficient and not able to handle large wood. The inter-trail treated area needs to match the boom size and ability of the machine to handle trees. The ability of machines to negotiate slopes existing in a block should be also considered as terrain conditions may impede access and reduce productivity. Previous studies identified the combination harvester and forwarder (Figure 3) as the most efficient in CT operations.

(a) **(b)**

Figure 3. Machines used in CT operations: (a) harvester; (b) forwarder.

The harvester-forwarder combination can be used in prescriptions that consist of clearcut trails and inter-trail selection zones. When feller-bunchers are used it is not feasible to apply the same prescription (i.e., alternation of clearcut trails and selection zones) and secondary trails must be cut perpendicular to the main trail, as presented in Figure 4.

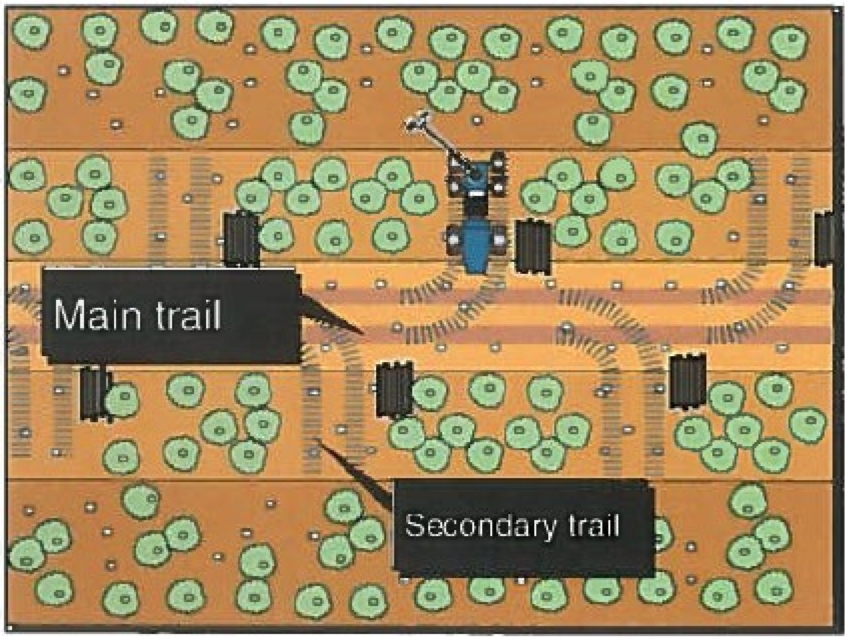


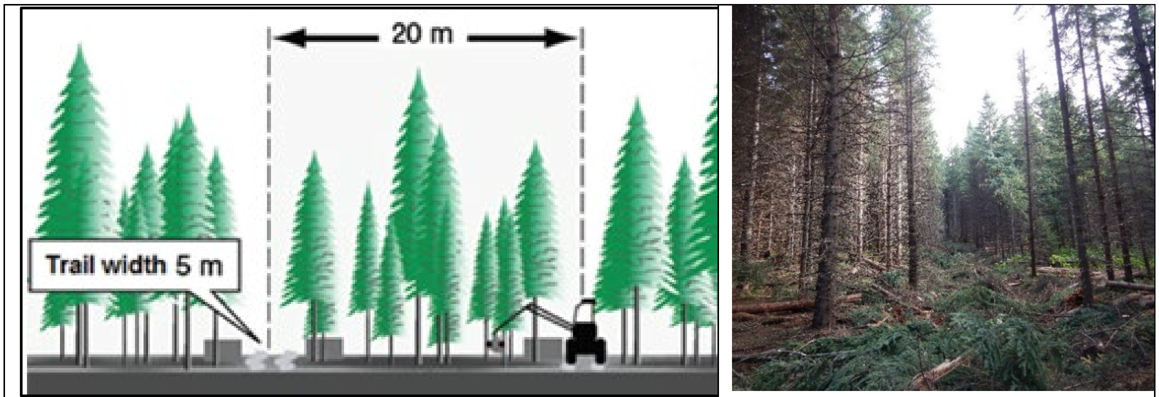
Figure 4. Example of secondary trails cut when feller-bunchers are used in CT.

Availability of experienced operators is of paramount importance. Based on previous experience and familiarity with the machine an operator new to CT may need a relatively long time to become proficient in CT operations. First-line supervisors may also need significant time to learn the specifics of CT. Supervisors need to be familiar with the application and control of CT and some practitioners believe that the cost of supervision for CT is three times greater than in the case of clearcuts.

3.3 Development of CT Prescription

The tree and stand attributes collected in the pre-harvest assessment phase are used for defining the prescription. Various criteria can be set with respect to layout of the block, trails' width and spacing, tree selection criteria and removal priorities in PCSim analyses. The only assumption is that the prescription defined in the planning phase (in the office) can be applied in the field.

The trail network is defined by the trails' width and their spacing, which are influenced by the size of the machines used (width and boom reach), the intensity of the intervention, and the locations of features associated with the block (streams, WTP, rock). As known from practice, the narrower the trail width, the better from site occupancy (growing space utilization) perspective. Figure 5 presents the layout of a block with 5-m trail width and 15-m selection zone (inter-trail treated area), and a view of a recently cut trail.



(a)	(b)

Figure 5. Layout of an operation with 5-m trail width and 15-m selection zone (a); field-view of a trail (b).

