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Contents

Abstract

Over the past 15 years, selective cutting prescriptions have been applied by forest operations in southeastern British Columbia as part of a strategy to reduce landscape-level susceptibility to damage from mountain pine beetle outbreaks. The prescriptions have been applied in stands where maintenance of some mature forest cover is needed to meet management objectives for viewscapes, recreation and habitat or to hold some pine volume during periods of rising beetle activity until it is required or available for harvest. In this study, we examined 10 of these sites 5 to 14 years after harvest, and determined current stand composition and structure from direct sampling and pre- and post-treatment stand characteristics from stand reconstruction. We then related these characteristics to original treatment specifications; the volume removed during harvest and remaining on site after treatment; subsequent losses to wind, snow or bark beetle damage; current stocking status; radial growth rates of residual overstorey trees; and the nature of fuel complexes created and effects of treatment on potential fire behaviour.

Résumé

Depuis 15 ans dans le sud-est de la Colombie-Britannique, les entreprises forestières pratiquent la coupe sélective dans le cadre d'une stratégie visant à réduire la vulnérabilité à l'échelle du paysage aux dommages causés par les flambées de dendroctone du pin ponderosa. Cette prescription de coupe a été appliquée aux peuplements dont il faut conserver un certain pourcentage de couvert forestier mature afin d'atteindre les objectifs de gestion en matière de préservation des vues panoramiques, d'usage récréatif et d'habitat, ou pour maintenir un certain volume de pins durant les périodes d'intensification de l'activité des dendroctones jusqu'à ce que les arbres soient prêts pour la récolte ou appelés à être récoltés. Dans le cadre de cette étude, nous avons examiné 10 de ces sites de 5 à 14 ans après la récolte afin de déterminer la composition et la structure actuelles du peuplement au moyen de l'échantillonnage direct, ainsi que les caractéristiques du peuplement avant et après le traitement à partir de la reconstruction du peuplement. Nous avons ensuite apparié ces caractéristiques aux spécifications de traitement originales; au volume de bois retiré pendant la récolte et à celui demeurant après le traitement; aux pertes subséquentes reliées au vent, à la neige ou au dendroctone du pin ponderosa; à la densité actuelle; aux taux de croissance radiale des arbres résiduels de l'étage supérieur; à la nature des complexes combustibles générés et aux effets du traitement sur l'éventuel comportement du feu.

Introduction

Outbreaks of mountain pine beetle, *Dendroctonus ponderosae* Hopk. (Col.: Scolytidae), have caused extensive damage to lodgepole pine (*Pinus contorta* Dougl. var *latifolia* Englm.) forests in British Columbia (B.C.) over the last several decades (Taylor and Carroll 2004). Range expansion in response to recent warming trends now threatens lodgepole pine in northern B.C. and western Alberta and raises concern for jack pine (*Pinus banksiana* Lamb.) forests across Canada (Taylor et al. 2006; Ono 2004). Unmanaged pine stands become increasingly vulnerable to mountain pine beetle infestations after about 80 years of age, when average tree diameters at breast height (dbh) are more than 20 cm, and stand densities (>12.5 cm dbh) are usually between 750 and 1500 trees/ha (Safranyik et al. 1974). Such stands are a major component of pine forests across western Canada at this time (Taylor and Carroll 2004).

Minimizing timber losses from mountain pine beetle requires keeping beetle populations low through aggressive control of incipient outbreaks, as well as sustained management to reduce the amount of susceptible stands and break up their continuity on the landscape through planned stand replacement (Safranyik et al. 1974; Shore et al. 2006; Whitehead et al. 2006a). In most operating areas in western Canada, it is difficult to quickly replace all susceptible stands without exceeding other constraints on harvest (e.g. adjacency rules or objectives for habitat supply, visual quality, or recreation), and it is often important to hold some mature stands in the harvest queue while other stands are replaced.

Whitehead et al. (2006a) reviewed research on landscape planning to reduce damage from outbreaks and on stand-level silviculture to prevent infestation of specific mature lodgepole pine stands while other susceptible stands are harvested. For the latter case, they recommended pine removal from the overstorey of mixed stands and "beetle proofing" in lodgepole pine-dominated stands by thinning from below to 4-m to 5-m intertree spacing (i.e., removing the smallest trees while spacing the larger, more vigourous trees at least 4 m apart). This prescription leaves a relatively windfirm stand with between 400 and 625 trees/ha, removes enough volume of sufficient piece-size to ensure a commercially viable logging operation and allows for release or establishment of a regeneration layer if desired (B.C. Ministry of Forests 1999). Thinning from below is specified to promote windfirmness and tree vigour, which may increase the ability of individual trees to produce resins that are a primary defence against attack (Keen 1958; Graham and Knight 1965; Larsson et al. 1983; Mitchell et al. 1983; Waring and Pitman 1985; Christiansen et al. 1987; Whitehead et al. 2006a). Removing smaller trees and increasing intertree spacing is specified to effect change in within-stand microclimate. Increased penetration of solar radiation and wind hinders beetle dispersal, host location, attack behaviour, and brood survival (Reifsnyder and Lull 1965; McGregor and Oakes 1987; Bartos and Amman 1989). Whitehead and Russo (2005) examined five research sites with side-by-side comparisons of treated and untreated stands 10 years after treatment with this prescription and found that beetle proofing effectively prevented initiation of outbreaks in treated stands when weather favoured expansion of endemic populations in untreated stands, but did not prevent significant loss in a stand subjected to very high beetle pressure from an uncontrolled landscape-level outbreak.

Selective cutting prescriptions that incorporate thinning to produce wide intertree spacing have been applied in southeastern B.C. as part of a strategy that requires reducing susceptibility of some pine stands in areas where mature forest cover is needed to meet management objectives for viewscapes, recreation, and habitat or to hold some pine volume until it is required or available for harvest (B.C. Ministry of Forests 1999). The present study examines 10 of these sites and focuses on the following questions:

1. In light of recent research, were the stands selected and prescriptions for treatment optimal for reducing stand susceptibility?
2. How much merchantable volume was removed, how much was left after harvest, and how much was subsequently lost to wind or snow damage?
3. What were the frequency and success of mountain pine beetle attack since treatment?

4. Are these stands now fully stocked, and are residual trees responding with increased growth to release from competition?
5. What are the current fuel complexes and implications for potential fire behaviour?

Methods

Site Selection and Stand Description

Forestry staff of three companies operating in the Columbia and Rocky Mountain Forest Districts identified approximately 50 sites that had been selectively cut within the last 15 years, where reducing susceptibility to mountain pine beetle was an objective at time of harvest. We examined their files, chose 25 sites for on-site inspection, and subsequently selected 10 cutblocks for detailed examination in the summer of 2004 or 2005. Where cutblocks were too large, or had more than one treatment unit, we chose a homogeneous and representative portion of the block for assessment.

Survey Layout

A strip cruise, designed to systematically sample 5% to 10% of the area in each cutblock, was used to collect data on overstorey characteristics, mountain pine beetle activity, and wind and snow damage. Five-metre-wide strips were spaced 50 m apart and oriented perpendicularly to a baseline established along one edge of the treatment. Each strip was divided into 50-m by 5-m (250-m^2) sections, so that some data could be examined spatially and reported on a per hectare basis. Regeneration and stocking were assessed in 3.99-m-radius fixed-area plots and with prism sweeps centred on a 100-m grid. One standard fuel-loading triangle as described by Trowbridge et al. (1994) was established at each site to measure fuel loading and coarse woody debris.

Overstorey Stand Characteristics

We determined current stand characteristics, and inferred the pre- and post-treatment characteristics through stand reconstruction from data obtained in the strip cruise. Stand density, species composition and diameter distribution were determined from a tally in each strip of all Layer 1 (dbh ≥ 12.5 cm) and Layer 2 (dbh: 7.5 to 12.4 cm) trees (living, dead, or damaged) and of all stumps with germination centres originating within the strip. Diameters were measured at stump height (0.3 m) and breast height (1.3 m) on all trees, and at stump height on all stumps. Breast-height diameter was projected for each stump using regression equations published by Demaerschalk and Omule (1978) if the stump diameter was measured outside the bark, and by Omule and Kozak (1989) if stump diameter was measured inside the bark. Heights were measured and diameter increment cores were taken at breast height to establish height-to-diameter ratios and stand age. Total stem volume (inside bark) was calculated using the standard provincial taper equations (Kozak 1988); adjustments to merchantable volume assumed a stump height of 30 cm, a minimum dbh of 12.5 cm, a top diameter of 10 cm, and a preferred log length of 5 m.

Pre-treatment stand values were calculated with the assumption that all trees and stumps were living, healthy trees prior to treatment. Post-treatment stand values were calculated with the assumption that all trees, including snags and windthrow identified at assessment time, were living and healthy after treatment. Current stand volumes were calculated from trees that were living and healthy at the time of our assessment (2004 or 2005).

Wind and Snow Damage

All trees within the strip cruise were assessed for wind or snow damage. Location, type of damage (uproot, snap, or lean), species, and dbh were recorded for each damaged tree. We assumed that trees damaged during spacing were removed during the course of the treatment and, therefore, all existing damage had occurred since treatment.

Mountain Pine Beetle Attack since Treatment

All trees within the strip cruise were visually inspected for evidence of mountain pine beetle attack (e.g. frass, pitch tubes, faded crowns, and larval galleries). Location, type of attack (mass, partial or resisted), dbh, and year of attack (2005, 2004, 2003, or older) were recorded for each attacked tree.

Radial Growth of Residual Layer 1 Pine

Increment core samples were taken at breast height from a subset of at least 22 lodgepole pine trees at each site. Cores were mounted on a grooved wooden board and sanded until a smooth surface was achieved. Annual ring width and age to pith were determined using a Measu-Chron® (L. Kutschenreiter Measuring Instruments, Vienna, Austria) or WinDENDRO® (Regent Instruments Inc.) analysis system.

Regeneration and Stocking

Frequency, condition, species and age of well-spaced conifers in Layers 3 (≥ 1.3 m tall with dbh < 7.5 cm) and 4 (≥ 0.3 m and < 1.3 m tall) were recorded in 3.99-m-radius plots. Layers were sampled independently of each other and, within each layer, trees were considered well spaced if at least 2 m apart. Species and percent cover of competing vegetation within each plot were also recorded.

Because the technique of averaging plot counts, employed by most conventional surveys, is generally inappropriate for assessing understorey stocking in partially cut stands (Martin et al. 2005a and 2005b), we used a method similar to that described by Bancroft et al. (unpublished 2003 B.C. Forest Investment Account report) and B.C. Ministry of Forests and Range (2004a), which takes a plot-by-plot approach to assessing stocking in partially cut stands in order to identify areas where volume production could be increased through additional planting. However, our assessment of "well-spaced conifers" in the fixed-area regeneration plots included trees in Layers 3 and 4 only, whereas Layer 2 trees were counted in prism sweeps. We estimated the number of Layer 2 trees that would fall within each 3.99-m-radius plot by using Equation 1 to sum the contribution of each tree in the prism sweep.

$$\text{No. of Layer 2 trees per plot} = \sum_{i=1}^{n} \left(\frac{10000\text{m}^2/\text{ha} \times \text{BAF}}{ba_i} \right) \times 0.005\text{ha} \text{ ,................. (1)}$$

where BAF is the prism basal area factor, n is the number of trees and ba_i is the basal area of an individual tree in square metres (m^2).

We made the following assumptions and caution that they may slightly overestimate stocking and underestimate the volume increase that could be gained through additional stocking:

1. All Layer 2 trees are countable (i.e., meet crop-tree acceptability and minimum intertree distance criteria);
2. Layer 2 trees do not reduce the count of Layer 3 trees; and,
3. Layer 2 and Layer 3 trees do not reduce the count of Layer 4 trees.

Fuel Loading

Surface Fuels

Surface fuel-load data was collected along the 30-m transects of the fuel-loading triangle as illustrated in Figure 1. Dead and down round woody fuels were measured using a line–intersect method described in Forest Resource Development Agreement (FRDA) Handbook 001 (Trowbridge et al. 1994). Woody fuel biomass (kg/m^2) was calculated using the CWD/Fuel Calculator program Version 1.0a (B.C. Ministry of Forests Research Branch, Victoria, B.C.).

Sampling techniques for duff, litter, herbaceous and understorey conifer fuels were based on the methods used by Hirsch and Pengelly (1999). Shrubs were destructively sampled in 1-m^2 sub plots located 1 m to the outside of the 15-m mark on each of the three transects, as illustrated in Figure 1. Percent cover of each species of shrub germinating within plot boundaries was visually estimated, then clipped at the base and divided by species and diameter class (using a “go–no–go” gauge) into sample bags. Duff, litter, herb and shrub samples were oven dried at 70° C for at least 48 hours to obtain oven-dry weights for calculation of biomass and bulk density. Understorey conifer fuel load was calculated using the regression equations of Delisle (1986).

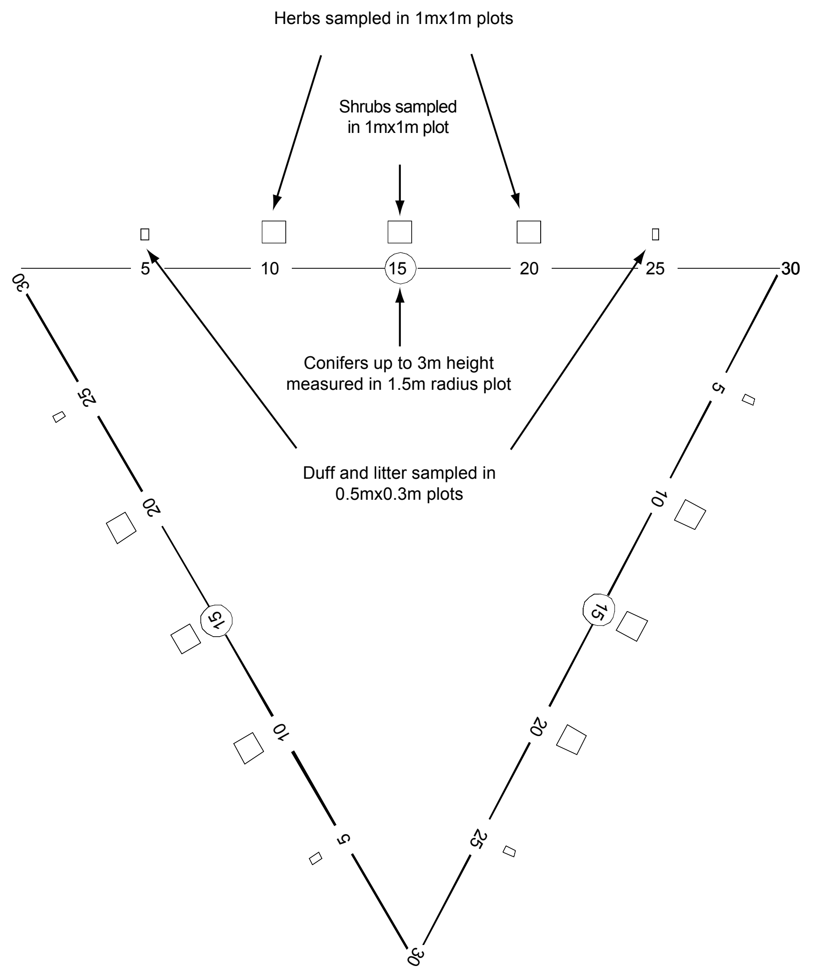


Figure 1. Plot layout for assessment of surface fuel loading along each 30-m transect of the fuel-loading triangle

Crown Fuels

Crown fuel characteristics (canopy fuel load, live canopy base height, and canopy bulk density) were calculated using stand descriptor information from data collected during the strip cruise. Canopy fuel load (kg/m^2) was calculated for foliage only, using species-specific equations from Standish et al. [1985; Foliar Biomass = $a + bD^2H$, where a and b are species specific constants, D is diameter at breast height (m), and H is height (m)]. Live canopy base height (LCBH) was calculated using the regression models of Cruz et al. (2003) for four fuel types (Douglas-fir, ponderosa pine, lodgepole pine, and mixed conifer). Because the stands did not easily fit into a single fuel type, they were separated into two fuel types (lodgepole pine, and mixed conifer). LCBH was calculated for the lodgepole pine component of each stand using the lodgepole pine model [$\text{LCBH} = -1.475 + (0.613 \times SH) + (0.043 \times BA)$, where BA is basal area (m^2/ha), and SH is the stand height (m)] and stand descriptors for the lodgepole pine component of the stand. The process was repeated using the mixed conifer model [$\text{LCBH} = -1.463 + (0.578 \times SH) + (0.026 \times BA)$, where BA is basal area (m^2/ha), and SH is stand height (m)] and the stand descriptor information of all other conifers combined. Total LCBH was calculated as a weighted average of the results from the two models. Canopy bulk density was calculated by dividing canopy fuel load by the average crown length.

