FOREST FUEL TREATMENT EFFICACY IN BC

Two Case Studies: Thinning and Broadcast Burning

Prepared For:
The B.C. Wildfire Service,
Ministry of Forests, Lands, Natural Resource Operations and Rural Development

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EXECUTIVE SUMMARY

Objectives and Scope

This project was initiated in 2019 by the B.C. Wildfire Service (BCWS), a branch of the Ministry of Forests, Lands, Natural Resource Operations and Rural Development. The project evaluated the effectiveness of fuel treatments in British Columbia (B.C.), identified knowledge gaps and data needs respecting fuel treatments and recommended ways to advance implementation of the fuel treatment program. The project was limited to interactions between wildfires that occurred within the last ten years and fuel treatments that occurred within the previous 25 years.

Methods

The project's first phase involved interviews with fuel management experts to better understand what treatments had been used historically and identify examples of where fuel treatments had interacted with wildfire. A review (and summary) of relevant literature was also completed to explore fuel treatment efficacy methodologies and identify what other researchers found effective. Based on this first phase, a work plan was prepared, and candidate study sites were selected based on expert advice, BCWS records, the B.C. Government RESULTS database, information from the Strategic Wildfire Protection Initiative (SWPI), and satellite and aerial imagery. Fuel treatments were found to be one of two types: i) thinning/debris disposal/ladder fuel removal or ii) broadcast burning. Only ten thinning/debris disposal sites and five broadcast burning sites were sufficiently large, with enough supporting data for field assessments. Field measurements focussed on the Fire Environment (topography, stand structure and fuels), Pre-Fire Fuel Treatments, Wildfire Chronology and Development (fire weather, indices, ignition, spread rate, intensity, size), Suppression Actions, and Treatment Impacts/Efficacy (treated stand versus untreated). A paired plot approach was used whenever possible to compare data collected in areas treated with those not treated during field data collection. Analysis of each type of treatment was described in a separate case study. A case study approach was used because of the scarcity of fuel treatments that had interacted with wildfire and because the variables influencing fire behaviour are too complex to use a solely statistical approach. A preliminary examination of potential fire behaviour was also made using fire behaviour predictions systems such as the BCWS Critical Surface Fire Intensity worksheet and CanFire (a Canadian Forest Service fire model). Results were compared to fire behaviour inferred from observed impacts in the field.Key Findings

Fuel treatments for both case studies spanned a range of biogeoclimatic zones in B.C.'s interior. The broadcast burning case study also included two coastal sites. Supporting documentation regarding fire weather was available for all sites, but prescription details and suppression reports were unavailable for some sites. There were not enough examples of wildfires interacting with fuel treatments in either case study to answer all the questions that arise when pondering which fuel treatment to use, how much surface fuel to tolerate, how frequently to retreat a fuel break, or how big an area should be treated for every combination of fuel type, weather condition, or environmental condition in B.C, however, the study did provide some insights. Some of the more critical findings included:

1. Fuel treatments involving thinning, debris removal, and ladder fuel reduction affect wildfire behaviour positively, and they are feasible at a larger scale.

2. Despite the past use of short, thin, linear strips in the C3, C4, and C7 fuel types associated with the thinning and debris disposal treatments, fire impacts (scorch height, tree mortality, and crown

involvement) were still modified at most sites, even with relatively high-intensity fires (>2000 kW/m).

3. Post-treatment crown spacing can be highly variable (clumpy) and still reduce crown fire and tree mortality if; there are frequent larger gaps (5 to 10m), canopy closure is less than 50% (it was more typically 25%), and leaving thickets of smaller stems that serve as ladder fuels (particularly in interior Douglas-fir stands) is avoided.

4. Fuel treatment that left loading as high as 25 tonnes/ha (~5 tonnes/ha was more typical) still positively influenced fire behaviour in terms of tree mortality and crown involvement as long as fuels were dispersed or patchy.