The first step in the prescription definition is assessment of the pre-harvesting stand conditions: the stand table, density (stems/ha) and BA. Based on tree selection criteria and trails' width and spacing the structure and the metrics of the residual stand are computed, and the final prescription is determined in an iterative procedure.

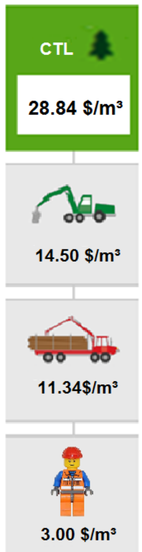
The order of tree selection relates to tree species, quality, size and spacing. For example, if all the trees in the immediate reach of the machine are potentially future crop trees (e.g., Q1 trees) the next order of selection would be on spacing or 'cut frequency'. Based on target BA or stand density PCSim can be used to determine that '1 out of 3' or '1 out of 4' trees can be cut, and the operator can take the smallest, or take the one that creates a uniform spacing in the residual stand. For practical reasons, the operator should be given no more than four or five selection criteria.

3.4 Economic Operability Analysis

The economic operability analysis aims at quantifying the cost and revenue generated by the operation and ensure that overall, the CT yields a positive cash flow result to the landowner and operator. The approach developed by FPInnovations reflects the bucking practices of the company and the most current fibre costs, is flexible with respect to utilization (topping diameter) standards and operational adjustment factors, and can accommodate many types of fibre (e.g., different categories including biomass). The revenue generated is a function of the initial stand (volume by species, distribution by DBH classes, defects), log dimensions and value, and the prescription defined. The costs are calculated based on the harvesting system used, machine cost and utilization rates.

PCSim displays detailed results on volume removed from trails and selection zones and their associated values based on the algorithm presented in Pavel and Andersson (2009). Results of analysis also capture the statistical nature of the stand assessment and valuation process and confidence limits are calculated for the most important stand attributes (i.e., BA and volume). Also, details are presented on the pre- and post-harvest stand conditions.

Productivity and costs of machines are determined based on stand and site attributes (piece size, stand density, extraction distance, slope, merchantable stem distribution). FPInnovations has developed detailed methodologies for determining machine productivity. Next, based on machine productivity, harvest volume, and expected machine utilization, the cost for all machines and total cost of the operation can be determined. An example of FPInnovations' costing methodology is presented in Figure 6.



	Shortwood Harvester	Forwarder
Unit cost ($/m^3)	14.50	11.34
Hourly cost ($/PMH)	271.15	210.95
Purchase price ($)	750000	550000
Residual value (%)	10	10
Economic life (years)	10	10
Scheduled usage (PMH/year)	2000	2000
Insurance ($/year)	16500	12100
Oil and lubricants ($/PMH)	1.37	1.37
Utilization rate (%)	75	80
Repairs ($)	862500	550000
Fuel consumption (L/PMH)	30	30
Profits/risks (%)	10	10
Other costs ($/year)	0	0
Interest rate (%)	10	10
Fuel ($/L)	1.3	1.3
Operator cost ($/h)	44.55	44.55
Productivity (m^3/PMH)	18.7	18.6

Figure 6. Example of FPInnovations' costing methodology.

Also, an example of the final results of an economic feasibility analysis as displayed in PCSim is presented in Figure 7.

Economic analysis (yellow cells represent user input)			
Merch. volume	m^3	7,647	
Wood value	$		645,769
Activity/description	**unit**	**Quantity**	**Cost**
Machine mobilization/demob.			4,000
Harvester	$/m^3	14.00	107,058
Forwarder	$/m^3	10.00	76,470
Loader	$/m^3	2.00	15,294
Road construction	$/Km	30,000	150,000
Road length	km	5.0	
Roads' maintenance	$		0
Transportation	$/m^3	5.0	38,235
Stumpage	$/m^3	15	114,705
Silviculture	$/m^3	1.5	11,471
Supervision	$/m^3	1	7,647
Others	$/m^3	1.0	7,647
Total Revenue	$		113,242
Revenue/m^3	$/m^3		14.8

Figure 7. Assessment of economic operability of a CT operation.

When the pre-harvest inventory is conducted using cruise plots PCSim also provides volume outputs for each plot. If a Canopy Height Model (CHM) of the stand is available it can be used in conjunction with the volume by plot to adjust block boundaries, i.e.: areas where the CHM shows low tree heights and the corresponding plot volumes are small should be excluded from the block.

3.5 Assessment of the Impact of CT Over the Entire Life of the Stand

An important concern related to the application of CT is high-grading and ensuring that the stands' value at final cut is not compromised. Stand volume and value can be estimated in the 'with- and without-CT' scenarios using stand table projection (STP) growth and yield models. The stand table in the 'without CT' scenario is essentially available through the pre-harvest assessment. For the post-harvest conditions ('with-CT'), the stand table can be simulated by PCSim (if we assume that the prescription is applied exactly as defined), or by doing a post-harvest inventory. In both scenarios, stand tables can be projected to the final harvest age using an STP model, and virtually buck all the trees (in the stand table) using PCSim. Essentially, STP models describe stand changes with respect to diameter and height growth and mortality. For this reason, stand tables must include also small-size trees which will contribute important volumes and value at the final harvest. Hence, both pre- and post-harvest inventories must be customized to correctly sample the small-size trees.

Comparisons can be made based on Net Present Value (NPV) and appropriate discount rates. The analysis should contrast the stand in the 'without CT' scenario with the cumulative results (thinning + final harvest) of the 'with CT' scenario for the entire life of the stand. Since the final harvest ages will be likely different for the two scenarios adjustments can be made through simple prorating or using methods based on land expectation value. A detailed methodology for assessing the impact of CT over the entire stand life is being developed by FPInnovations and will provide a plausible assurance that if all assumptions hold true, application of CT in a certain case has a positive or neutral impact on the stand.