Coarse Woody Debris

Coarse woody debris (CWD) greater than 7.5 cm in diameter was sampled, using the methodology outlined by Meidinger (1998), except that, instead of sampling along two 24-m transects, two 30-m transects (Lines 1 and 2 of the fuel-loading triangle) were sampled. Volume and pieces per hectare were calculated using the CWD/Fuel Calculator program (Version 1.0a).

Results and Discussion

Study Sites, Prescriptions and Stand Descriptions

General locations of the 10 sites chosen for examination are shown in Figure 2. Specific site information, including the silvicultural system prescribed, and a photograph taken at time of assessment is presented for each site in Figure 3. All sites had pine-leading stands that were selectively cut 5 to 14 years prior to our assessments with reduction of stand susceptibility to mountain pine beetle as one of the stand-level objectives. Nine of the 10 stands chosen for study were characterized as 'mature' when harvested, ranging in age at breast height from 66 years at Frost to 103 years at Hobo. Although the Lodgepole site was considered 'immature' at only 45 years old, the pre-harvest silviculture prescription specified 4.8-m spacing as a commercial thinning entry "for beetle proofing" and a residual basal area of 23 m^2/ha, which suggests an average dbh of about 24 cm for residual trees. Prescriptions at all other sites characterized this harvest entry as the preparatory or regeneration cut of a shelterwood silvicultural system. Hobo, Boyce, Park, Fran, Frost, Whiskey and Face specifically targeted a 5-m intertree spacing for the residual overstorey.

At the time prescriptions were written, mountain pine beetle was already active within the proposed cutblocks at six sites. The level of infestation was characterized as "low" at Beaver, Boyce, Park and Hurst, and "moderate" at Fran and Frost. Pheromone baiting before harvest was employed at Park, Fran and Frost.

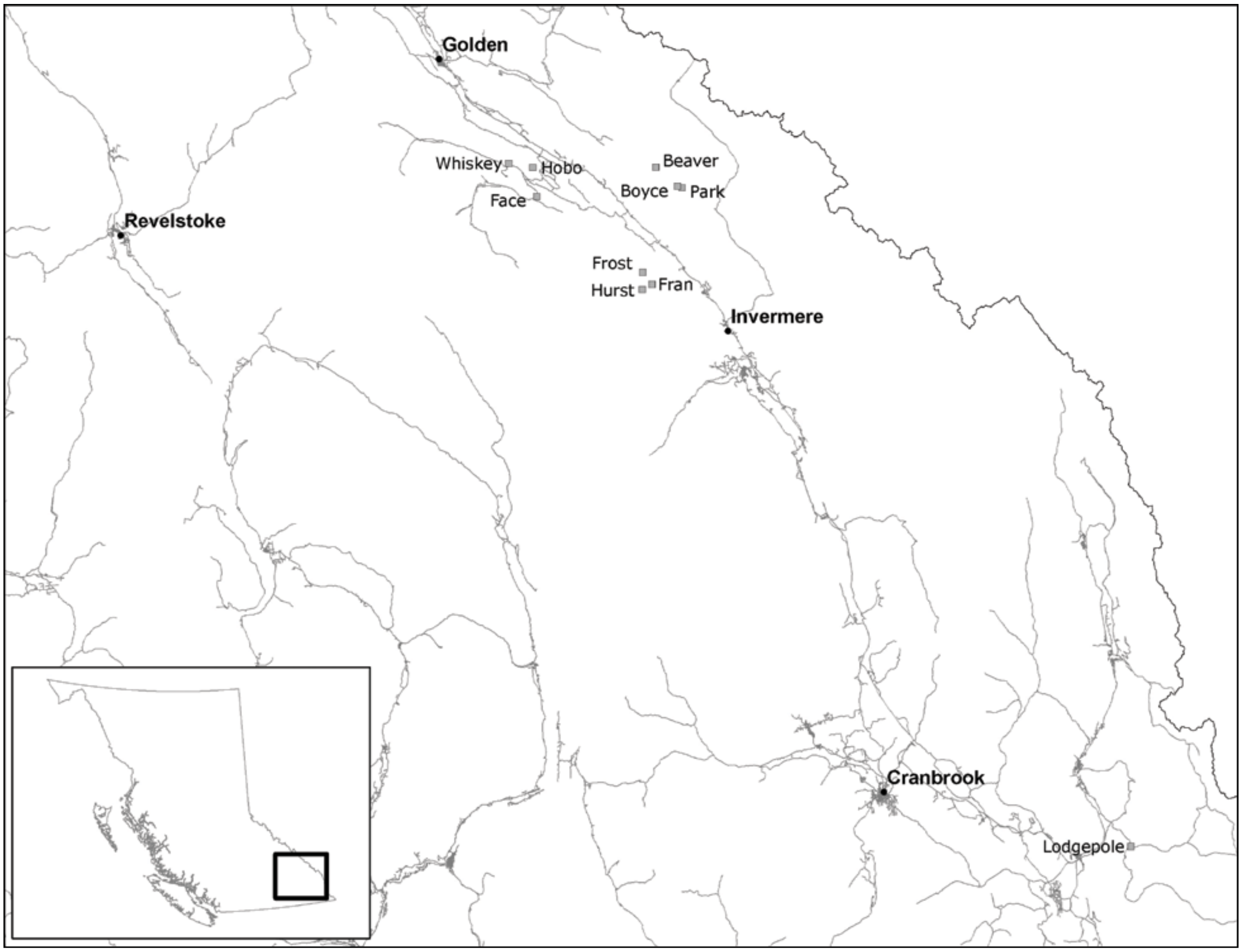


Figure 2. Locations of the 10 operationally beetle-proofed sites examined in this study

Preference for retention of non-pine overstorey trees, intermediates and/or advanced regeneration to meet other objectives was a common feature in all prescriptions. At Boyce, Park and Fran, non-pine species were reserved from harvest altogether, regardless of their effect on residual spacing. The stand-level prescription recommended for beetle proofing was developed for, and tested in, nearly pure lodgepole pine stands. The prescriptions and harvest reports on file suggest a considerable range in original species composition in the operations we surveyed; this was confirmed by stand reconstructions from our survey data (Table 1 and 2). For example, the percentage of lodgepole pine in Layers 1 and 2 varied from roughly 95% in the original stands at Lodgepole and Hobo and more than 80% at Frost and Fran, to about 75% at Whiskey, Face and Hurst and only 64%, 52% and 47% at Beaver, Park and Boyce, respectively (Table 2).

Figure 3a. Site-specific information for the Lodgepole site

Licence	Cutting Permit	Block
MF27	122	31
Latitude	**Longitude**	**Elevation (m)**
49° 18.384´	-114° 55.641´	1020
Year of Treatment	**Block Size (ha)**	**Sampled Area (ha)**
1991	9.0	0.53

Silviculture System Commercial thinning to 4.81-m spacing. Reserve non-pine species

Ecological Classification ICH cl 04: Oregon grape - pinegrass association of the Elk River Moist Cool Interior Cedar Hemlock Subzone

Current Stand Characteristics

Layer	Silviculture Label	Avg. Age	Ht. (m)	Trees/ha	Conifers/ha	Well Spaced Free Growing Conifers/ha
1	$Pl_{99}Lw_{1}$	58	19.9	406	406	406
2	$Pl_{64}Sx_{36}$	na	12.7	21	21	21
3	$Pl_{80}Cw_{10}Sx_{10}$	9	1.8	211	167	111
4	$Fd_{64}Pl_{35}B_{11}$	9	0.7	2378	2344	933

Ac=black cottonwood; At=trembling aspen; Bl=subalpine fir; Bp=noble fir; Cw= western red cedar; Fd=Douglas-fir; Hw=western hemlock; Lw=western larch; Pl=lodgepole pine; Sx=spruce

Figure 3b. Site-specific information for the Face site

Licence	Cutting Permit	Block
TFL 14	159	101
Latitude	**Longitude**	**Elevation (m)**
50° 58.759’	-116° 40.907’	1230
Year of Treatment	**Block Size (ha)**	**Sampled Area (ha)**
1997/1998	15.0	1.18

Silviculture System Uniform shelterwood
Ecological Classification MSdk 04: Pl - Oregon grape - Pinegrass association of the Dry Cool Montane Spruce Subzone

Current Stand Characteristics

Layer	Silviculture Label	Avg. Age	Ht. (m)	Trees/ha	Conifers/ha	Well Spaced Free Growing Conifers/ha
1	$Pl_{67}Fd_{21}Sx_{9}Bl_{3}$	101	24	503	491	491
2	$Sx_{54}Bl_{29}Fd_{12}Pl_{5}$	na	12.6	76	74	74
3	$Sx_{50}Bl_{30}Fd_{20}$	32	2.2	760	133	133
4	$Pl_{40}Fd_{28}Bl_{16}Sx_{16}$	8	0.6	680	507	333

Ac=black cottonwood; At=trembling aspen; Bl=subalpine fir; Bp=noble fir; Cw= western red cedar; Fd=Douglas-fir; Hw=western hemlock; Lw=western larch; Pl=lodgepole pine; Sx=spruce

Figure 3c. Site-specific information for the Hobo site

Licence	**Cutting Permit**	**Block**
TFL 14	163	282
Latitude	**Longitude**	**Elevation (m)**
51 01.992	-116 41.026	1290
Year of Treatment	**Block Size (ha)**	**Sampled Area (ha)**
1997	12.0	1.17

Silviculture System Uniform shelterwood. Space pine to 5 m for beetle proofing

Ecological Classification MSdk 04: Pl - Oregon grape - Pinegrass association of the Dry Cool Montane Spruce Subzone

Current Stand Characteristics

Layer	Silviculture Label	Avg. Age	Ht. (m)	Trees/ha	Conifers/ha	Well Spaced Free Growing Conifers/ha
1	$Pl_{86}Bl_{6}Sx_{4}Fd_{4}$	110	23.3	303	302	302
2	$Sx_{39}Bl_{31}Pl_{20}Fd_{8}Hw_{2}$	na	14.3	44	44	44
3	$Fd_{64}Bl_{18}Sx_{18}$	17	2.2	267	133	122
4	$Fd_{82}Pl_{14}Bl_{4}$	8	0.6	511	489	311

Ac=black cottonwood; At=trembling aspen; Bl=subalpine fir; Bp=noble fir; Cw= western red cedar; Fd=Douglas-fir; Hw=western hemlock; Lw=western larch; Pl=lodgepole pine; Sx=spruce

Figure 3d. Site-specific information for the Hurst site

Licence	Cutting Permit	Block
FL A18979	172	9
Latitude	**Longitude**	**Elevation (m)**
50 43.5	-116 21.0	1220 m
Year of Treatment	**Block Size (ha)**	**Sampled Area (ha)**
1996	7.5 ha.	0.80

Silviculture System Uniform shelterwood. Reserve non-pine species. Remove all infested pine.

Ecological Classification MSdk 01: Sxw-Soopalallie-Grouseberry association of the Dry Cool Montane Spruce Subzone

Current Stand Characteristics

Layer	Silviculture Label	Avg. Age	Ht. (m)	Trees/ha	Conifers/ha	Well Spaced Free Growing Conifers/ha
1	$Pl_{63}Fd_{16}Cw_{10}Sx_{8}Bp_{1}Bl_{1}Hw_{1}$	104	20	534	526	526
2	$Cw_{30}Fd_{26}Pl_{18}Sx_{17}Bl_{8}Hw_{1}$	na	13	198	198	198
3	$Bl_{25}Pl_{25}Fd_{20}Sx_{15}Cw_{15}$	23	2.7	880	580	400
4	$Pl_{32}Fd_{29}Sx_{19}Bl_{10}Hw_{6}Cw_{3}$	12	0.7	2800	1860	620

Ac=black cottonwood; At=trembling aspen; Bl=subalpine fir; Bp=noble fir; Cw= western red cedar; Fd=Douglas-fir; Hw=western hemlock; Lw=western larch; Pl=lodgepole pine; Sx=spruce

Figure 3e. Site-specific information for the Whiskey site

Licence	**Cutting Permit**	**Block**
TFL 14	158	234
Latitude	**Longitude**	**Elevation (m)**
51 02.977	-116 46.047	1250
Year of Treatment	**Block Size (ha)**	**Sampled Area (ha)**
1996/1997	18.0	1.56

Silviculture System Uniform shelterwood
Ecological Classification MSdk 01: Sxw-Soopalallie-Grouseberry association of the Dry Cool Montane Spruce Subzone

Current Stand Characteristics

Layer	Silviculture Label	Avg. Age	Ht. (m)	Trees/ha	Conifers/ha	Well Spaced Free Growing Conifers/ha
1	$Pl_{60}Sx_{29}Bl_{9}Fd_{2}$	99	22.1	413	410	410
2	$Sx_{55}Bl_{36}Pl_{6}Fd_{2}Cw_{1}$	na	12.3	99	99	99
3	$Sx_{69}Bl_{19}Lw_{6}Fd_{3}Pl_{3}$	22	2.7	833	467	356
4	$Sx_{60}Pl_{21}Bl_{12}Lw_{6}Fd_{1}$	10	0.8	1767	1356	867

Ac=black cottonwood; At=trembling aspen; Bl=subalpine fir; Bp=noble fir; Cw= western red cedar; Fd=Douglas-fir; Hw=western hemlock; Lw=western larch; Pl=lodgepole pine; Sx=spruce

Figure 3f. Site-specific information for the Frost site

Licence	Cutting Permit	Block
FL A18979	153	1
Latitude	**Longitude**	**Elevation (m)**
50 45.788	-116 20.419	1123
Year of Treatment	**Block Size (ha)**	**Sampled Area (ha)**
1995	6.0	0.41

Silviculture System Uniform shelterwood. Space overstorey to 400 trees/ha with removal of smaller stems. Remove infested trees

Ecological Classification MSdk 01: Sxw-Soopalallie-Grouseberry association of the Dry Cool Montane Spruce Subzone

Current Stand Characteristics

Layer	Silviculture Label	Avg. Age	Ht. (m)	Trees/ha	Conifers/ha	Well Spaced Free Growing Conifers/ha
1	$Pl_{71}Sx_{21}At_8Ac_1$	76	23.3	556	511	511
2	$Sx_{87}At_8Pl_5$	na	17.1	110	101	101
3	Sx_{100}	29	2	1050	450	325
4	$Sx_{71}Pl_{29}$	15	0.6	1925	450	350

Ac=black cottonwood; At=trembling aspen; Bl=subalpine fir; Bp=noble fir; Cw= western red cedar; Fd=Douglas-fir; Hw=western hemlock; Lw=western larch; Pl=lodgepole pine; Sx=spruce

Figure 3g. Site-specific information for the Fran site

Licence	Cutting Permit	Block
FL A18979	153	6
Latitude	**Longitude**	**Elevation (m)**
50 44.056	-116 18.840	1200
Year of Treatment	**Block Size (ha)**	**Sampled Area (ha)**
1995	13.0	1.03

Silviculture System Uniform/group shelterwood. Target 400 trees/ha, but allow removal of small patches of infestation

Ecological Classification MSdk 04: Pl - Oregon grape - Pinegrass association of the Dry Cool Montane Spruce Subzone

Current Stand Characteristics

Layer	Silviculture Label	Avg. Age	Ht. (m)	Trees/ha	Conifers/ha	Well Spaced Free Growing Conifers/ha
1	$Pl_{87}Fd_{6}Sx_{5}Bl_{1}$	93	20.2	374	344	344
2	$Pl_{46}Fd_{35}Sx_{17}Bl_{2}$	na	11.9	67	61	61
3	$Pl_{66}Fd_{17}Bl_{17}$	11	2.2	2327	127	109
4	$Pl_{85}Fd_{6}B_{16}Sx_{3}$	7	0.7	5036	891	582

Ac=black cottonwood; At=trembling aspen; Bl=subalpine fir; Bp=noble fir; Cw= western red cedar; Fd=Douglas-fir; Hw=western hemlock; Lw=western larch; Pl=lodgepole pine; Sx=spruce

Figure 3h. Site-specific information for the Park site

Licence	**Cutting Permit**	**Block**
FL A17645	163	4
Latitude	**Longitude**	**Elevation (m)**
50 56.456	-116 09.481	1300
Year of Treatment	**Block Size (ha)**	**Sampled Area (ha)**
1997	16.0	1.15

Silviculture System Irregular shelterwood. Remove pine < 17.5 cm dbh. Space pine > 17.5 cm dbh to 5 m. Reserve non-pine.