5. In this study, it did not appear that any of the thinning and debris disposal treatment areas were large enough to be used in suppression efforts (for example, to be used as anchor points, or for back burning, or to slow fire progress to provide more time for suppression personnel), except at the Nazko South site.

6. Treatments were generally located where there was a heightened risk to human property and life. However, it did not appear that they were necessarily strategically located with respect to surrounding fuel types, topography, and areas of fire resistance. In the provincial strategic threat analysis, they occupied a very small fraction of the area classified as high or extreme threat. Several authors in other jurisdictions express the need for a landscape approach, with larger treatment units and a much higher proportion of the landscape treated, to positively impact fire spread, fire intensity, and suppression capability.

7. Broadcast burn treatments evaluated in this project were generally older than the thinning and debris disposal treatments and likely conducted to achieve silviculture objectives rather than fuel management objectives. As a result, these treatments were less effective in influencing wildfire behaviour than the thinning and debris disposal treatments. However, they may not reflect what could be achieved today with a fuels-oriented approach and new tools to forecast fire behaviour. Nonetheless, broadcast burning is not an easy tool to use because of the many variables involved, uncertainty about the weather, and the potential magnitude and consequence of an escape burn.

8. Fire behaviour prediction tools tested in this study revealed a lack of current data on expected post-harvest or post-infestation fuel loading. Several examples of fuel types in B.C. are not well described in the Canadian Forest Fire Behaviour Prediction System. In addition, the models and calculators in use today are not always adapted for use in comparing fire behaviour before and after fuel treatments and are sometimes very sensitive to some input variables. Both these findings impede the ability of fuel managers to plan fuel reduction strategies.

9. As was the case with the thinning/debris disposal/pruning treatments, the geographic location of a treatment unit as it relates to topography, resistant fuel types, and values at risk is important in terms of wildfire mitigation. Landscape level planning will help identify where fuel reductions can be most useful, but if broadcast burning depends on the relatively random selection of blocks that are burned for other reasons (to meet abatement requirements or for silvicultural purposes, for

example), then the treatment may not be helpful in terms of meeting wildfire management objectives.

Recommendations

In addition to some specific practical suggestions provided at the end of the report (not repeated here), there were a number of recommendations that are broader in scope as follows:

1. Given the cost of thinning and debris disposal fuel treatments ($1800 to $3800/ha) and the potential costs of catastrophic wildfire, there is a need for increased investment in the science that underpins fuel treatment decisions and treatments. Some examples include:
    a. Conducting controlled burn experiments at, for example, 90th percentile weather indices to quantify the effectiveness of fuel treatments in fuel types that are most at risk.
    b. Quantifying fuel treatment longevity and the need for fuel break maintenance on selected sites in the most commonly burned fuel types by describing and quantifying the build-up of fuels year over year.
    c. Quantifying the influence of prior burn mosaics on subsequent wildfire behaviour.
    d. Quantifying the impact of repeated treatments.

    These types of investments will not only improve understanding of fuel treatment efficacy but also provide important training opportunities for suppression personnel and fuel managers implementing fuel treatments.

2. Given that fire behaviour models and calculators have the potential to provide answers to fuel management questions like how much fuel can be tolerated, how large do fuel treatments need to be, and when and where they should be used, consideration should be given to supporting their continued development and adapting them to be used in modelling fuel treatment impacts. Providing more training to a broader range of fire management personnel within government and industry could be part of such an approach.

3. Augmenting fuels management in the province will require increased effort in collecting supporting data and reporting treatment and research results. There are a number of new data collection forms that have been developed (for example, the FP Innovations Rapid Response Kit: Data Collection Methods For Documenting Encounters Between Wildfires and Forest Fuel Treatments) and a new system in the provincial RESULTS database for reporting "*projects involving wildfire risk reduction..",* and next steps for the BCWS could include more training in the use of these forms and a mechanism (for example, a dedicated team within the BCWS that can be deployed to selected wildfires during an incident to collect the data) to help advance the use of these tools.