4 IMPLEMENTATION OF CT

Once the prescription is defined, the preliminary economic analysis is finished, and the operation is assessed to be economically feasible, the CT operation can proceed following the phases presented below (Gaudreau 2019):

1. Coach operators on trail layout, i.e., width of trails and selection zones, and cutting practices.
2. Coach operators on selection rules.
3. Ensure adequate trail spacing
4. Monitor the operation.
5. Measure productivity
6. Post-harvest assessment.

Details on each step of the implementation process are presented in the remainder of this section.

4.1 Coach Operators on Trail Layout

Trail width is in general determined by the width of the machines used, and distance between trails (selection zone) should be marked/flagged at the beginning of each trail. For new operators it is recommended that complete trail layout be done before the operation. Trail width is essential for managing crown spacing and is always of concern and difficult to minimize especially when using large machines. The so-called “gate trees” can be used as reference points for maintaining a constant trail width. These are trees located on opposite sides of the trail to mark its limit and are offset (relative to each other) to avoid creating a pinch point that would increase the risk of damaging the residual stand. Examples of “gate trees” are presented in Figure 8. In general, there is no specific requirement for trails to be straight, and curved trails are preferred especially if the block is managed for wildlife habitat, to help mitigate windthrow risk, and for visual quality.

(a) **(b)**

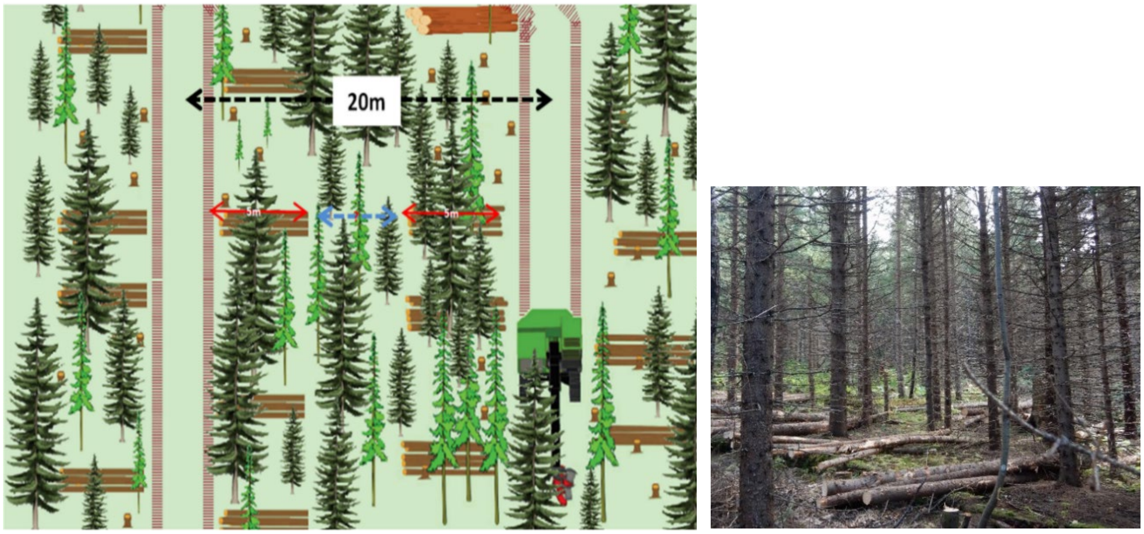
Figure 8. “Gate trees” used to determine trail width.

Figure 8 illustrates also the difficulty in estimating the trail width. While the actual width removed by the machine can be measured directly in the field, part of the trail is still used by the residual stand as crowns extend in the trail, as well. For this reason, as the prescription is being defined it is important to experiment with different trail widths and analyze their impact on the economic return of the operation.

As marking of trails is expensive a method for trail spacing is proposed based on using wood piles, aiming at reducing the cost of this phase. For example, for a 15-m spacing (selection zone) and if 16’ (5-m) logs are bucked the following procedure can be used:

- Place the logs at about 1 – 1.5 m from the trail’s edge.
- On the way back (on the next trail) lay the logs/piles at 2 – 3 metres from the old pile.
- Make sure that the piles in the new trail are placed at the same distance as in the previous trail, i.e., 1 – 1.5 m from the trail’s edge.

This procedure will produce a selection zone of approx. 15 m, and for a 5-m trail width this will result in a 20-m distance between trails' center lines. The principles of this method are depicted in Figure 9. Similar procedures can be developed for different inter-trail distances and logs' lengths. Also, newer machines are equipped with on-board navigation systems that can assist with setting the selection zones' widths.



(a) (b)

Figure 9. Setting the inter-trail distance using processed logs.

4.2 Coach Operators on Selection Rules

Tree selection guidelines must be simple and limited in number as the operator has very little means to control residual density or apply a sophisticated analysis of tree vigor. Visual estimations must remain simple so this can be done while operating the equipment, even during night shifts or in poor weather conditions. Operators need to identify crown openings without looking at tops (night shift considerations) and must choose natural openings or plan ahead to create space for felling/processing. Also, the processed wood should not interfere with the next tree to be cut or the next phase of the harvesting system. A simplified example of these steps is presented in Figure 10, which portrays the differences between falling and layout of logs and trees with harvesters compared to feller-bunchers.