Ecological Classification MSdk 04: Pl - Oregon grape - Pinegrass association of the Dry Cool Montane Spruce Subzone

Current Stand Characteristics

Layer	Silviculture Label	Avg. Age	Ht. (m)	Trees/ha	Conifers/ha	Well Spaced Free Growing Conifers/ha
1	$Sx_{61}Pl_{32}Bl_{4}At_{2}Fd_{1}$	88	21.3	304	297	297
2	$Sx_{79}Bl_{18}Pl_{2}At_{1}$	na	11.5	58	57	57
3	$Sx_{54}Bl_{38}Pl_{8}$	21	2.3	227	200	173
4	$Sx_{64}Bl_{31}Pl_{3}Fd_{2}$	12	0.7	1680	1333	773

Ac=black cottonwood; At=trembling aspen; Bl=subalpine fir; Bp=noble fir; Cw= western red cedar; Fd=Douglas-fir; Hw=western hemlock; Lw=western larch; Pl=lodgepole pine; Sx=spruce

Figure 3i. Site-specific information for the Boyce site

Licence	Cutting Permit	Block
FL A17645	810	3
Latitude	**Longitude**	**Elevation (m)**
50 56.834	-116 10.347	1300
Year of Treatment	**Block Size (ha)**	**Sampled Area (ha)**
1997	18	1.3

Silviculture System Uniform shelterwood. Target 5-m spacing. Remove infested pine and pine < 17.5 cm dbh. Reserve non-pine regardless of spacing

Ecological Classification MSdk 01: Sxw-Soopalallie-Grouseberry association of the Dry Cool Montane Spruce Subzone

Current Stand Characteristics

Layer	Silviculture Label	Avg. Age	Ht. (m)	Trees/ha	Conifers/ha	Well Spaced Free Growing Conifers/ha
1	$Sx_{52}Pl_{46}Bl_{2}$	87	19.9	308	308	308
2	$Sx_{78}Bl_{17}Pl_{4}Fd_{1}$	na	11.5	73	73	73
3	$Sx_{50}Bl_{44}Pl_{6}$	31	2.7	369	369	246
4	$Sx_{51}Bl_{36}Pl_{13}$	14	0.6	1877	1738	723

Ac=black cottonwood; At=trembling aspen; Bl=subalpine fir; Bp=noble fir; Cw= western red cedar; Fd=Douglas-fir; Hw=western hemlock; Lw=western larch; Pl=lodgepole pine; Sx=spruce

Figure 3j. Site-specific information for the Beaver site

Licence	**Cutting Permit**	**Block**
FL A17645	811	2
Latitude	**Longitude**	**Elevation (m)**
50 59.804	-116 14.534	1240
Year of Treatment	**Block Size (ha)**	**Sampled Area (ha)**
2000/2001	7.9	0.5

Silviculture System Irregular shelterwood. Space pine overstorey, remove all infested pine and all pine < 17.5 cm dbh to reduce windfall risk. Reserve non-pine species.

Ecological Classification MSdk 05: Swx - Soopalallie - Snowberry association of the Dry Cool Montane Spruce Subzone

Current Stand Characteristics

Layer	Silviculture Label	Avg. Age	Ht. (m)	Trees/ha	Conifers/ha	Well Spaced Free Growing Conifers/ha
1	$Pl_{51}Sx_{49}$	90	19.6	520	520	520
2	$Sx_{85}Pl_{13}Bl_{2}$	na	11.2	244	244	244
3	$Sx_{90}Pl_{10}$	na	3.4	450	400	250
4	$Sx_{64}Pl_{29}Bl_{7}$	10	0.7	400	400	350

Ac=black cottonwood; At=trembling aspen; Bl=subalpine fir; Bp=noble fir; Cw= western red cedar; Fd=Douglas-fir; Hw=western hemlock; Lw=western larch; Pl=lodgepole pine; Sx=spruce

Table 1. Pre-treatment, post-treatment, and current (after losses to wind and snow, mountain pine beetle, or other causes) density (trees/ha) of trees in Layers 1 and 2

		Pre-treatment density				Post-treatment density				Losses			Current density			
Site	Layer	Pl	Sx	Other	Total	Pl	Sx	Other	Total	Wind/Snow	MPB	Other	Pl	Sx	Other	Total
		trees / hectare														
Lodgepole	1	975	2	13	990	480	2	6	488	61	0	21	398	2	6	406
	2	114	8	2	124	40	8	0	48	23	0	4	13	8	0	21
Face	1	889	49	191	1129	379	48	130	557	14	1	39	333	45	126	504
	2	131	54	50	235	18	42	36	96	9	0	11	4	40	33	77
Hobo	1	1141	13	43	1197	344	12	33	389	72	3	11	260	12	31	303
	2	414	19	21	454	27	17	18	62	9	0	9	9	17	18	44
Hurst	1	916	53	186	1155	408	49	159	616	48	0	35	336	45	153	534
	2	303	41	162	506	105	36	153	294	61	0	35	35	34	129	198
Whiskey	1	877	140	67	1084	287	121	54	462	32	1	15	244	118	51	413
	2	184	72	47	303	15	56	41	112	5	0	7	6	55	38	99
Frost	1	1177	135	73	1385	503	121	53	677	76	8	37	393	118	45	556
	2	244	129	15	388	73	101	9	183	31	0	42	6	96	8	110
Park	1	390	251	40	681	134	202	28	364	38	11	10	96	184	24	304
	2	17	77	15	109	3	50	13	66	4	0	3	1	46	11	58
Fran	1	688	20	65	773	405	20	59	484	73	13	24	302	19	53	374
	2	108	12	34	154	73	12	33	118	31	0	20	28	11	28	67
Boyce	1	503	377	41	921	186	178	8	372	42	13	8	142	161	5	308
	2	49	165	42	256	7	66	16	89	11	0	5	3	57	13	73
Beaver	1	834	304	26	1164	324	260	2	586	18	0	48	264	254	2	520
	2	252	266	12	530	118	218	4	340	36	0	60	32	208	4	244

Post-Treatment Stand Structure and Composition

Variations in original stand composition and in the way cutting prescriptions were tailored to accommodate other management objectives also resulted in a considerable range in post-treatment stand composition and structure. Silviculture labels (species composition in percent for crop tree species only, based on tree density), by layer at time of assessment, are presented for each site in Figure 3.

In all cases, pine formed a smaller component of the dominant tree layers after harvest. At Park, Boyce, Beaver and Whiskey, other species comprised 68%, 54%, 49% and 40% of Layer 1 trees, and 98%, 96%, 87% and 94% of Layer 2 trees, respectively. The Layer 3 strata at Face, Hurst, Whiskey, Boyce and Beaver were abundant and dominated by other species. Reserving non-pine species from spacing, or protecting a well-developed pole or sapling layer, could prevent achievement of the desired microclimate effects of beetle proofing, because full-crowned trees like Engelmann spruce (*Picea engelmannii* Parry) or subalpine fir [*Abies lasiocarpa* (Hook.) Nutt.] shade the boles of residual pine trees and obstruct wind flow through the stand (Whitehead and Russo 2005). Where these species are a significant component of Layers 1 and 2, or of an abundant Layer 3, species conversion through complete pine removal from the overstorey, which would accelerate succession to a well-stocked non-susceptible stand, may be a better choice for reduction of susceptibility to damage from mountain pine beetle than would be a partial harvest entry that leaves a number of pine trees still susceptible to infestation.

Spacing to between 4 m and 5 m is recommended to achieve the desired effect on microclimate with acceptable risk to wind and snow damage. We did not directly measure intertree spacing; however, examining stand density in each 50-m by 5-m section of the strip cruise at each site (Figure 4) provides some insight. Uniform 4-m to 5-m spacing should result in a stand density of 400 to 625 overstorey trees/ha in a high proportion of these sections. At Hurst, Beaver, Frost and Face, more than half of the plots sampled had densities greater than 625 trees/ha, which suggests that the minimum spacing recommended to influence beetle dispersal, attack and development was not achieved. The majority of the plots at Hobo and Park had densities of fewer than 400 trees/ha, which suggests spacing may have exceeded the maximum recommended to avoid wind damage.

Reconstructions of the overstorey diameter distribution of pine and other species, before and after treatment at each site, are presented in Figure 5. Thinning from below should result in fewer small-diameter trees, a higher average dbh, and larger average piece size (Table 3) after harvest. Lodgepole, Hobo, Face, Boyce and Frost had characteristics generally consistent with thinning from below. There was no obvious shift towards larger-diameter classes after harvest at Park, Whiskey or Hurst, nor was there any increase in average breast-height diameter or piece size of merchantable trees at the Beaver and Fran sites.

Table 2. Proportion of the overstorey (Layers 1 and 2) composed of lodgepole pine trees, before and after treatment

	Proportion of lodgepole pine trees in Layer 1 and 2		Ratio Layer 1: Layer 2	
Site	Before treatment	After treatment	Before treatment	After treatment
Lodgepole	98%	97%	8.0	10.2
Face	75%	61%	4.8	5.8
Hobo	94%	82%	2.6	6.3
Whiskey	76%	53%	3.6	4.1
Frost	80%	67%	3.6	3.7
Park	52%	32%	6.2	5.5
Boyce	47%	42%	3.6	4.2
Hurst	73%	56%	2.3	2.1
Fran	86%	79%	5.0	4.1
Beaver	64%	48%	2.2	1.7

Table 3. Average piece size removed during harvest and average piece size remaining

Site	Average piece size			
	All trees		Merchantable trees	
	Removed	Standing	Removed	Standing
	m^3			
Lodgepole	0.20	0.35	0.23	0.37
Face	0.22	0.40	0.28	0.46
Hobo	0.17	0.35	0.25	0.40
Hurst	0.15	0.21	0.20	0.28
Whiskey	0.23	0.34	0.30	0.42
Frost	0.22	0.33	0.28	0.39
Park	0.37	0.50	0.42	0.59
Fran	0.31	0.30	0.35	0.35
Boyce	0.19	0.31	0.24	0.39
Beaver	0.22	0.19	0.29	0.28
Average	**0.23**	**0.33**	**0.28**	**0.39**

Table 4. Merchantable volume (m^3/ha) before and after harvest, by site

Site	Merchantable volume				
	Pre-treatment	Removed by harvest	Post- treatment	Lost since treatment	At time of assessment
	m^3/ha (%)				
Lodgepole	279	113 (41)	166	17 (10)	149
Face	407	158 (39)	249	15 (6)	234
Hobo	354	203 (57)	151	31 (21)	120
Hurst	273	111 (41)	162	11 (7)	151
Whiskey	377	188 (50)	189	16 (8)	173
Frost	443	197 (44)	246	29 (12)	217
Park	343	133 (39)	210	30 (14)	180
Fran	264	100 (38)	164	33 (20)	131
Boyce	276	132 (48)	144	24 (17)	120
Beaver	327	170 (52)	157	10 (6)	147
Average	**334**	**151 (45)**	**184**	**22 (12)**	**162**

Merchantable Volume Removed, Retained, and Lost Since Treatment

Merchantable volume removed during harvest ranged from about 100 to 115 m^3/ha at Fran, Hurst and Lodgepole to about 200 m^3/ha at Hobo and Frost (Table 4). Merchantable volume remaining on site after post-treatment losses to wind, snow, mountain pine beetle, or natural mortality ranged from 120 m^3/ha to 234 m^3/ha. In 8 of 10 cases (Fran and Beaver excepted), average piece size of residual trees was considerably larger than those removed at harvest (Table 3). The B.C. Ministry of Forests (1999) stated that a viable commercial thinning requires harvesting at least 100 m^3/ha to 125 m^3/ha (depending on haul distance). It appears that this harvest entry achieved this criterion at all sites and left a good residual stand that is fully developed for a future harvest entry.

Wind and Snow Damage

Cumulative volume of merchantable wood lost to wind and snow damage at each site is presented in Table 5. Partial cutting late in the rotation of a previously unmanaged, mature lodgepole pine stand increases risk of wind and snow damage as crown exposure to winds is increased and the damping effects of crown contact between trees are reduced (Quine et al. 1995). The proportion of merchantable volume lost since treatment ranged from 1.6% (4.0 m^3/ha) at Face, where the lightest harvest entry removed 39%

of the original merchantable volume, to 18.3% at Hobo (27.5 m^3/ha), where the most aggressive harvest entry removed 57% of the original volume and produced wide intertree spacing.

Areas of particular hazard to wind and snow damage can generally be predicted and identified during the prescription process through careful consideration of terrain (exposure to damaging winds) and soil characteristics (texture, drainage and depth), in conjunction with stand conditions (density, live crown size, cover and exposure; Quine et al. 1995). Clearcutting or reserving dense patches (more than about 1700 trees/ha) of smaller pine with high height-to-diameter ratios has been recommended (B.C. Ministry of Forests 1999). The prescriptions at Beaver, Boyce, Park and Hurst specified removal of all pine between 12.5-cm and 17.5-cm dbh to reduce risk of wind damage, yet these sites still lost 6% to 12% of the trees and 2.6% to 9.0% of the volume remaining after harvest. Coates (1997) noted that stands are not usually considered for salvage if less than 10% of the stand (in terms of trees per hectare) has been damaged. Wind or snow damaged more than 10% of the trees since treatment at 7 of 10 sites (Table 5). Prescriptions at several sites recognized a need for post-treatment monitoring, and there was evidence that salvage had occurred at Hobo, Lodgepole, Boyce, Fran and Park. Our survey underscores the importance of planning for salvage after partial cutting in mature pine stands.