4. The development of key metrics for treatment success such as target surface fire fuel loads, or surface fire intensity targets and rate of spread for the most common/critical fuel types, terrain, and fire weather conditions and incorporating them into, for example, the BCWS Fuel Management Practices Guide would help facilitate more effective fuel treatment prescriptions and planning.

5. More emphasis on landscape-level fuel management planning will be required to significantly reduce wildfire impact on values at risk. The over-arching objective is to create landscape-level fuel discontinuity, and wildfire-resistant stands, by, for example:
    a. reducing fuels through timber harvesting that integrates wildfire objectives.

b. broadcast burning after logging.
c. thinning and debris disposal in strategic locations.
d. under-burning in some timber types.
e. establishing a network of wildfire-resistant second-growth stands (pine, spruce, and subalpine fir that are 20 to 40 years old).
f. encouraging deciduous stands in some areas.
g. tying fuel treatments into naturally resistant features.

6. Because timber harvesting and post-harvest treatments by forest licensees impact fuel loading at the landscape level more than any other factor, it makes sense to develop ways to engage them in achieving landscape fire management objectives. For example, during the planning process, locating harvesting in areas where there is a higher potential for a running crown fire or where, 20 years into the future, a wide area of fire-resistant second-growth close to key values will be created. Other examples include using treatments such as improved utilization, broadcast burning, and trenching (mechanical site preparation) to reduce fuel loading and break up fuel continuity at the site level, which could provide silviculture benefits as well as fire management benefits.

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- Brad Martin: B.C. Wildfire Service, Senior Wildfire Officer – Prevention, NW Fire Centre
- Andrew Flockhart: B.C. Wildfire Service, Wildfire Technician – Prevention
- Rory Colwell: B.C. Wildfire Service, Fuels Superintendent

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1. BACKGROUND

Case Study Scope and Objectives

In North America, there has been significant emphasis on fire suppression and, until recently, less emphasis on forest fuel treatments as a preventative measure. Fuel treatments are an essential prevention tool when it comes to wildfire risk reduction (WRR) around communities and critical infrastructure. Understanding fuel treatment objectives, approaches to designing and implementing fuel treatments, and the linkages to final outcomes is fundamental to a successful WRR program. In 2019, after two consecutive record-breaking fire seasons, the BC Wildfire Service (BCWS) initiated a project to evaluate the degree to which fuel treatments have been effective in changing wildfire behaviour. The project objectives were to:

1. Describe and categorize fuel treatments that have been used in recent years.
2. Evaluate the effectiveness of fuel treatments when they have been challenged by wildfire.
3. Identify knowledge gaps and provide recommendations to improve field data collection and enable further studies.
4. Provide recommendations for program tools and guidance for implementing a fuel treatment program.

In this project, a case study approach was used to evaluate fuel treatment efficacy due to a scarcity of treatments that have interacted with wildfire and because the variables influencing fire behaviour are too complex to use a solely statistical approach. The scope of the project was restricted to treatments within the last twenty five years that interacted with wildfires that occurred in the last ten years. These time envelopes were chosen on the basis that there would be a reasonable chance that records would be available and that outcomes would still be distinguishable during field evaluations.

In a GIS analysis of fuel treatments and wildfires that had occurred in the last ten years across B.C., we found that there was sufficient information to draw reasonable conclusions on only fifteen treatment sites. These sites tended to be relatively small in size and located near infrastructure. This finding is consistent with broader findings elsewhere. In a publication on the *Effectiveness of Fuel Treatments For Mitigating Wildfire Severity*, Omi and Martinson (2009)[1] reviewed over 1,200 publications worldwide regarding fuel treatment efficacy and found only sixty two that documented the performance of actual fuel treatments. Of these, only nineteen had sufficient control for variations in weather, topography, and impacts to be used to evaluate efficacy. One possible reason for the lack of fuel treatments interacting with wildfire in B.C. was that program funding up until 2017 came mainly from the Strategic Wildfire Prevention Initiative (SWPI), which targeted only those areas that were classified as high and extreme fire threat and located in the wildland-urban interface (WUI).