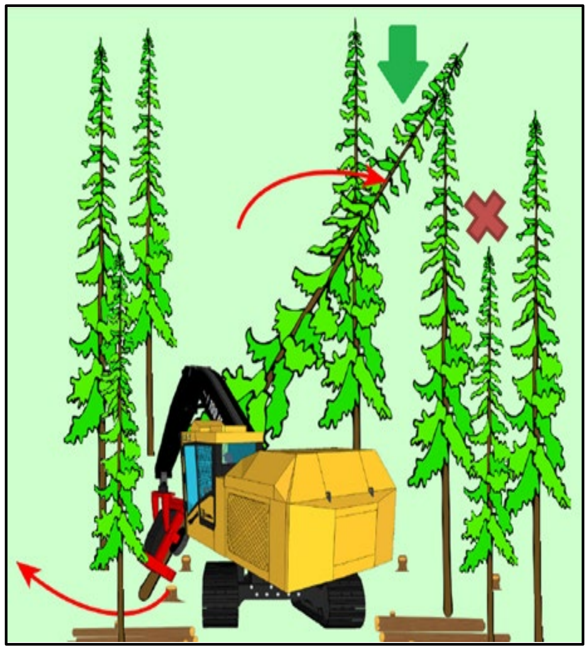


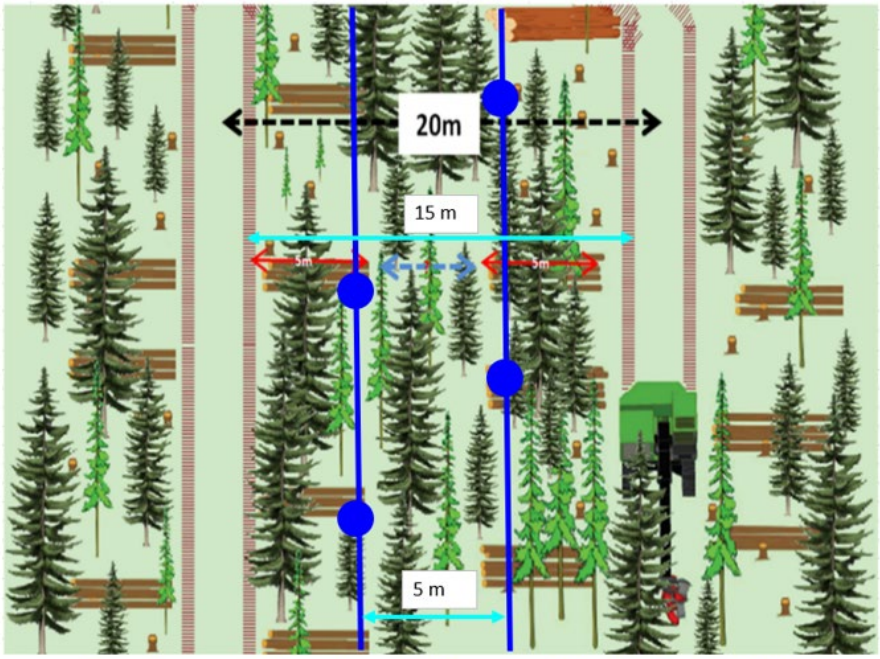
Figure 10. Schematic representation of tree cutting in CT.

4.3 Monitor the Operation

Monitoring should start very shortly after the beginning of the CT operation to provide feed-back to the operators in relation to the width of the trail and the tree selection process. Depending on the complexity of prescription and the operator's experience, supervisory control at the beginning of the operation can last less than one shift or a few shifts until the quality of the operation is satisfactory. Monitoring should be done continuously for the entire duration of the operation.

For trails' widths one measurement every 50 - 100 m is recommended, and if trails are short, then each trail should be measured at least once. Trails' width is based on a visual assessment of their boundaries and when available, the "gate trees" can be used as reference points.

The machine operator can quickly control the cutting intensity by using optical prisms similar to the ones used in timber cruising. When prisms are used, minimal training is required, along with some reference numbers in relation to cutting intensity. Prism measurements can be taken as described in Figure 11, to ensure that measurements cover all the possible differences between zones closer to the trail and those further away.



Operation monitoring: prism plots for computing BA, Trees/ha, Vol.

Figure 11. Location of sampling points (blue dots) for operation monitoring.

Alternatively, to avoid the additional cost of prisms (which cost about $ 100 and can be easily lost), a simple device can be used to achieve the same functionality: this consists of a metal plate with openings of certain width and attached to a string of a specified length. Regardless of the device used it is important that the correct number of trees be calculated and communicated to the operator, e.g.: "you need to see on average 6 trees with this prism or through opening no. 4 of the metal plate".

If fixed-area plots are used we recommend that one dimension (of the plot) be larger than half of the selection zone, e.g.: for a 15-m selection zone, a 100-m^2 plot with dimensions of 12.5-m x 8-m should be used to ensure that it extends beyond the center of the selection zone and captures the differences that may exist in zones closer or further from the trail. For the fixed-area plots an app can be developed for quick determination of stand density and BA (i.e., free spreadsheet app to be installed on the phone). However, for fixed-area plots the user should be familiar with statistics related to this sampling method, namely: (i) the sample size (number of plots) needed to achieve the desired sampling error; and (ii) be aware of the (known) shortcomings of fixed-area plots in relation to sampling over the range of DBH's (i.e., sampling a greater number of small trees compared to large trees).