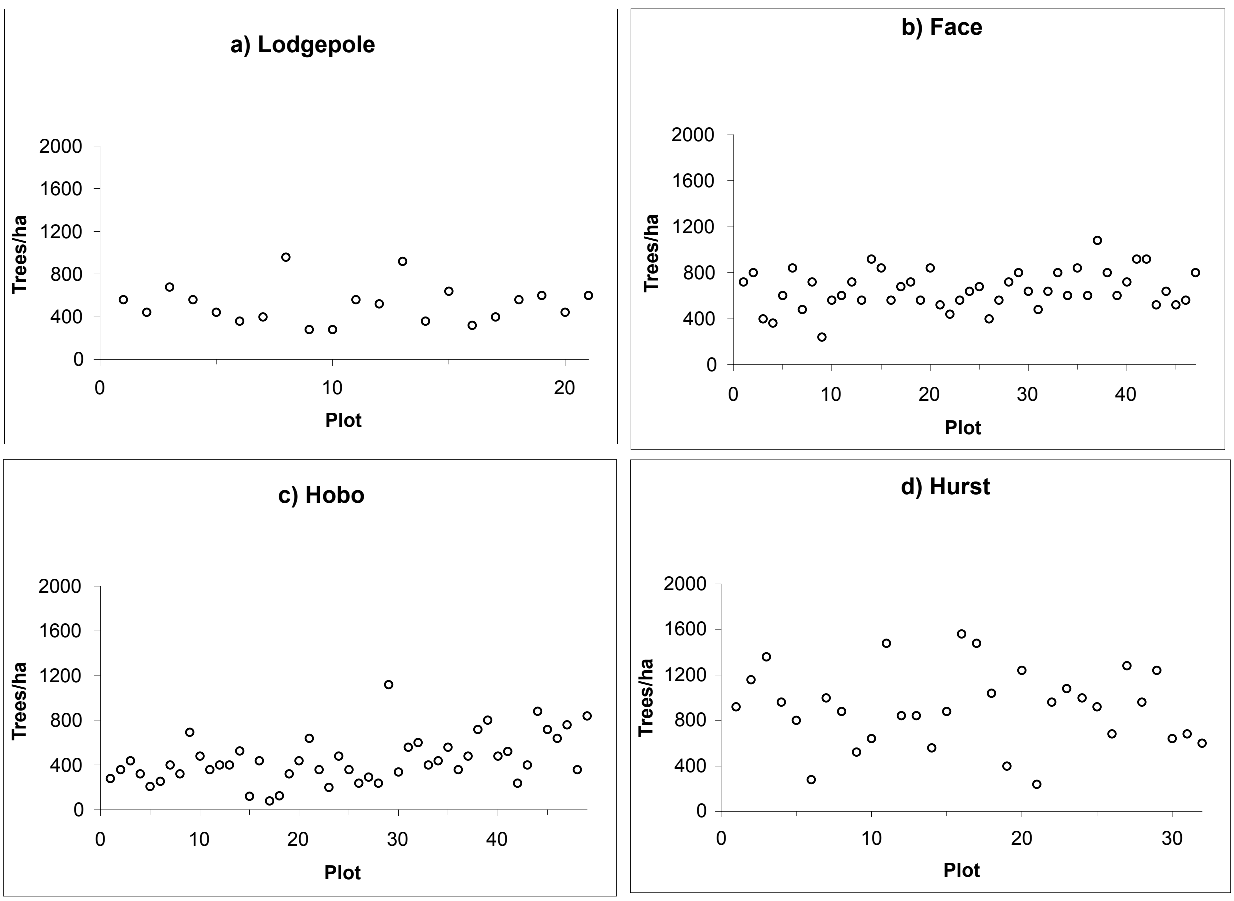


Figure 4 (a–d). Stand density after treatment (trees/ha) of each 5-m by 50-m section of strip cruise. Thinning to an even 4-m to 5-m inter-tree distance would result in a density of 400 to 625 trees/ha.

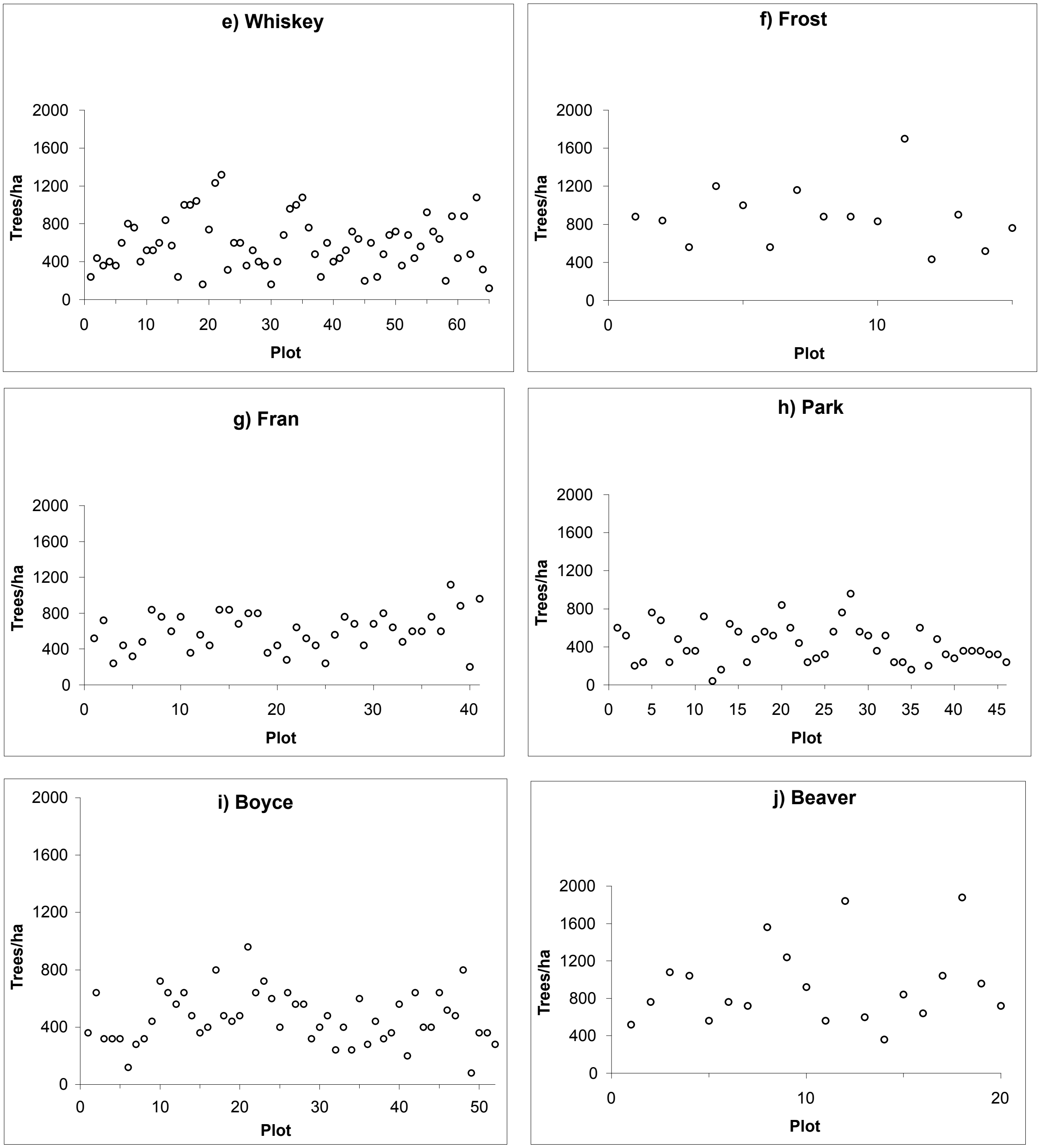


Figure 4 (e–j). Stand density after treatment (trees/ha) of each 5-m by 50-m section of strip cruise. Thinning to an even 4-m to 5-m inter-tree distance would result in a density of 400 to 625 trees/ha.

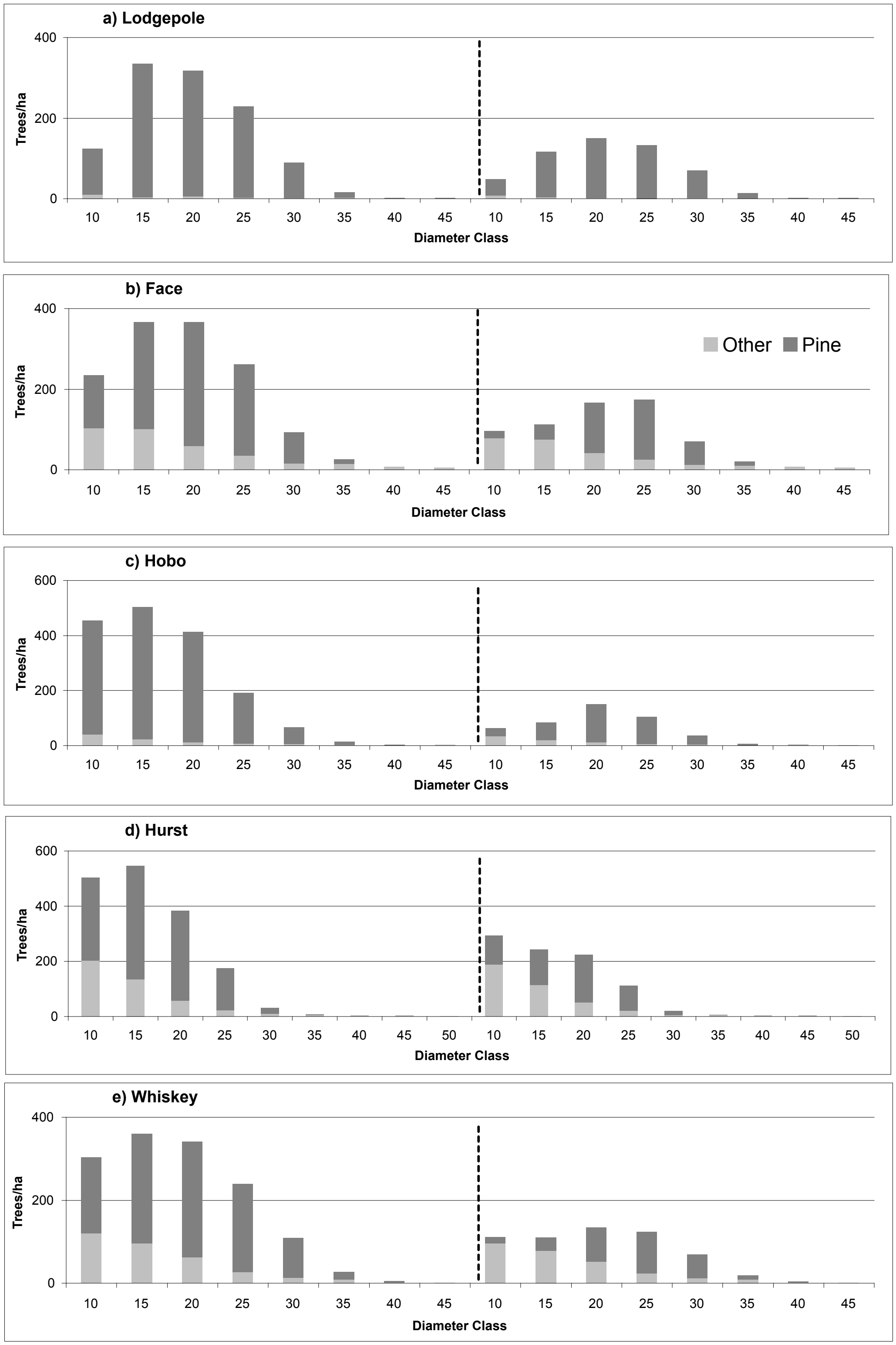


Figure 5 (a–e). Diameter distribution (trees/ha), by site. Pre-treatment values are located left of the dashed vertical line; post-treatment values, to the right.

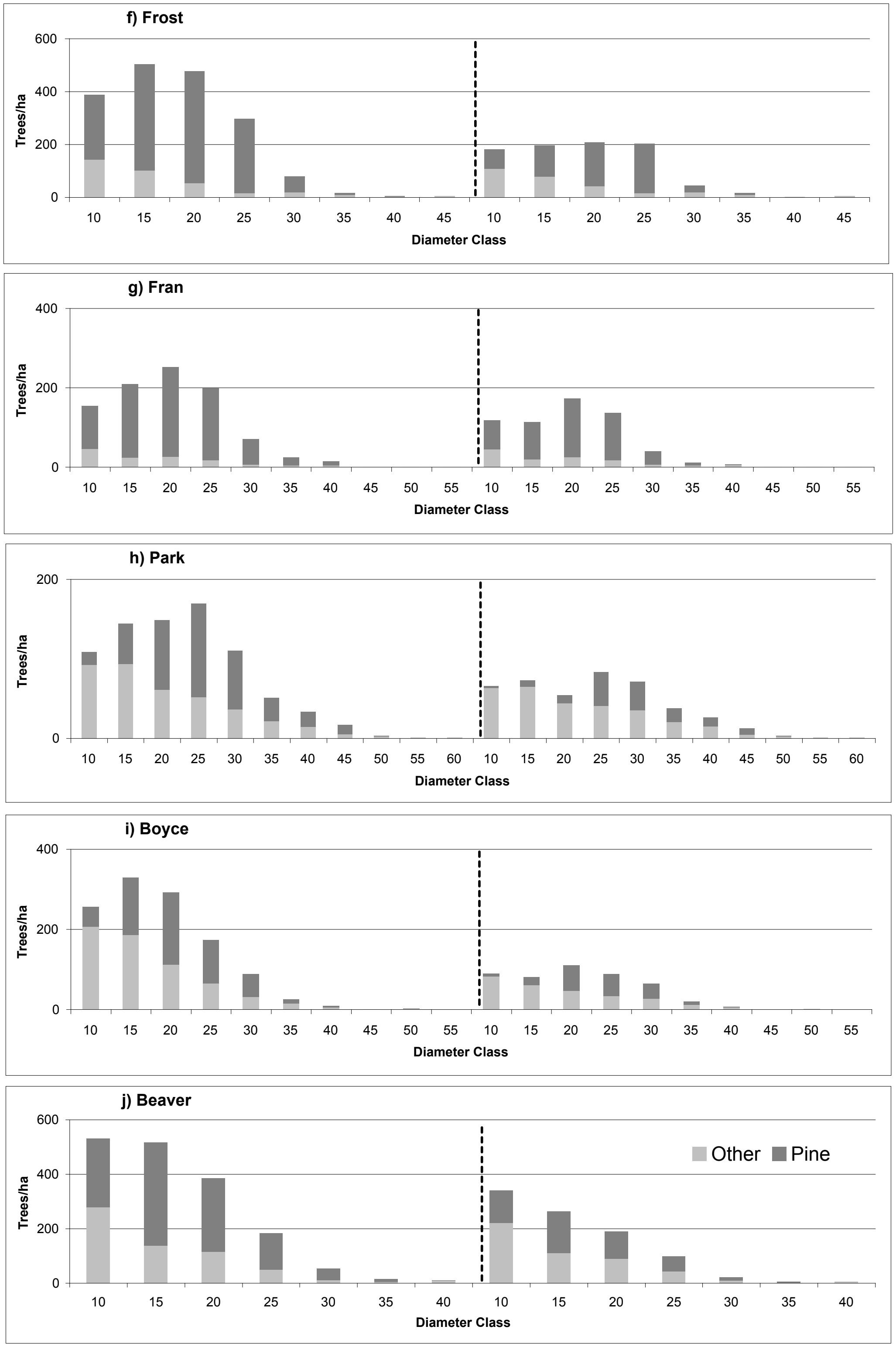


Figure 5 (f–j). Diameter distribution (trees/ha), by site. Pre-treatment values are located left of the dashed vertical line; post-treatment values, to the right.