Methods

A list of potential sites from across the province was compiled using the following data sources:

1. The B.C. Government's Wildfire Service records on fires in the last 10 years.
2. Information from the Strategic Wildfire Protection Initiative on fuel treatments.
3. Treatment history in harvested areas obtained from the B.C Government's provincial RESULTS database.

[1] Omi, PN and EJ Martinson. 2009. Effectiveness of Fuel Treatments for Mitigating Wildfire Severity: A Manager-Focused Review and Synthesis. JFSP Project Number 08-2-1-09.

4. Interviews with local BC government wildfire staff.
5. Satellite and aerial imagery.

All potential sites were spatially located using ArcGIS mapping tools and provided to the Wildfire Service for review and comment.

A shortlist of candidate sites was then developed, and a field reconnaissance was completed. As a result of this process, some sites were dropped because treatments were not apparent, the treatment area was too small, or there was no wildfire interaction. At sites that were considered to be suitable, information was collected using a paired plot approach where data was collected in both areas that were treated and areas that were not treated. In some cases, data from unburned areas in similar stands nearby were also used to understand pre-burn conditions better. Data collected in the field included: location, topography, ecological classification, basic soils information, understory vegetation, conifer regeneration, stand structure and volume information, coarse wood debris, fuel loading and distribution, information on non-timber values, mitigating factors, and treatment efficacy. Observations on treatment implementation and apparent fire behaviour (e.g. scorch height, burn depth, crown consumption) were also made. Associated fuel treatment prescriptions, weather data, fire reports, and any other observations or information from fire managers were also obtained where available. Drone imagery was acquired at some sites where it provided insight into fire behaviour, and conventional 35mm photos were taken at all sites. Geographic coordinates were obtained at all plots and observation points, and all photos were geotagged.

Field data was compiled in a Microsoft Excel spreadsheet and divided such that information for treatment areas was juxtaposed with paired plots that were not treated. This document is an integral part of this report and includes all data respecting each plot at each study site. An ArcGIS project map was created depicting the location of all field data points, the location of all ground-based still photography (hyperlinked to the actual photo), historic fire boundaries, cadastral features, burn severity (where available), fuel types, wildland-urban-interface risk classes, natural resource features, and the provincial vegetation resources inventory data. Satellite imagery and B.C. Government WMS imagery was used as base layers for visual reference.