Regular supervision and control plots during treatment are important parts of this stage to ensure that the prescription is correctly applied, and residual stand objectives are met.

4.4 Measure Productivity

Measuring the productivity of machines used in CT operations is useful for assessing the time needed to complete a block and its cost, and for planning purposes for estimating when machines will be available to start a new operation. Productivity measurement should start when the operator has sufficient experience in the activity performed.

Two methods can be used for calculating the productivity of harvesters:

- Using data from on-board computers (OBC). This method is highly efficient and accurate. However, it may present some technical complexities and can be used only when operators are comfortable with accessing the OBC data.
- An alternate method consists in conducting time-and-motion studies. Observation of the machine can be used to determine the number of trees cut and logs manufactured. The corresponding volume can be determined either by directly measuring the log piles produced or using the volume from corresponding inventory plots in the area.

For forwarders, distance travelled is most efficiently determined using on-board computers such as FPDat systems mounted in the cab. FPDat's can determine the GPS position of machines at defined time intervals and record and store them via satellite signal. Volume transported can be calculated by direct measurement or more efficiently using a phone app like Timbeter[1].

4.5 Post-Harvest Assessment

The objective of post-harvest assessment is to check if the prescription was correctly applied in the operation and determine the post-harvest stand attributes. Essentially, the post-harvest survey should follow the same field procedures as the pre-harvest evaluation. If pre-harvest plots can not be retrieved new ones should be laid-out. Since it is very likely that numerous plots will be at the boundary between trails and selection zones, the Walkthrough Method has to be applied as described in the BC Cruising Manual (Province of BC 2018a) and Iles (2003). The principles of this method are presented in Appendix II.

For determining the intensity of the cut the stand is considered to be stratified in a clearcut (the trails) and the selection zone. The stand and tree metrics for the block represent the combined attributes of the two strata. The post-harvest analysis will provide a detailed comparison with respect to the state of stand before and after the operation, as presented in Table 4.

Table 4. Main indicators of pre- and post-harvest stand attributes.

Observed elements	Density (st/ha)	Basal Area (m^2/ha)	Merch. Vol. (m^3/ha)	Avg. Merch. Vol. (m^3/stem)
Pre	697	53	386	0.554
Post	325	30	226	0.695
Harvested	372	23	160	0.141
Removal (%)	53	43	41	25

[1] Details on the app available at https://timbeter.com/ ; accessed December, 2021.

The BC Silviculture Surveys Procedures Manual (Province of BC 2018b) provides general guidance in relation to post-harvesting assessments. Also, the assessment of stands after harvesting can be done using fixed-area plots with the same observations (limitations) presented earlier (in the previous sub-section).

Apart from stand assessment the post-harvest plots can be used for analyzing the economics of stands in the with- and without-CT scenarios as described in the previous section.

5 GENERAL COMMENTS ON APPLICATION OF CT IN BC

CT represent a versatile stand enhancement tool that can be used to improve and maximize the value of stands over a rotation as described in Buongiorno and Giles (2003). The long-term influence of CT on timber supply and distribution of stands (e.g., age class, geographic, etc.) needs to be investigated in timber supply analyses and consider them in conjunction with all the other constraints. Timber supply analyses must address changes in volume harvested over the planning horizon (timber flow), along with environmental, and socio-economic values. An example of a timber supply analysis for a timber supply area (TSA) in interior BC is presented in Griess et al. (2018). Adjustments of Annual Allowable Cut (AAC) may result after such analyses which may represent new opportunities for licensees and contractors.

The influence of CT on appearance and physical attributes of the wood, which relate to presence of large knots and changes in wood properties (density, modulus of elasticity, etc.) was studied in numerous publications. However, the impact of CT needs to be further investigated and attempt to predict the impact of current operations on the stand at the time of final cut (e.g., is it more important to have a stand with 300 m^3/ha of low-density wood or 250 m^3/ha of high-density wood ?). Best application of CT is in pre-CT stands and plantations, therefore application of these combined treatments should be investigated. However, it is important to note that optimum planning for CT commences at stand establishment.

In BC particularly, CT represents a viable response for addressing large-scale disturbances. However, application of CT presents numerous challenges. The first challenge relates to the economic operability of stands, which have low volumes per ha and relatively small piece sizes or consist of less desirable species (for which there is no market) indicate that implementation of CT based on value of wood recovered limits their application. A possible solution is to recognize and compensate for the other values created or increased from this type of stand treatment. Over the last years, stumpage fee adjustments have been implemented to incentivize enhanced silviculture and CT in BC. However, a balance must be struck as CT operations may need to demonstrate a fair return to the landowner (crown) in order to garner public support. Also, application of CT is strongly influenced by the tenure system. CT are essentially stand-enhancement investments, and the investors need to be sure that they will realize the benefits of their investments in the future.

Considering the equipment fleet available and the learning curve for operators is extremely important. For licensees and contractors working in CT operations it is necessary to develop strategies to manage costs and develop appropriate planning methodologies for this type of operations. As a long-term strategy the development of local expertise and contractor capacity for operating in CT systems is of paramount importance. Forest licensees that have big CT programs which involve harvesting large volumes over longer periods of time can make decisions on machine procurement based on stands to be harvested.