Table 5. Total losses to wind and snow damage since treatment

Site	Years since treatment	Proportion Lost		Leans >45°	Volume Lost (m^3/ha)			Total
		Trees	Merchantable Volume		Snaps	Uproots	Wind Stumps[a]	
Lodgepole	13	12.70%	5.80%	-	1.9	2.6	5.2	9.7
Face	7	3.40%	1.60%	-	1.9	2.1	-	4.0
Hobo	7	18.00%	18.30%	0.1	4.1	12.0	11.3	27.5
Hurst	9	12.00%	4.90%	-	4.0	3.9	-	7.9
Whiskey	8	6.50%	6.00%	-	4.9	5.8	0.6	11.3
Frost	10	12.40%	7.80%	0.6	14.0	4.6	-	19.2
Park	8	10.00%	7.20%	-	3.4	7.8	4.0	15.2
Fran	10	17.30%	13.00%	-	7.8	8.2	5.2	21.2
Boyce	8	11.50%	9.00%	-	2.4	1.7	8.9	13.0
Beaver	5	5.80%	2.60%	-	3.2	0.9	-	4.1

a Wind Stumps: our label for overturned stumps with root wads still attached. Unless immediately adjacent to a skid trail, these stumps were assumed to be remnants of windthrow salvage and were recorded as wind damage

Table 6. Number of trees attacked by mountain pine beetle since treatment, by site

Location	Assessment Date	No. trees attacked[1]			Beetle Pressure[2]	Area Surveyed (ha)
		Red/Gray	Red	Current		
Lodgepole	May 10/04	0	0	0	L	0.53
Face	Sept. 11/04	1M, 1R	0	1R	M	1.18
Hobo	June 11/04	2M, 1P	0	0	M	1.17
Hurst	June 27/05	0	0	0	H	0.80
Whiskey	July 18/04	1M	1M, 1R	0	M	1.56
Frost	Sept. 26/05	3M	0	0	H	0.41
Fran	May 11/05	3M	3M, 1P, 2R	8M, 6R	H	1.03
Park	July 25/05	8M, 1R	2M	3M	H	1.15
Boyce	Aug. 10/05	1M	3M, 1P, 1R	13M, 1P, 4R	H	1.30
Beaver	Aug. 13/04	0	0	0	H	0.50

1 M=Mass Attack; R=Resisted Attack; P=Partial Attack
2 A subjective assessment of beetle pressure in the area based on local and aerial observation where: L=Low; M=Moderate; H=High

Mountain Pine Beetle Attack since Treatment

The number of trees attacked since treatment (Table 6) was assessed at Lodgepole, Whiskey and Hobo before the mountain pine beetle flight in 2004, whereas Beaver, Hurst, Face, Fran, and Park were assessed after the 2004 flight, and Frost and Boyce were assessed after the 2005 flight. The different assessment periods make it difficult to compare all sites directly. However, at 6 of the 10 sites, there was no evidence of developing infestation. There was no attack since treatment at Lodgepole and Hurst, very low levels of successful attack at Whiskey, Hobo and Face, and no attack for at least two years preceding assessment at any of these sites. Similarly, at Frost, where a total of eight trees/ha had been attacked since treatment, there had been no attack for three years prior to our assessment. These earlier attacks at Frost may be associated with the use of pheromone attractants placed at the site before harvest. Beetles often concentrate a large number of attacks on baited trees, and some will remain in stumps after harvest; others may be present at lower numbers in residual trees missed at harvest.

Fran, Park, and Boyce stand out with the highest amount of cumulative attack since treatment, a recent increase in number of attacks with time, and a higher percentage of Layer 1 pine successfully attacked. A combination of factors is likely involved: the prescription at these three sites specifically reserved non-pine from cutting regardless of effect on intertree spacing; all three sites had active infestations at time of treatment; and, at both Fran and Park, pheromone baits were deployed before harvest. Stand composition after harvest at Park and Boyce was spruce-leading in all layers, and both sites are located in very close proximity to an uncontrolled outbreak of mountain pine beetle in Kootenay National Park. Although Beaver is in the same area and also is subject to high beetle pressure, our systematic strip survey did not pick up any attack since treatment. However, we saw red-attacked trees on the north and northwest edges of the treatment boundary and noted a few new attacks on trees between survey strips where pockets of retained Layer 2 spruce and saplings were dense (Figure 6).

Figure 6. A well-spaced lodgepole pine overstorey remains susceptible to attack by mountain pine beetle if lower boles are shaded and winds are blocked by dense intermediate and sapling layers. This photo was taken between two survey strips at the Beaver site.

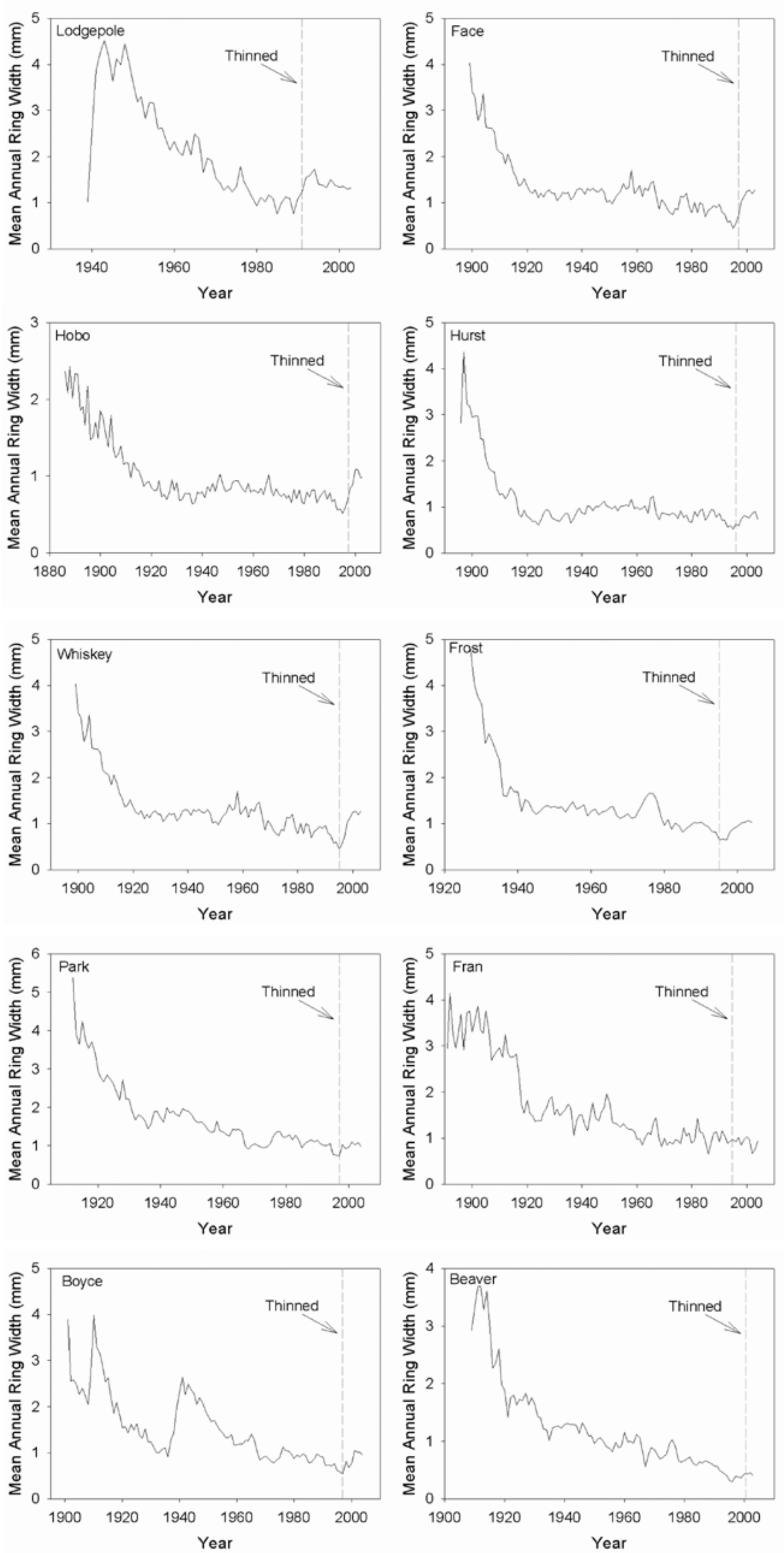


Figure 7. Mean annual ring width of residual lodgepole pine trees at each site

There is no evidence of developing infestation at the six sites where wide spacing of the pine overstorey was achieved and sparse intermediate and sapling layers ensured that the lower tree boles were exposed to increased solar radiation and wind after harvest. In contrast, three of the four sites with recent beetle attack have a significant spruce component in Layers 1 and 2, and the fourth site (Fran) has dense sapling and regeneration layers (Fig. 3: g, h, i, j). Retaining unspaced patches or large numbers of full-crowned trees, saplings and advanced regeneration results in shaded tree boles and low within-stand winds. This microclimate favours successful host location and attack, and provides centres for initiation of patch infestations (Whitehead and Russo 2005). The use of pheromone baiting in stands planned for selective harvest is not recommended, as beetles remaining in stumps or missed residual trees after harvest may leave sufficient populations to overcome a healthy residual tree and contribute to risk of successful infestation.

Radial Growth of Residual Layer 1 Pine

We measured diameter increment in residual lodgepole pine only (Figure 7), and then compared periodic annual increment (PAI) for the 10 years preceding treatment to PAI calculated for the available post-treatment period, which varied from 4 to 10 years, depending on the site (Table 7). At Fran, Park, Beaver, Hurst and Frost, there was no clear evidence of a pronounced change in mean annual ring width in residual pine trees following harvest. We did not measure growth response in the other species. The largest increases in PAI for pine (42%, 49%, 55% and 66% at Lodgepole, Hobo, Face and Whiskey, respectively) were seen at sites that had a relatively high proportion of pine before and after harvest and where removals targeted smaller trees. Whitehead and Russo (2005) found similar increases in diameter growth at four of five mature pine sites examined 10 to 14 years after thinning from below to uniform spacing of 4 m to 5 m.

Table 7. Mean periodic annual increment before treatment (10-year average) and after treatment (average of all years since treatment)

Site	Mean periodic annual increment		
	Before	After	Change
	--------------------*mm*--------------------		------%-----
Lodgepole	2.06	2.93	42
Face	1.14	1.77	55
Hobo	1.31	1.95	49
Hurst	1.45	1.55	7
Whiskey	1.45	2.40	66
Frost	1.82	1.80	–1
Park	1.96	2.03	4
Fran	1.95	1.81	–7
Boyce	1.49	1.79	20
Beaver	0.82	0.86	5

Regeneration and Current Stocking

Average age, density and species composition of Layers 3 and 4 at each site are presented in Figure 3. The Lodgepole site was under-planted in 1995; Whiskey, in 1997; Fran, Park, Boyce and 1.5 ha of Hurst, in 1999; and Beaver, in 2001. Frost, Face and Hobo were not planted. In general, the well-spaced conifers of Layer 4 at each site were a mix of trees that were already established at the time of treatment and trees that became established, either through planting or natural regeneration, following treatment. The most damaging agents of Layers 3 and 4 at these sites were Cooley spruce gall adelgid (*Adelges cooleyi* Gillette), which was noted at 8 of the 10 sites, animal browsing, and western gall rust (*Endocronartium harknessii* J.P. Moore), which were both noted at four sites (Table 8). Percent cover of the most common non-crop vegetation at each site is presented in Table 9.

Table 8. Number of Layer 3 and 4 trees damaged by various agents noted at assessment

	Aphids/ Adelgids	Browse/ Trample	Cooley Spruce Gall Adelgid[a]	Needle Disease	Rodent Damage	Root Rot	Rust	Western Gall Rust[b]	Scale Insect
Lodgepole	22	1066		33		11		133	
Face		13	53						
Hobo		11							
Hurst	20	20	120						20
Whiskey			511				11	22	
Frost	25		475		50		25		
Park			213				13		
Fran		56	18					56	
Boyce	15		277				62	46	
Beaver			400						

[a] *Adelges Cooleyi* (Gillette)
[b] *Endocronartium harknessii* (J.P. Moore)

Table 9. Average cover of most common species of competing vegetation at each site

Site	Average cover	Top three species (by cover)
Lodgepole	26%	Alder / Soopolallie / Douglas Maple
Face	26%	Alder / Soopolallie / Willow
Hobo	39%	Soopolallie / False Azalea / Douglas Maple
Hurst	29%	Soopolallie / Douglas Maple / False Azalea
Whiskey	41%	Soopolallie / Thimbleberry / Alder
Frost	13%	Snowberry / Soopolallie / Red Ozier Dogwood
Park	36%	Soopolallie / Alder / Thimbleberry
Fran	8%	Soopolallie / Saskatoon / Common Juniper
Boyce	14%	Soopolallie / False Azalea / Willow
Beaver	3%	Soopolallie / Willow / Prickly Rose

At all sites, the majority of the assessed plots met the partial-cutting stocking standards for the Rocky Mountain Forest District (BC Ministry of Forests and Range 2004b; Table 10), but there was also potential to increase volume production through fill-planting. The largest potential for benefit from targeted planting was at Hobo (6 of 18 plots were classified as "open"), where losses to wind and snow damage was highest, and at Fran (3 of 11 plots were classified as partially stocked), where intertree spacing of the overstorey often exceeded 5 m. Although Table 10 suggests some significant gains in volume at rotation from fill-planting at several sites, these calculations ignore the temporary nature of reduced stocking in the case of a commercial thinning or initial cut of a shelterwood that can be efficiently addressed after the follow-up harvest entry.

Table 10. Summary of stocking, and potential to increase volume through fill-planting, at each site

Site	# Plots	# Plots in each category			Potential for volume increase	
		Stocked	Partially stocked	Open	Range	Average
Lodgepole	18	18	0	0	0–8%	3%
Face	15	14	0	1	0–62%	11%
Hobo	18	12	0	6	0–100%	27%
Hurst	10	9	0	1	0–65%	7%
Whiskey	18	18	0	0	0–13%	3%
Frost	8	7	0	1	0–86%	16%
Park	15	14	1	0	0–21%	5%
Fran	11	8	3	0	4–38%	16%
Boyce	13	12	0	1	0–45%	7%
Beaver	8	8	0	0	0–20%	6%

Coarse Woody Debris

Coarse woody debris (CWD) has been defined as "sound and rotting logs and stumps, and coarse roots in all stages of decay, generally greater than 3 inches (7.6 cm) in diameter, that provide habitat for plants, animals, and insects and a source of nutrients and structures for soil development" (Stevens 1997). British Columbia's Forest Planning and Practices Regulation (2004) requires agreement holders who carry out timber harvesting in the interior to retain at least four pieces of CWD per hectare, each of at least 2 m in length and 7.5 cm in diameter at one end. All 10 sites exceeded the minimum piece per hectare criteria (Table 11). Different communities of invertebrates occupy different decay classes, so maintaining a range of decay classes is also important (Harmon et al. 1986; Samuelsson et al. 1994). At least three of the five decay classes were present at each site, and, where data is available for comparison, total volume of CWD at each site falls within the range identified for unmanaged stands with the same biogeoclimatic classification (Table 12).