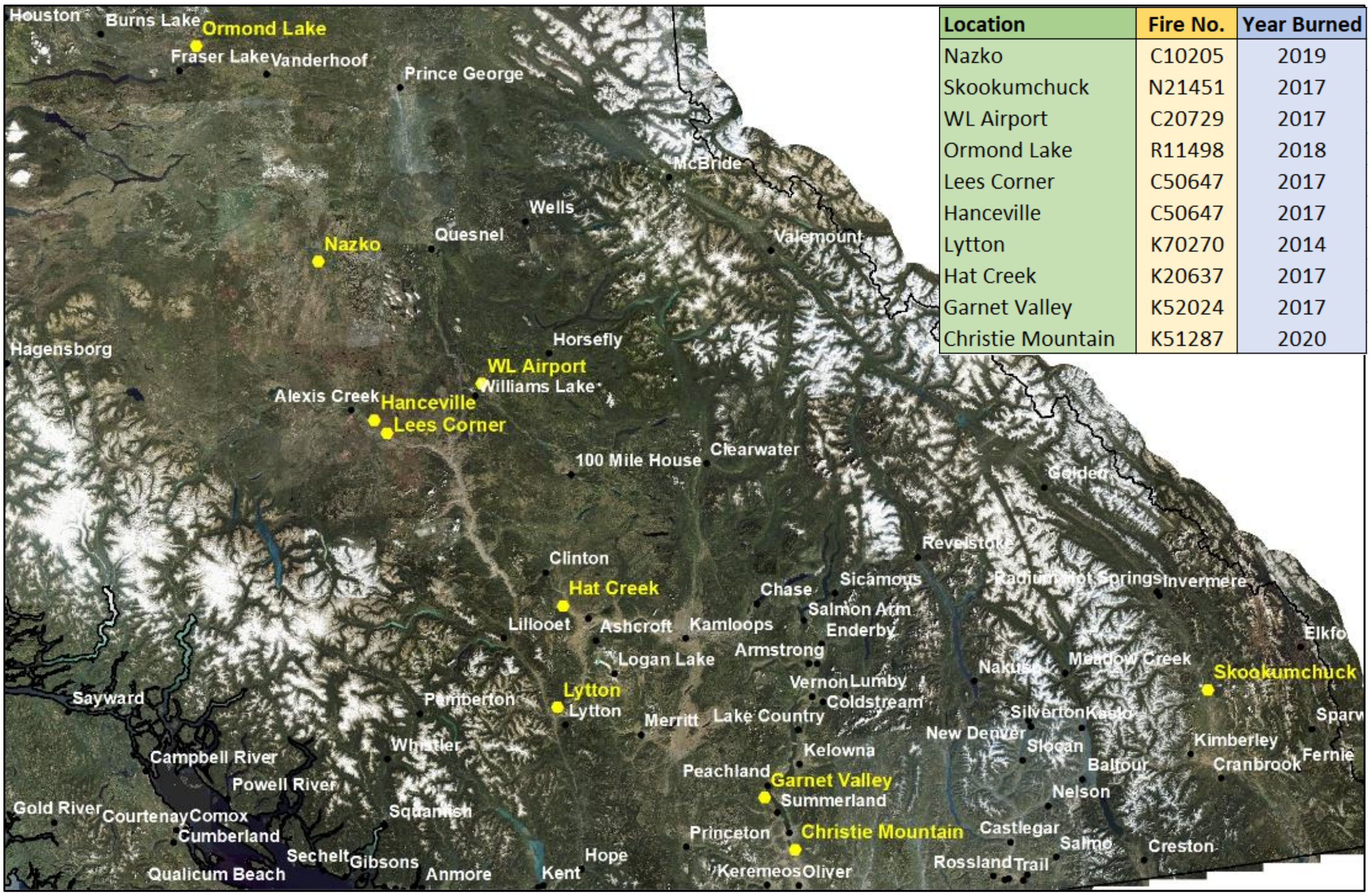
All of the treatment areas that interacted with wildfire in BC were one of two types: i) manual treatment of older stands involving stand thinning, debris disposal ± pruning, and ii) broadcast burning after timber harvesting. Each type of treatment is described in a separate case study. In both types of case studies, the Fire Environment (topography, stand structure and fuels), Pre-Fire Fuel Treatments, Wildfire Chronology and Development (fire weather, indices, ignition, spread rate, intensity, size), Suppression Actions, Treatment Impacts/Efficacy (treated stand versus untreated), and Lessons Learned are described. Recommendations for both case studies are combined in the final section of the report. Each of the case studies focuses on one or two benchmark study sites augmented with data from other sites that had the same fuel type(s) and treatments. Other sites were included in the discussion for the benchmark site(s) to illustrate how/whether changes in site condition, treatment implementation, wildfire characteristics, and suppression efforts at these other locations impacted outcomes.

2. FUEL TREATMENTS INVOLVING STAND THINNING AND DEBRIS DISPOSAL

The Fire Environment

Location

The location of the ten thinning treatment sites that had interacted with wildfire in B.C. within the last ten years that were evaluated in this case study are shown in figure 1.



Location	Fire No.	Year Burned
Nazko	C10205	2019
Skookumchuck	N21451	2017
WL Airport	C20729	2017
Ormond Lake	R11498	2018
Lees Corner	C50647	2017
Hanceville	C50647	2017
Lytton	K70270	2014
Hat Creek	K20637	2017
Garnet Valley	K52024	2017
Christie Mountain	K51287	2020

Figure 1: Geographic location of the treatments (yellow placemarks).