For economic feasibility analysis of CT operations new models need to be developed for better computing the cost of CT operations. Utilization of on-board computers (OBC) and tools such as FPDat and FPTrack open new opportunities to correlate production with geographic location and better model productivity. For big CT programs the entire supply chain should be analyzed, e.g., dimension processing lines in the sawmill, coordinate with facilities for converting biomass available in the area. Detailed economic analysis for the entire supply chain (including mill outturn, and other costs including harvesting, transportation, etc.) can be done using models developed by FPInnovations: (i) WoodValue, as described in Charette et al. (2017) for all the costs related to sawmilling; and (ii) FPInterface for detailed cost of harvesting, transportation, planning and silviculture.

The approach presented in this Operational Manual was also adapted for application on operations that aim at creation and/or preservation of wildlife habitat. Details are presented in Appendix III. Also, a methodology was developed for calculating crown spacing as a function of tree DBH to be applied in conjunction with fire risk assessment techniques for stands with fuel management as the primary concern, as described in Appendix IV.

Application of CT considering the wider legislative and policy requirements and planning at strategic, tactical and operational levels are presented in the Guidance developed by the CT Working Group (Province of BC 2021), which also addresses the concept of adaptive management and other planning considerations. The Operational Manual introduces a methodology for preliminary selection of CT candidate stands, assessment of their economic operability, selection of prescriptions and harvesting systems, and monitoring the operations. Subsequent versions of the manual will update the theoretical and practical knowledge acquired to date on planning and application of CT as well as additional values. Also, a “live” document in the form of an ArcGIS Online Story Map will be available on FPInnovations’ site with the most updated information on CT techniques and applications.

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APPENDIX I. THE FOUR CT STRATEGIES

Details of the four CT strategy are presented in Table A1; the third strategy has two variants. Stands that meet criteria of stragegy 1 are typically those with a high site index, a minimum pre-harvest density of 1200 stems per hectare and basal area of 36 m^2/ha. Stands with a history of silvicultural treatments such as pre-commercial thinning (PCT) and fertilization are especially good candidates.

The second strategy is similar to the first except that, depending on the objectives at the stand and landscape level, the final harvest may or may not be delayed for growth response. Stands that meet these criteria are similar to those in the first strategy however the objectives are more related to managing age class distributions and redistributing volume harvests over time.

Table I-1. The four CT strategies.

Strategy	Description	How	Candidate Stands
1. Accelerate growth to reduce technical rotation age.	In productive pre-mature stands, manage stand density to speed up tree growth and reach the minimum harvestable tree size earlier and/or in a future critical period. This strategy is similar to redistributing the harvest over time (Strategy 2).	Commercial thinning • Crown • Systematic A delay between thinning and final felling is required for growth response.	Highly productive managed (PCT'ed and/or fertilized stands).
2. Anticipated harvest in young stands	In pre-mature stands, harvest part of the volume during a critical period and leave a sufficient volume in a non-critical period.	Commercial thinning • Crown • Systematic A delay between thinning and final felling is preferred but not critical.	Even-aged pre-mature stands with sufficient volume and tree size to make at least a cost-neutral partial harvest.
3a. Partial harvest with extended rotation, without continuous cover.	In mature stands with extended rotation due to non-timber objectives, harvest part of the volume during a critical period while maintaining key non-timber attributes and leave sufficient volume for the final harvest. Selecting trees with high risk of mortality or decay to increase wood production	• Uniform shelterwood • Extended irregular shelterwood A delay between thinning and final felling is required for advanced growth response	Land units identified for VQO or units with late seral stage targets Even-aged mature and over-mature and uneven-aged stands with sufficient volume and tree size to make at least a cost-neutral partial harvest

Strategy	Description	How	Candidate Stands
3b. Partial harvest with extended rotation, with continuous cover.	In mature stands where non-timber objectives require continuous cover, periodic partial cuts to harvest mature trees and promote continuous recruitment in all growth stages. In even-aged stands, stand structure conversion cuts can be done to develop an uneven-aged structure. A regulated continuous wood production may or may not be considered.	Selection system (with continuous production management) Continuous cover irregular shelterwood (without continuous production management)	Land units identified as Mule Deer Winter Range Even-aged mature and over-mature and uneven-aged stands with shade-tolerant species and tree size to make at least a cost-neutral partial harvest
4. Manage mixed stands.	In even-aged mixed stands, harvesting the shorter-lived species first to increase stand-level wood production.	Commercial thinning with species selection A delay between thinning and final felling is required for growth response	Mixed stands of desirable species in the dominant canopy layer, with differing maturation ages (e.g. 50% Pine – 50% Spruce)

The third strategy is suited to mature and over-mature stands and is typically associated with ecological, wildlife or other values in addition to fibre production. There are two variants to this strategy, with and without continuous cover. Applications of the first variant without continuous cover includes harvesting in visual quality corridors or managing for late seral attributes. Treatments are intended to replicate natural disturbance process and/or accelerate even-aged stands towards an uneven-aged condition with more vertical and horizontal structural variability. Even though there is reference to a final harvest it is not expected to occur for a very long time, typically beyond the lifetime of most people implementing the treatment.

The second variant with continuous cover is suited to the continuous management of values on the landscape including wildlife habitat structural requirements (e.g. mule deer winter range, goshawk and caribou habitat, etc.), timber production and visual quality corridors. There is no final harvest as part of this strategy and the site is maintained permanently with tree cover. Work is currently under way to adapt the operational process of CT for specific examples of this strategy which will be included in future versions of this manual.

The fourth strategy has more flexibility with respect to timing of entry depending on the species mix and the treatment objectives. For example, earlier entries to a mixed hardwood and softwood stand may be possible if there is a market for fast growing hardwood. Later entries may be possible in a true fir/cedar mix to remove fir before it is subject to decay and leave more growing space for longer lived cedar. Pending more data on what is available on the landscape this strategy may account for significant opportunities for addition of fibre that may otherwise become unmerchantable.