Table 11. Pieces per hectare of coarse woody debris, by length class

Site	Zone	CWD (>7.5 cm in diameter) by length class (m)						
		0.1–6	>6–12	>12–18	>18–24	>24–30	>30–36	Total
		pieces/ha						
Lodgepole	ICHcl 04	1047	29	70	12	0	0	1159
Face	MSdk 04	2007	145	17	25	19	0	2214
Hobo	MSdk 04	1134	524	140	25	0	8	1831
Hurst	MSdk 01	2095	87	0	0	0	0	2182
Whiskey	MSdk 01	1658	175	17	37	0	0	1887
Frost	MSdk 01	2880	495	52	12	0	0	3439
Park	MSdk 04	611	233	52	0	0	0	896
Fran	MSdk 04	436	204	70	87	0	0	797
Boyce	MSdk 01	785	58	0	0	0	0	844
Beaver	MSdk 05	1658	495	87	0	0	0	2240

Table 12. Volume of coarse woody debris at each site, by decay class

Site	Zone	Decay Class					
		1[a]	2[b]	3[c]	4[d]	5[e]	TOTAL
		m³/ha					
Lodgepole	ICHcl 04	1.3	8.0	9.0	29.2	48.7	96.2
Face	MSdk 04	30.8	18.1	27.0	16.8	6.0	98.7
Hobo	MSdk 04	10.5	83.6	17.9	1.6	0.0	113.6
Hurst	MSdk 01	0.0	15.9	38.1	6.2	0.0	60.2
Whiskey	MSdk 01	10.8	29.5	21.6	2.3	17.3	81.5
Frost	MSdk 01	22.1	32.9	60.3	8.1	0.0	103.2
Park	MSdk 04	1.5	11.8	13.5	17.4	2.3	46.6
Fran	MSdk 04	48.5	27.0	18.0	4.8	1.7	99.8
Boyce	MSdk 01	0.0	0.0	30.8	1.9	4.2	36.9
Beaver	MSdk 05	22.6	76.1	20.6	6.2	0.0	125.5

[a] Intact, hard; elevated on support points; twigs <3 cm present (if originally present); bark intact
[b] Intact, hard to partially decaying; elevated but slightly sagging; twigs <3 cm absent; bark intact to partly missing
[c] Hard, large pieces, partially decaying; sagging near ground, or broken; twigs <3 cm absent; bark trace
[d] Small, blocky pieces; on ground, sinking; twigs <3 cm absent; bark absent
[e] Many small pieces, soft portions; all on ground, partially sunken; twigs <3 cm absent; bark trace (Meidinger 1998)

Fuel Loading

Aspects of fire behaviour most pertinent to fuel management and wildfire suppression planning include the potentials for ignition, crown fire initiation and severe crown fire behaviour. Selective harvest of a forest stand is expected to influence all of these, because harvest entries change forest structure in ways that affect amount and distribution of potential fuels and within-stand microclimate. Changes in surface fuel loading, fine fuel moisture content and within-stand winds affect surface fire behaviour, and consequently crowning potential, which also depends on the distance separating surface and crown fuels (Rothermel 1983; Scott and Reinhardt 2001). Potential for continuous (or "active") crown fire, which is particularly important to fuel management in the wildland–urban interface, is a function of two inversely related factors: crown bulk density and rate of fire spread (Van Wagner 1977). Harvesting reduces crown bulk density, which implies that a higher rate of spread is required to sustain an active crown fire and therefore, all else being equal, more extreme (and less frequently occurring) weather conditions.

The current surface fuel load at all sites is described in Table 13; specific aspects of stand structure that were used to predict potential fire behaviour are presented in Table 14. Basal area, stand density, height and diameter were directly sampled in "current" stands, and were derived from stand reconstructions for the pre- and post-treatment stands. Live canopy base height, canopy bulk density and canopy fuel load were derived from models, using these estimates, in all cases (Cruz et al. 2003). Because we did not directly measure all of these parameters, we advise some caution when applying interpretations based on our data.

Table 13. Characteristics of the surface fuel complex, by site

Understorey Fuels	Lodgepole	Face	Hobo	Hurst	Whiskey	Frost	Park	Fran	Boyce	Beaver
Current										
Understorey conifer biomass (kg/m^2)	0.368	0.002	0.049	0.043	0.603	0.278	0.007	0.000	0.004	0.000
Shrub biomass (kg/m^2)	0.07	0.22	0.30	0.02	0.31	0.01	0.01	0.13	0.49	0.03
Herbaceous biomass (kg/m^2)	0.09	0.08	0.06	0.03	0.01	0.03	0.03	0.02	0.03	0.03
Herbaceous cover (%)	59	27	24	27	22	36	62	66	33	43
Woody fuels <3 cm in diameter (kg/m^2)	0.17	0.24	0.27	0.24	0.32	0.28	0.32	0.18	0.23	0.35
Woody fuels 3–7 cm in diameter (kg/m^2)	0.29	0.81	2.06	0.96	0.32	1.71	0.52	0.11	0.40	0.70
Woody fuels >7 cm in diameter (kg/m^2)	3.12	3.85	3.96	2.27	2.37	4.34	1.78	3.55	1.51	5.08
Litter[a] biomass (kg/m^2)	0.14	0.28	0.56	0.34	0.25	0.26	0.17	0.26	0.25	0.33
Litter bulk density (kg/m^3)	18.6	21.2	29.7	30.9	24.4	29.1	11.0	23.9	13.8	39.1
Litter depth (cm)	0.7	1.3	1.9	1.1	1.0	0.9	1.6	1.9	1.8	0.9
Duff[b] bulk density (kg/m^3)	158.5	64.4	54.6	77.9	178.0	122.8	87.3	101.2	107.1	57.3
Duff depth (cm)	2.9	5.6	7.1	6.6	5.0	5.3	10.2	4.3	7.0	11.1

[a] Litter mainly consisted of needles leaves and very fine twigs
[b] Duff consisted of the fermentation and humus layer

Table 14. Characteristics of the crown fuel complex, by site

Conifers >7.49 cm DBH	Lodgepole	Face	Hobo	Hurst	Whiskey	Frost	Park	Fran	Boyce	Beaver
Pre Treatment										
Basal area (m^2/ha)	35.4	42.1	41.0	37.4	41.1	45.7	35.9	29.6	35.1	41.1
Density (trees/ha)	1114	1342	1645	1636	1384	1705	777	878	1175	1694
Height (m)	18.4	21.2	19.8	17.7	19.9	21.5	20.1	18.7	17.7	18.2
Diameter at breast height (cm)	19.2	18.9	16.8	16.0	18.3	17.6	22.6	19.5	18.3	16.4
Live crown base height (m)	11.2	12.5	12.2	10.2	11.8	13.1	11.2	11.0	9.7	10.4
Canopy bulk density: foliage (kg/m^3)	0.13	0.17	0.19	0.21	0.19	0.20	0.14	0.11	0.19	0.25
Canopy fuel load: foliage (kg/m^2)	0.97	1.51	1.45	1.54	1.52	1.71	1.22	0.87	1.55	1.92
After Treatment										
Basal area (m^2/ha)	20.0	24.4	15.4	21.7	19.7	23.0	21.6	18.1	17.1	21.2
Density (trees/ha)	535	637	450	894	570	798	418	556	461	926
Height (m)	19.0	22.2	22.0	17.7	20.1	21.6	19.8	18.5	18.4	16.9
Diameter at breast height (cm)	20.8	20.8	19.9	16.4	19.7	18.2	23.7	19.2	20.3	15.9
Live crown base height (m)	11.0	12.4	12.4	9.6	11.0	12.2	10.6	10.5	9.7	9.0
Canopy bulk density: foliage (kg/m^3)	0.06	0.09	0.05	0.12	0.08	0.10	0.08	0.07	0.08	0.15
Canopy fuel load (kg/m^2)	0.51	0.87	0.50	0.96	0.78	0.90	0.78	0.57	0.68	1.18
Current (measured in 2004 or 2005)										
Basal area (m^2/ha)	17.5	22.6	12.2	19.3	17.9	19.6	18.6	18.0	14.3	19.0
Density (trees/ha)	427	566	345	724	509	612	355	406	381	764
Height (m)	19.5	22.5	22.2	18.1	20.1	22.2	19.7	18.9	18.3	17.0
Diameter at breast height (cm)	22.0	21.4	20.2	17.2	19.9	19.3	23.8	19.8	20.5	16.7
Live crown base height (m)	11.2	12.5	12.4	9.7	10.9	12.4	10.4	10.5	9.7	8.9
Canopy bulk density: foliage (kg/m^3)	0.05	0.08	0.04	0.10	0.08	0.08	0.07	0.05	0.07	0.13
Canopy fuel load (kg/m^2)	0.43	0.80	0.40	0.82	0.71	0.77	0.68	0.44	0.58	1.06

Potential for Surface Fire Ignition

Surface fire ignition potential depends on the quantity, distribution and moisture content of available fine surface fuels. Models developed by Lawson and Dalrymple (1996) for dry and moist pine sites indicate that wind speed is also an important factor in determining ignition probability. Schroeder et al. (2006) tested potential for sustained ignition in a nearly pure lodgepole pine stand in the MSdm (dry, mild Montane Spruce subzone) near Kelowna, B.C., two years after thinning from below to 4-m spacing with a single-grip harvester/processor. They found that sustained ignition occurred more frequently in treated areas where logging slash was left in place (47% of attempted ignitions were successful) than it did in untreated control areas (7%) or in thinned areas where all slash was removed (15%). In contrast, in the stands we studied, whole trees were skidded to a landing for processing and debris disposal, and there had been 5 to 14 years since the harvest entry was completed for settling and decay of fine surface fuels. The amount of down and dead woody fuel smaller than 3 cm in diameter on our sites ranged from 0.17 kg/m^2 to 0.35 kg/m^2, which is considerably lower than the range for pre-thinning and untreated control values (0.48 kg/m^2 to 4.27 kg/m^2; Hawkes, unpublished data) on the site that Schroeder et al. (2006) studied. This suggests that, 5 to 14 years after treatment, the amounts of fine surface fuels on sites that we studied are not contributing to high ignition probability.

Rates of wetting and drying of fine surface fuels are influenced by microclimatic factors that are expected to change when a stand is partially cut. These factors include canopy interception of rainfall and solar radiation, near-surface air temperature, relative humidity and within-stand wind speed (Rothermel 1983; Forestry Canada 1992). In a comparison of spaced and unspaced mature lodgepole pine stands in the MSdk (dry, cool Montane Spruce subzone) near Cranbrook, B.C., Whitehead et al. (2006b) found no differences in moisture content of lodgepole pine needle litter or fuel moisture sticks, except after rain events when fire danger was very low. However, they also reported that within-stand winds at 3 m above ground were consistently higher in the spaced stand than in the unspaced control through 14 fire seasons. Lawson and Dalrymple (1996) suggests that higher within-stand winds will raise the ignition probability. Schroeder's observations suggest that the amount of fine surface fuel available has a larger effect.

Surface Fire Behaviour and Crown Fire Ignition Potential

Surface fire behaviour depends on the amount of fine surface fuels, recent weather conditions and near-ground microclimate (relative humidity, windspeed, etc.). The Canadian Fire Behaviour Prediction (FBP) System was developed for a wide range of unmanaged stand structures, but does specifically account for the potential changes in fire behaviour that might result from microclimatic changes after partial cutting within natural stands, so we cannot use it to predict surface fire behaviour with confidence. We also do not know how much surface fuel was available for consumption before and immediately after harvest. However, for a given fuel loading and moisture content, surface fire spread rate and intensity are expected to increase with within-stand winds; further research is required to quantify the effects of partial cutting on surface fire behaviour within thinned stands.

For transition from a surface fire to a crown fire, enough heat must be released from burning surface fuels to cause ignition of crown fuels. Where overstorey trees or pole and sapling layers with full crowns reaching to the ground provide a nearly continuous pathway for fire between the surface and crown fuels (ladder fuels), the transition may occur at relatively low surface fire intensity. When distance separating the two fuel strata is greater and relatively uniform, the threshold or critical surface fire intensity (CSI) required may be calculated as a function of live canopy base height (LCBH) and foliar moisture content (Van Wagner 1977; Forestry Canada 1992).

Fire intensity is a function of heat of combustion, mass of fuels consumed, and the fire's rate of spread (Byram 1959). Based on the model projections of LCBH and assuming foliar moisture content (FMC) of 100, we calculated CSI for pre-treatment, post-treatment and current stand conditions at each site (Table 15), using equation 2.

$$CSI = 0.001 \times LCBH^{1.5} \times (460 + 25.9 \times FMC)^{1.5} \qquad (2)$$

LCBH was very high in all cases (8.9 m to 13.1 m) and consequently the CSI values calculated for crown fire initiation reflect quite extreme fire intensity (4,000 kW/m to 8,000 kW/m). Achieving these intensities with the low surface fuel loads we observed would require very high rates of surface fire spread and is therefore unlikely in these stands; however, higher slash loading or the presence of ladder fuels could significantly increase the probability of crowning. Sites where abundant spruce or fir in the overstorey, pole, and sapling layers was reserved from harvest (e.g., Fran, Boyce and Beaver) are of most concern, as these species tend to have full crowns which may expand after selective cutting allows more light into the stand. The objective for retaining these stems may be to accelerate succession to a non-pine stand, and it is important to remember that this will also result in a shift in fuel characteristics and expected fire behaviour over time. The Canadian FBP System recognizes spruce-dominated overstorey as a different fuel type (C-2) from lodgepole pine-dominated overstorey (C-3) and predicts more severe fire behaviour. Sites that were thinned from below and where there was little or no non-pine component pre-harvest (e.g., Lodgepole, Face, and Hobo) are least likely to develop crown fires from surface ignitions, because surface and crown fuels are widely separated and few ladder fuels, if any, are present. These sites are likely to remain at relatively low hazard until the final overstorey is removed at rotation.

Table 15. Surface fire intensity required to initiate crown fire (CSI) before treatment, after treatment and under current stand conditions

Site	Surface fire intensity required for crown fire initiation		
	Before	After	Current
	kW/m		
Lodgepole	6314	6145	6314
Face	7444	7355	7444
Hobo	7178	7355	7355
Hurst	5487	5010	5089
Whiskey	6828	6145	6062
Frost	7987	7178	7355
Park	6314	5813	5649
Fran	6145	5731	5731
Boyce	5089	5089	5089
Beaver	5649	4548	4472

Potential for Severe Crown Fire Behaviour

Continuous or "active" crown fires are very difficult to suppress and are, therefore, of major concern when planning protection of values at risk. Crown bulk density (CBD) is recognized as an important fuel complex variable that influences the type of crown fire behaviour exhibited by a particular fire. Using criteria described by Van Wagner (1977), Cruz et al (2005) developed an empirical model to predict the transition point between "passive" (i.e., predominantly surface fire with occasional torching of crowns) and "active" crown fire behaviour, based on specific values of CBD for a range of 10-m open wind speed and estimated fine fuel moisture, as described by Rothermel (1983). For the sites we examined, we used this model to display the effect on the threshold between active and passive crown fire that resulted from reducing crown bulk density by partial cutting (Figure 8). In all cases, more extreme wind and fuel moisture conditions would be required to sustain an active crown fire after partial cutting, with the magnitude of this effect varying with the intensity of removal at harvest and the species composition. The largest effects were observed on sites with the heaviest removals and least amount of non-pine species retained in the post-treatment stand.