Fuel treatments spanned a range of biogeoclimatic zones in B.C.'s interior including the SBSmc2, SBSdw2, IDFdk3, IDFdk4, PPxh2, IDFxh2, and IDFdm2. Sites tended to be located in valley bottoms or on lower slopes, where summer conditions are warmer and dryer.

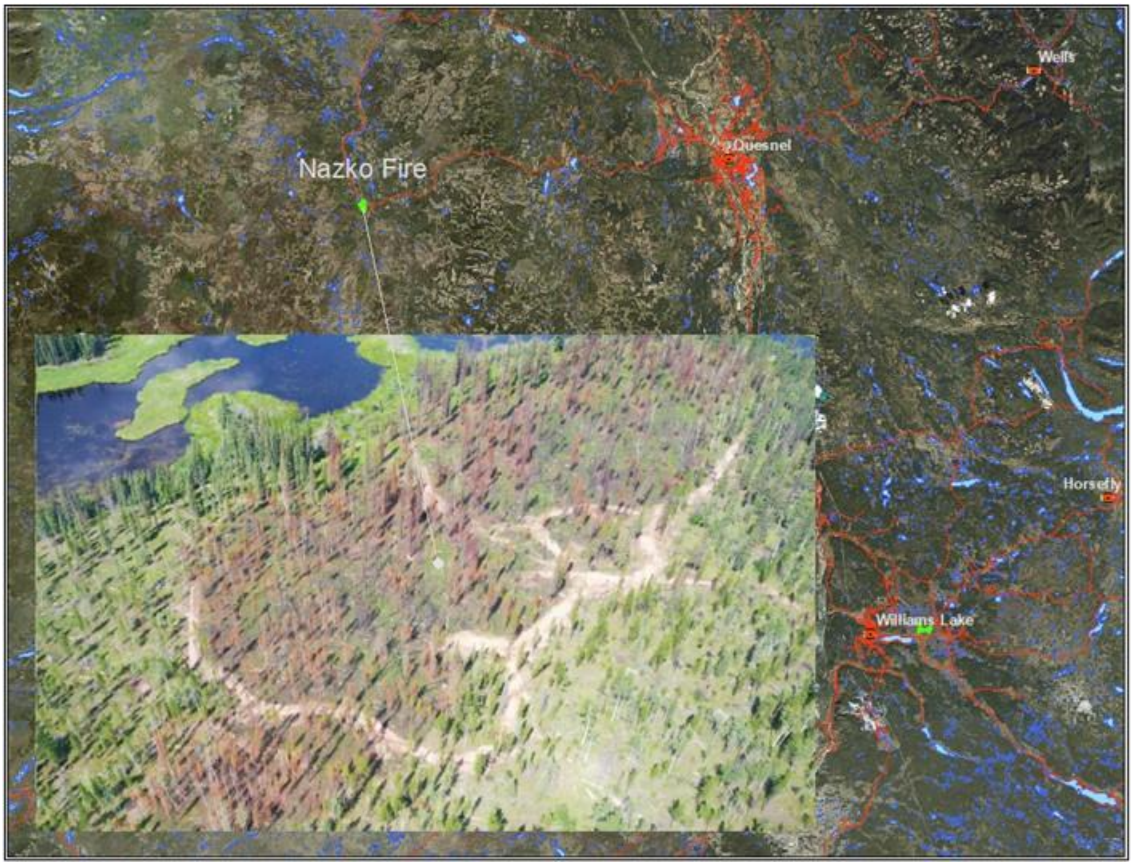


Figure 2: Geographic location of the Nazko South fire with drone image inset of the burn area.

One of the two benchmark sites for thinning, Nazko, is located in the sub-boreal spruce zone (SBSdw2), in the middle of B.C.'s central plateau, where many of the large fires over the last ten years have occurred. The other benchmark site is Christie Mountain, located in the ponderosa pine zone (PPxh1). Although the Nazko fire was small at only four ha (see figure 2), fire weather data, suppression information, and treatment information were all readily available, and fire weather conditions at the time of the fire were less extreme than many of the larger fires and, therefore, possibly more indicative of conditions under which fuel treatments might be successful. The Christie Mountain fire was chosen because both treatments and the wildfire were recent, and it was more indicative of the Douglas-fir ponderosa pine fuel type common at all the other sites except Ormond Lake.