Effective deployment of the first and second strategies depends on stand and landscape objectives. The primary criteria for treatment is that current harvest volumes do not negatively impact future volumes or values. Decision aids for modelling scenarios are described in this document to provide support in the stand selection process.

APPENDIX II. POST-HARVESTING ASSESSMENT

Post-harvest inventory should be done using the same methodology as pre-harvest inventory, considering first that trails are clearcuts. For the selection zone, if old plots can not be retrieved new ones must be laid-out. As some (many) plots in the selection zone will be located in the proximity of trails, the “Walkthrough Method” should be used for collecting tree data, as described in the BC Cruising Manual and presented in Fig. II-1.

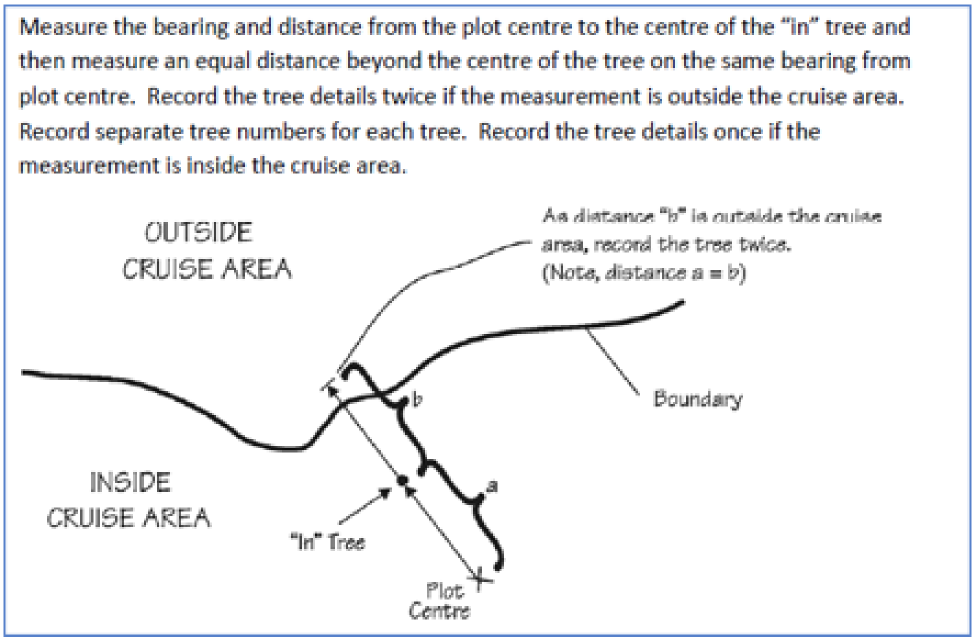


Figure II-1. Description of the Walkthrough Method (from the BC Cruising Manual) – to be used for prism plots located near boundaries.

APPENDIX III. ADAPTATION OF PCSIM FOR HABITAT CREATION AND PRESERVATION

FPInnovations’ PCSim model was adapted for habitat creation and preservation. The main change consists in redefining the quality classes (Q classes) to reflect habitat values. These are coded as wildlife (W) classes and represent (mostly) the opposite of Q classes defined for timber production. A description of W classes is presented in Table III-1. A visual comparison of Q1 and W1 trees is presented in Fig. III-1. The principles for stand pre-harvest assessment, prescription definition, and economic analysis are the same as for operations aiming at fibre production.

Table III-1. Description of Wildlife (W) tree classes.

Classification	Description	Examples
W1	• Tree with major indicators that clearly identify it as suitable wildlife habitat • Very low economic chance	• Mistletoe • Large cavities • Large diameter
W2	• Tree with some indicators • 50/50 economic chance	• Minor cracks, holes • Signs of decay
W3	• Tree with no indicators • Good timber quality	Healthy, no pathological indicators