a) Lodgepole

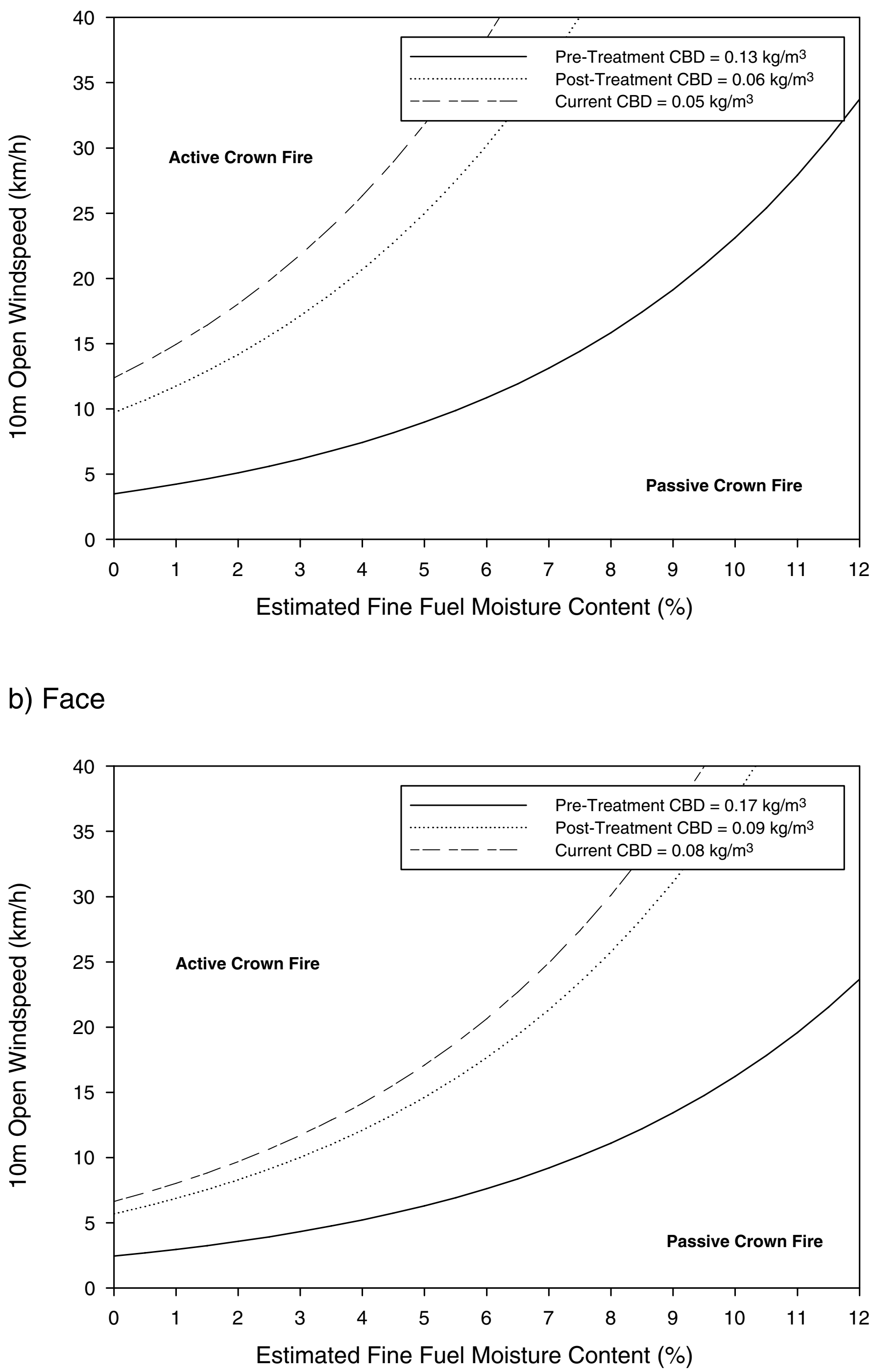
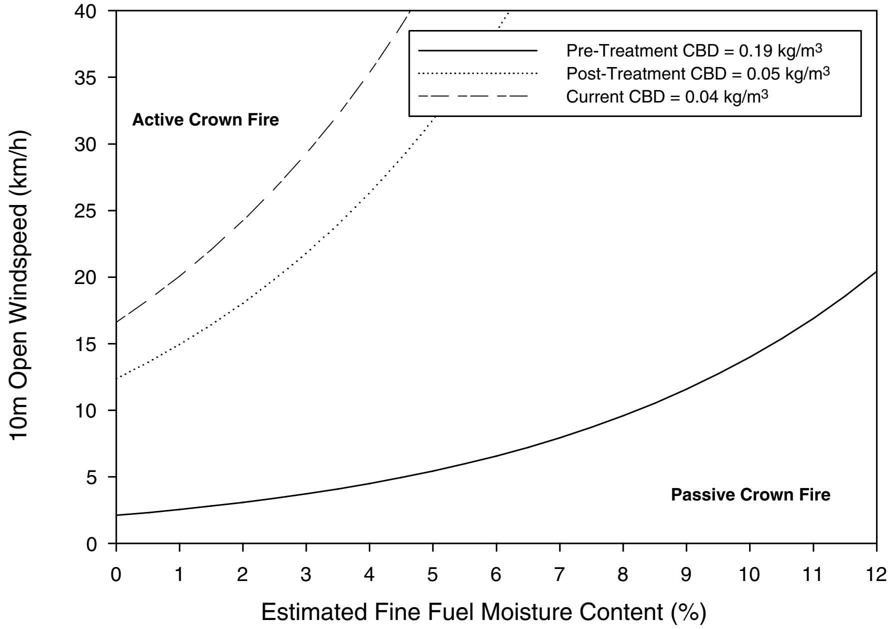


Figure 8 (a, b). Combinations of 10-m open wind speed and estimated fine fuel moisture content required to transition from passive to active crown fire for calculated site-specific crown bulk densities

c) Hobo



d) Hurst

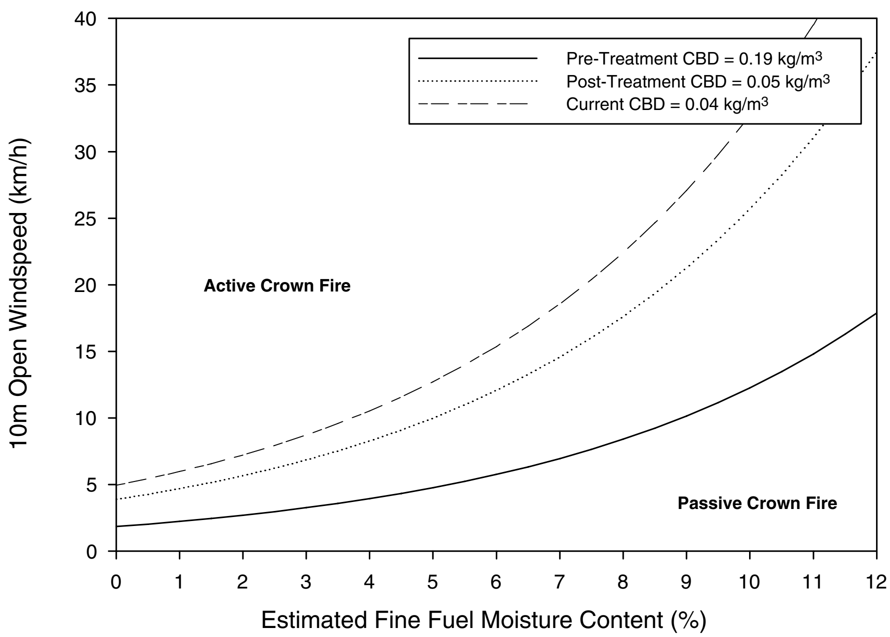
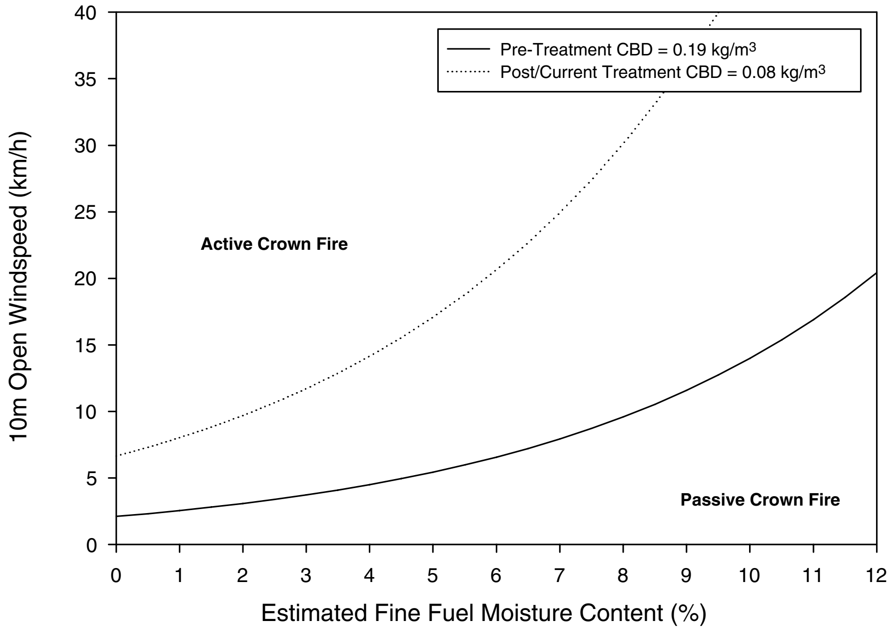


Figure 8 (c, d). Combinations of 10-m open wind speed and estimated fine fuel moisture content required to transition from passive to active crown fire for calculated site-specific crown bulk densities

e) Whiskey



f) Frost

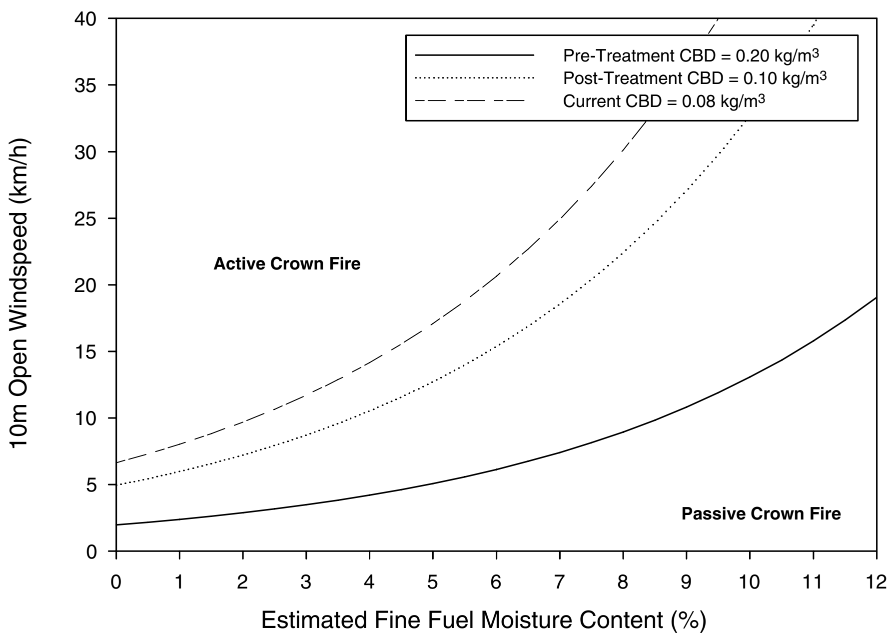
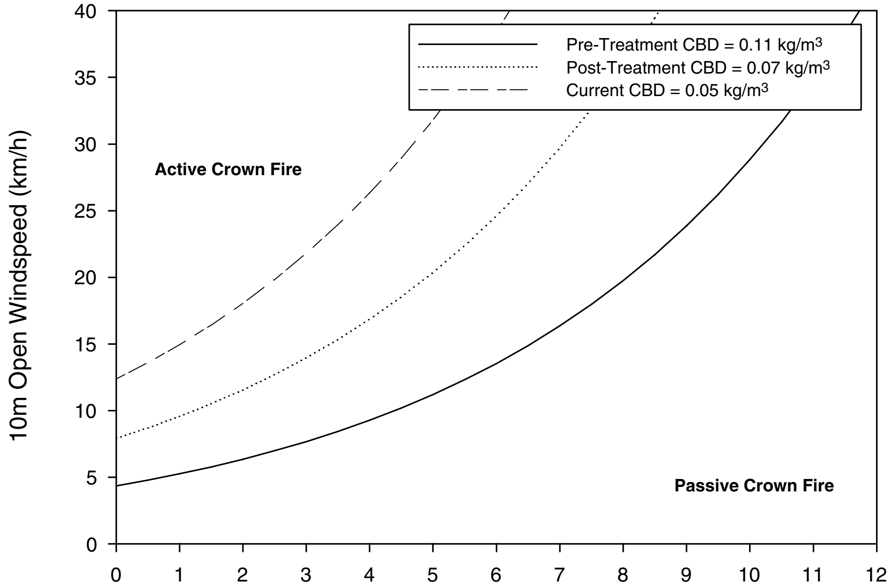


Figure 8 (e, f). Combinations of 10-m open wind speed and estimated fine fuel moisture content required to transition from passive to active crown fire for calculated site-specific crown bulk densities

g) Fran



h) Park

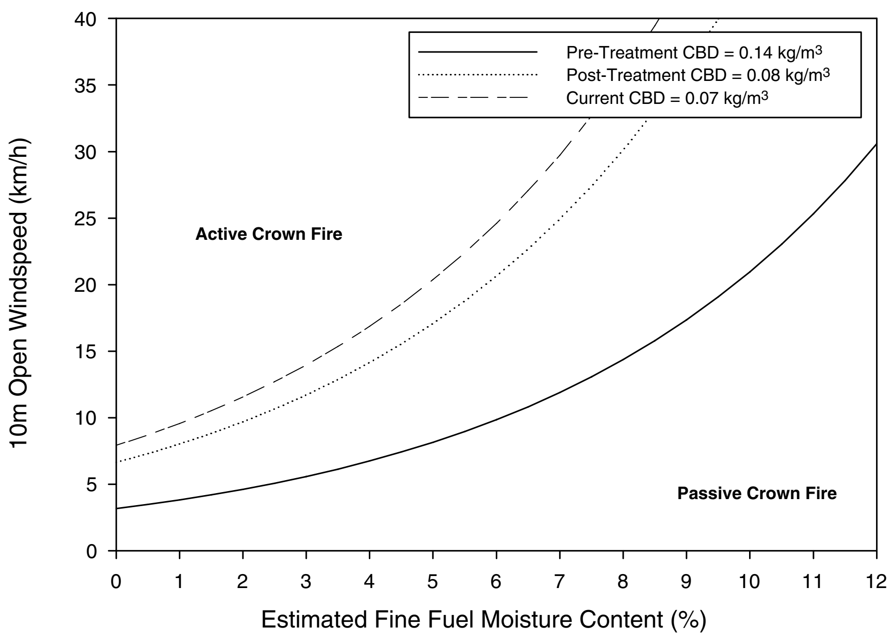
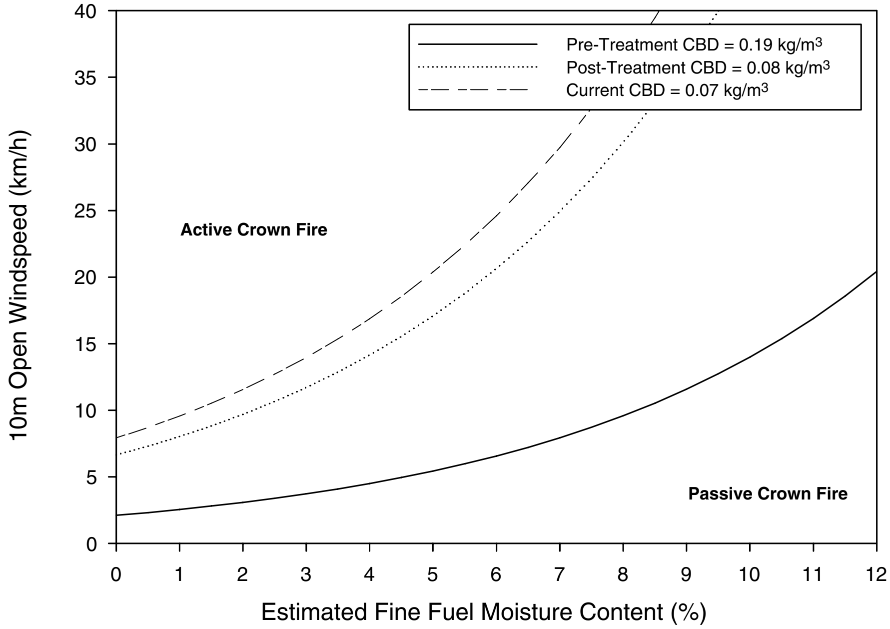