Topography

All the study sites tended to occur on rolling or undulating terrain, on a variety of aspects on lower slopes or valley bottoms, and slope always averaged less than 20%. Elevation varied from 500 m to 1100 m. At the Nazko South benchmark site, the terrain in the burned area was nearly flat with a 2% NW slope at an elevation of about 845m. The area was undulating to even and relatively uniform. Slope-induced fire behaviour would not have occurred at this site. Table 1 summarizes key physiographic attributes for each site.

Table 1: Physiographic characteristics of each of the Thinning study sites.

Location	BEC Unit*	Terrain	Aspect	Slope Range	Elevation Range
Nazko	**SBSdw2**	**Flat**	**NW**	**0 to 5**	**830 to 860**
Ormond Lake	SBSdw3	Undulating	S	0 to 7	840 to 850
Williams Lake	IDFdk3	Rolling	NW	0 to 5	915 to 935
Hanceville	IDFdk4	Undulating	SW	0 to 5	1100
Lees Corner	IDFdk3	Flat	Flat	0 to 2	1070
Hat Creek	PPxh2	Rolling	S, W	5 to 40	615 to 681
Lytton	IDFxh2	Undulating	SE, SW	5 to 35	665 to 720
Garnet Valley	PPxh1	Undulating	E, SW	5 to 30	680
Christie Mountain	PPxh1	Rolling	W	20 to 40	510 to 560
Skookumchuck	IDFdm1	Flat to Rolling	E, W	5 to 30	895 to 920

* Biogeoclimatic zone, subzone, and variant.

Fuels

Post-treatment statistics on stand structure for all 10 study sites are summarized in table 2. Crown values are from treated areas that were not burned in the wildfire where available. Otherwise they were inferred from residual dead stems (e.g. Ormond Lake and Hat Creek). Shrub and herb percent cover values represent what was present at the time of the survey (post-treatment and post-wildfire).

Table 2: Post-treatment stand structure data for selected variables at the Thinning study sites.

Location	Tree Species	Stand Age	Stand Ht (m)	Live Vol (m3/ha)	Dead Vol (m3/ha)	%Crown Closure	Crwn Base Ht (m)	%Live Crwn	Shrub % Cover	Herb % Cover
Nazko	**Pl7Sx2At1**	**50**	**10**	**0**	**12**	**20**	**3**	**60**	**25**	**80**
Ormond Lake	PL9Sx1	100	14	37	50	25	1-3	65	50	30
Williams Lake	Fd10	115	12	56	5	50	6-9	50	1	98
Hanceville	Fd9At1	90	12	36	9	50	3-6	65	1	90
Lees Corner	Fd9Pl1	150	15	45	20	25	2-5	80	1	90
Hat Creek	Fd9Py1	50	11	0	29	5	1-4	85	1	75
Lytton	Fd9Py1	100	20	67	0	10	6-12	50	20	75
Garnet Valley	Py9Fd1	105	15	20-80	0-65	10-25	8(Py), 2(Fd)	50-80	2-15	75
Christie Mountain	Py7Fd3	40-180	20-30	200	unknown	15-40	1-8	50-90	5	10-80
Skookumchuck	Fd9Pl1	70-100	10-14	0-50	0-50	8	3-8	50-95	8	100

Stand density, including L3 and L4 layers prior to treatment, was variable (300 to 3000 stems/ha), with the smaller Sx acting as a ladder fuel. Stand density in the treated area was 200 to 400 stems/ha in the L1/L2 layer (≥7.5cm dbh) and 100 to 500 stems/ha in the L3/L4 layers (<7.5 cm dbh). Live merchantable stand volume in the treated, unburned area at the Nazko site was low at less than 30m^3/ha. Based on data from the unburned, treated area, as well as remaining evidence in the burned and treated area, the pre-wildfire fuel type at the Nazko site, with a stand age of 30 to 70 years, would be best described as a mix of immature lodgepole pine (C4) and mature lodgepole pine (C3) – see figures 3 and 4. The species composition in the treated area was Pl7Sx2At1 with a stand height of 10m (6 to 11m), a crown base height of 3m (2 to 6m), a live crown of 60% (Pl) to 80% (Sx), and relatively low canopy bulk density.