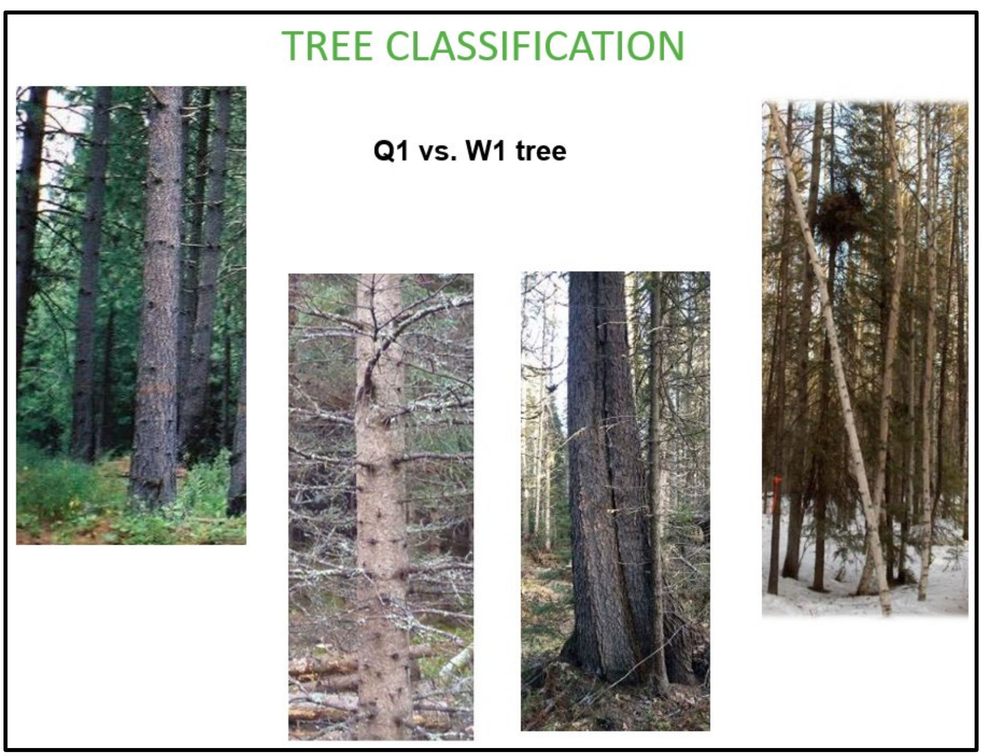
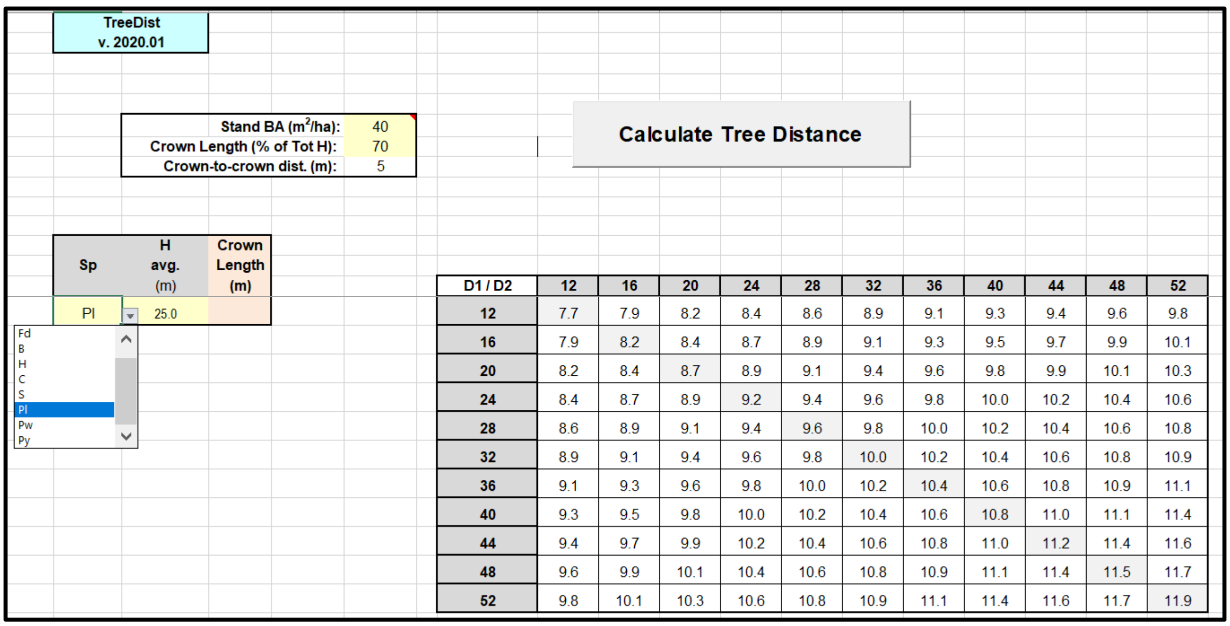


Figure III-1. Visual comparison of Q1 and W1 trees.

APPENDIX IV. REDUCING THE STAND'S RISK OF WILDFIRE: DETERMINING CROWN DISTANCES AS A FUNCTION OF DBH

A spreadsheet model was developed for calculating crown spacing based on tree and stand metrics, or conversely, the distance between trees if a certain distance between crowns is wanted. Essentially, the model uses the stand's average BA, average crown length, projected distance between crowns, main species and its average height, and for different DBH classes it determines the projected distance between stems. The inputs used by the model and an example of results are presented in Fig. IV-1.



D1 / D2	12	16	20	24	28	32	36	40	44	48	52
12	7.7	7.9	8.2	8.4	8.6	8.9	9.1	9.3	9.4	9.6	9.8
16	7.9	8.2	8.4	8.7	8.9	9.1	9.3	9.5	9.7	9.9	10.1
20	8.2	8.4	8.7	8.9	9.1	9.4	9.6	9.8	9.9	10.1	10.3
24	8.4	8.7	8.9	9.2	9.4	9.6	9.8	10.0	10.2	10.4	10.6
28	8.6	8.9	9.1	9.4	9.6	9.8	10.0	10.2	10.4	10.6	10.8
32	8.9	9.1	9.4	9.6	9.8	10.0	10.2	10.4	10.6	10.8	10.9
36	9.1	9.3	9.6	9.8	10.0	10.2	10.4	10.6	10.8	10.9	11.1
40	9.3	9.5	9.8	10.0	10.2	10.4	10.6	10.8	11.0	11.1	11.4
44	9.4	9.7	9.9	10.2	10.4	10.6	10.8	11.0	11.2	11.4	11.6
48	9.6	9.9	10.1	10.4	10.6	10.8	10.9	11.1	11.4	11.5	11.7
52	9.8	10.1	10.3	10.6	10.8	10.9	11.1	11.4	11.6	11.7	11.9

Figure IV-1. Computation of distance between trees as a function of tree and stand metrics and projected distance between crowns.

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