Figure 8 (g, h). Combinations of 10-m open wind speed and estimated fine fuel moisture content required to transition from passive to active crown fire for calculated site-specific crown bulk densities

i) Boyce



j) Beaver

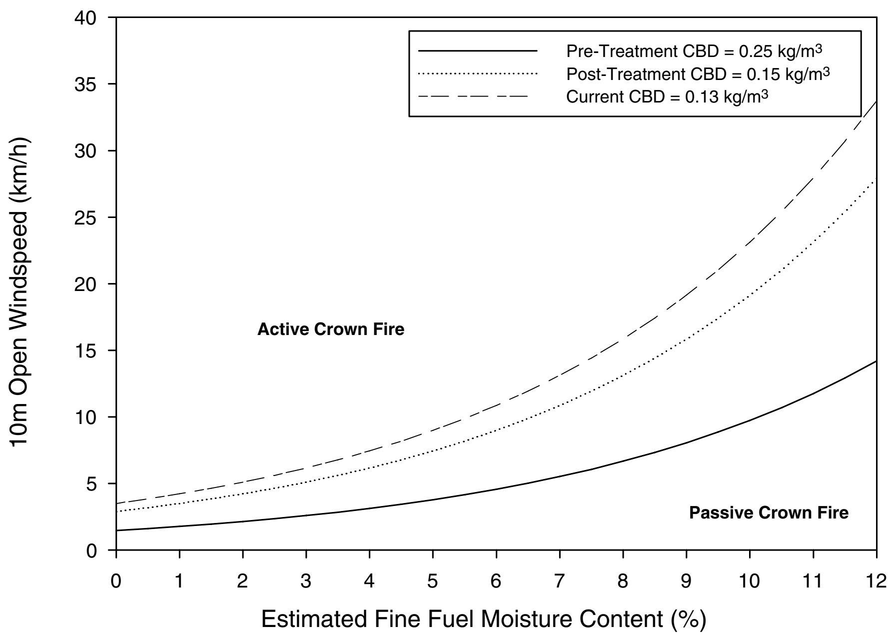


Figure 8 (i, j). Combinations of 10-m open wind speed and estimated fine fuel moisture content required to transition from passive to active crown fire for calculated site-specific crown bulk densities

For example, at Hobo, where CBD was reduced from 0.19 kg/m^3 to 0.05 kg/m^3, wind speed required for active crown fire was 4.5 km/hr prior to harvest, when fine fuel moisture content is very low (4%). Following treatment (CBD = 0.05 kg/m^3), the wind speed required for active crowning is 26 km/hr and 35 km/hr in the current stand (CBD = 0.04 kg/m^3). In contrast, if the same fine fuel moisture conditions were present at the Beaver site, where harvest was less intense and spruce was more common in the residual stand, the wind speed required to support an active crown fire was only 3 km/hr prior to treatment (CBD = 0.25 kg/m^3), 6 km/hr following treatment (CBD = 0.15 kg/m^3), and 7.5 km/hr in the current stand (CBD = 0.13 kg/m^3; these examples illustrate effects of changes in CBD, and are not specific to particular site associations; as Beaver is located in the MSdk(05), a fine fuel moisture content as low as 4% would be rare.). It is important to note that selective cutting intended to accelerate succession to a non-pine–dominated stand implies crown expansion of Layer 2 spruce or Douglas-fir and growth of the understorey into the upper crown, which will increase CBD and result in more severe fire behaviour as the fuel complex changes over time.

Winds up to 10 km/hr are not uncommon during the fire season, so the effect of thinning stands at sites similar to Beaver may seem academic. To further explore the practical significance of the model outputs discussed above, we examined available historical records from the B.C. Ministry of Forests and Range fire weather stations that would normally be used for fire behaviour prediction or suppression planning at the sites we examined. Table 16 presents the approximate equivalents between Fine Fuel Moisture Code (FFMC) and Rothermel's (1983) estimated fine fuel moisture content we used when examining the databases. Table 17 presents the frequency of occurrences for combinations of 10-m open wind speed at 1600h and daily FFMC that the model predicts would result in active crown fire on days above the 70th percentile for FFMC (89).

The influence of stand density, species composition and stand structure at different sites before and after treatment are pronounced. Before treatment, active crown fires would have been possible on 1% to 5% of the days for which we have weather data available at Lodgepole, Park and Fran, on 8% to 11% of the days at Face, Boyce, Whisky and Hobo, and on 16% to 20% of the days at Beaver, Frost and Hurst. After partial cutting, conditions that would support active crown fire were infrequent at all sites. After harvest, active crown fire was predicted by the model for less than 1% of the time at 7 of the 10 sites, 3% of the time at Frost, and 6% of the time at Beaver and Hurst. Although none of the prescriptions for these sites specified any fuel management objective, partial cutting achieved results of considerable practical significance for fire suppression planning.

Table 16. Approximate equivalents between estimated fine fuel moisture and FFMC

Estimated Fine Fuel Moisture Content (%)[1]	1	2	3	4	5	6	7	8	9	10	11	12
Approximate FFMC equivalent	100	99	98	97	96	95	94	93	92	91	90	89

[1] Described by Rothermel (1983)

Table 17. Expected fire behaviour based on historical fire weather records and model outputs for crown bulk density before and after partial cutting

Weather Station	Site	Treatment	CBD kg/m^3	FFMC < 89 # Days (%)	FFMC >= 89 # Days (%) Passive	FFMC >= 89 # Days (%) Active
Flathead2 (1993 - 2006) Total Days = 2156 Lat. 49º 04’ 15’’; Long. 114º 32’ 14’’ Elevation: 1311m	Lodgepole	Pre	0.13	1436 (67)	686 (32)	34 (1)
		Post	0.08		720 (33)	0 (0)
		Current	0.07		720 (33)	0 (0)
Whiskey (1995 - 2006) Total Days = 2024 Lat 5º1 03’ 55’’; Long. 116º 47’ 06’’ Elevation: 1300m	Whiskey	Pre	0.19	1386 (68)	417 (21)	221 (11)
		Post	0.08		637 (31)	1 (<1)
		Current	0.08		637 (31)	1 (<1)
	Hobo	Pre	0.19	1386 (68)	417 (21)	221 (11)
		Post	0.05		637 (31)	1 (<1)
		Current	0.04		637 (31)	1 (<1)
	Face	Pre	0.17	1386 (68)	480 (24)	158 (8)
		Post	0.09		633 (31)	5 (<1)
		Current	0.08		637 (31)	1 (<1)
Marion (1994 - 2006) Total Days = 2082 Lat 51º 02’ 32’’; Long. 116º 21’ 50’’ Elevation: 1300m	Park	Pre	0.14	1405 (67)	591 (29)	86 (4)
		Post	0.08		674 (32)	3 (<1)
		Current	0.07		676 (32)	1 (<1)
	Boyce	Pre	0.19	1405 (67)	465 (23)	212 (10)
		Post	0.08		674 (32)	3 (<1)
		Current	0.07		676 (32)	1 (<1)
	Beaver	Pre	0.25	1405 (67)	345 (17)	332 (16)
		Post	0.15		559 (27)	118 (6)
		Current	0.13		619 (30)	58 (3)
Brisco (2004 - 2006) Total Days = 532 Lat 50º 49’ 09’’; Long. 116º 14’ 41’’ Elevation: 930m	Frost	Pre	0.20	354 (66)	78 (15)	100(19)
		Post	0.10		162 (31)	16 (3)
		Current	0.08		170 (32)	8 (2)
	Hurst	Pre	0.21	354 (66)	73 (14)	105 (20)
		Post	0.12		145 (28)	33 (6)
		Current	0.10		162 (31)	16 (3)
	Fran	Pre	0.11	354 (66)	151 (29)	27 (5)
		Post	0.07		176 (33)	2 (<1)
		Current	0.05		178 (34)	0 (0)

Note: The Fine Fuel Moisture Code (FFMC) is a component of the Canadian Fire Weather Index System (Van Wagner 1987). It is a numeric rating of the moisture content of litter and other cured fine fuels calculated from standard fire weather station outputs.

Summary and Recommendations

The 10 sites we examined had been selectively harvested with reduction of stand-level susceptibility to mountain pine beetle as one objective of treatment. Harvest entries, which were characterized as either initial cuts of a shelterwood system or as commercial thinning, removed between 100 m^3 to 200 m^3 of merchantable volume and left 120 m^3 to 234 m^3 5 to 14 years after harvest. In 8 of 10 cases, the average piece size of residual trees was considerably larger than those removed during the harvest entry.

Variations in the original stand composition and in the way cutting prescriptions were applied and tailored to accommodate other management objectives produced a range of post-treatment stand compositions and structures. For discussion, it is useful to consider two main groupings: stands that were predominantly lodgepole pine overstorey with poorly developed intermediate and sapling layers before and after cutting, and stands which had a significant component of spruce (and sometimes other non-pine conifers) in the overstorey or intermediate and sapling layers before harvest, which formed an even more prominent part of the stand after selectively harvesting the pine overstorey.

There was no evidence of any developing infestation by mountain pine beetle at the six sites where wide spacing of a predominantly pine overstorey was achieved and sparse intermediate and sapling layers ensured that the lower tree boles were exposed to increased solar radiation and wind after harvest. In contrast, three of the four sites with recent beetle attack had a significant spruce component in Layers 1 and 2, and the fourth had dense non-pine sapling and regeneration layers that likely impeded penetration of sunlight and wind after harvest. Retention of unspaced patches or large numbers of full-crowned trees, saplings and advanced regeneration is not recommended when beetle proofing the stand is a high-priority objective, because they shade the lower tree boles and block within-stand winds, favouring successful host location and attack, and providing centres for initiation of patch infestations in treated stands.

There was evidence of attack soon after harvest on three sites where pheromone baits had been deployed to concentrate beetle populations in the stand before harvest. Pheromone baiting prior to selective harvest is not recommended, because beetles remaining in stumps or missed residual trees may produce enough beetles after harvest to overcome healthy residual trees and contribute to risk of successful infestation.

Partial cutting late in the rotation of a previously unmanaged stand will increase risk of wind and snow damage as crown exposure to winds is increased and the damping effects of crown contact between trees are reduced. The proportion of merchantable volume lost since treatment ranged from 1.6% (4.0 m^3/ha) where the lightest harvest entry removed 39% of the original merchantable volume to 18.3% (27.5 m^3/ha) where the most aggressive harvest entry removed 57% of the original volume and left intertree spacing greater than 5 m in parts of the stand. Risk of significant damage is higher at the widest spacings, and it is recommended that mature pine should not be thinned to more than 5-m spacing.

Areas of particular hazard to wind and snow damage are generally predictable and should not be selectively harvested. They can usually be identified during the prescription process through careful consideration of terrain and soil characteristics in conjunction with stand and tree characteristics. Smaller-diameter, slender trees with limited root development are most vulnerable and are generally found in previously unmanaged stands in small patches with more than about 1700 trees/ha. Clearfelling in a group selection or reserving these denser patches until the final removal cut is recommended.

The largest increases in periodic annual increment for pine were seen at sites with a relatively high proportion of pine before and after harvest and where removals targeted the smaller trees. On sites with a high component of spruce and significant understorey development, there was no clear evidence of a pronounced change in mean annual ring width for residual pine overstorey following harvest; we did not measure growth response in other species.

At all sites, the majority of assessment plots met stocking standards for partially cut stands in the Rocky Mountain Forest District. There was some potential to increase volume production through fill planting identified on most sites, but given the temporary nature of reduced stocking in the case of a commercial thinning or initial cut of a shelterwood, we feel it would be more efficient to address fill planting after final overstorey removal.

Although none of the prescriptions for these sites specified any fuel management objective, we found that changes in stand structure were generally beneficial from this perspective. All sites were harvested with full tree removal for processing and debris disposal at the landing or roadside, and surface fuel loading at all sites 5 to 14 years later was remarkably low. The amount of down and dead woody fuel that was smaller than 3 cm in diameter ranged from 0.17 kg/m^2 to 0.35 kg/m^2, which suggests that ignition potential at this time on these sites is relatively low, although the effects of increased near-surface winds after selective harvest have not been demonstrated.

Live canopy base height determined from modeling was also very high in all stands (8.9 m to 12.5 m) suggesting that there would be little potential for crown fire development, given the low surface fuel loading. Sites that were thinned from below and where there was little or no non-pine component pre-harvest are least likely to develop crown fires from surface ignitions, because surface and crown fuels are widely separated, and few ladder fuels, if any, are present. These sites are therefore likely to remain at relatively low hazard until the final overstorey is removed at rotation. However, the presence of ladder fuels on sites with a significant component of spruce in the overstorey, intermediate, and sapling layers provides a conduit for crown fire development at lower surface fire intensities on these sites; this problem usually increases with time as crowns develop.

In all cases, the potential for active crown fire was reduced after partial cutting (i.e., more extreme wind and fuel moisture conditions are required to sustain an active crown fire), but the magnitude of this effect varies with the intensity of removal at harvest and the species composition after harvest. The largest effects were observed on sites with the heaviest removals and least amount of non-pine species retained in the post-treatment stand. The objective of partial cutting may be to accelerate succession to a non-pine–dominated stand, but expanding crowns of Layer 2 spruce or Douglas-fir and growth of the understorey into the upper crown will increase Crown Bulk Density and may result in more severe fire behaviour as characteristics of the fuel complex change.

If operations wish to optimize the effects of selective cutting for fuel management objectives, we recommend the best sites for treatment are those with a predominantly pine overstorey and sparsely developed understorey, that residual trees be uniformly spaced by thinning from below while surface fuel accumulations are kept as low as possible, and that full-crowned trees, poles and saplings should be targeted for removal rather than retention. This prescription is also optimum for reducing stand susceptibility to mountain pine beetle.

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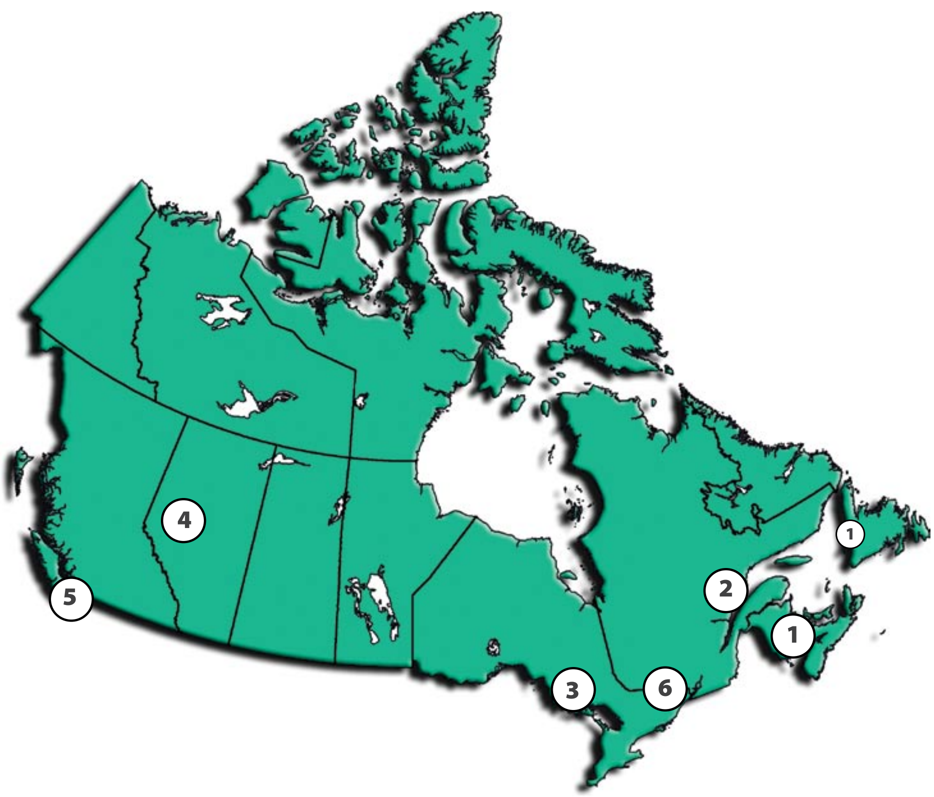

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