Figure 3: Nazko site: untreated, no wildfire.

Figure 4: Nazko site: Thinned, piles burned, wildfire.

Understory shrubs in the treated area at Nazko were less than 1.0 m tall with 10 to 25% cover, and there was a considerable amount of flashy, herbaceous cover (80%) that was primarily grass and fireweed. The term *flashy* assumes that grass and herbs are cured (dead and dry) and could ignite easily and carry a wildfire in the early spring before new growth occurred, or late in the summer or fall when the new growth is dead and dry. Other sites in the study also had relatively open canopies with low overstory volumes (except Christie Mountain), low to moderate crown closure, low to moderate shrub cover, and higher cover of grass, fireweed, coltsfoot, and other herbs. Sites in the Ponderosa Pine (PP) biogeoclimatic unit were more open than the Subboreal Spruce (SBS) or Interior Douglas-fir (IDF) sites, and surface fuels had a higher component of herbs and grasses than at the SBS sites. Trees at the IDF sites were generally taller (9 to 20m), there were more stems per hectare in the L1/L2 tree layer (200 to 1200), and crown base height was higher. Table 3 summarizes woody debris and duff depths at the study sites. Fuel loading values reported in table 3 at the Ormond, Williams Lake Airport, Hanceville, Lees Corner, Hat Creek, and Skookumchuck sites represent post-treatment conditions after the wildfire passed through the area (highlighted with light grey fill in table 3). There were no examples available of a treated area that did not burn in the wildfire. At the other four sites, there were representative areas that were treated but not burned in the wildfire.

Table 3: Post-treatment woody debris levels and duff depths at the Thinning study sites.

Location	CWD >12.5 cm diam. (Tonnes /Ha)	% Cover CWD >12.5 cm Diam.	% Cover Fine Debris 7.5 cm to 12.5 cm Diam.	% Cover Fine Debris <7.5 cm Diam.	Woody Debris Continuity	Duff Depth (cm)
Nazko	**5-28**	**3**	**3**	**5**	**Semi-Cont.**	**1**
Ormond Lake	2	1	1	1	Dispersed	<1
Williams Lake	1-15	2	0	0	Dispersed	<1
Hanceville	1	1	<1	<1	Dispersed	<1
Lees Corner	1	1	<1	<1	Dispersed	<1
Hat Creek	5	1	1	1	Dispersed	<1
Lytton	9	1	1	1	Patchy	1-2
Garnet Valley	35	10	1	2	Patchy	2-13
Christie Mountain	5	<1	<1	<1	Dispersed	2(13)
Skookumchuck	3	1	<1	1	Dispersed	<1

The Nazko and Ormond Lake sites (northern locations) were a C3/C4 fuel type (mature or immature lodgepole pine), while the rest of the study sites fell into a C7 fuel type (Ponderosa pine/Douglas-fir). Coarse woody debris levels were low at most sites but moderate at the Nazko and Garnet Valley sites. In both cases, this was because not all piles or dispersed material that had been felled was burned during treatment and because there were plots for these two sites within treated areas that did not get burned in the wildfire. At all the other sites, the amount of fine material left after treatment and wildfire was very low, at less than 2% cover. Understory ladder fuels were generally low at all sites, except in occasional thickets of young Douglas-fir in the C7 fuel types. Pre-wildfire duff depth at all sites was generally less than 5 cm, typically only about one cm in most areas, but unburned (and some burned) areas in the ponderosa pine forest at Garnet Valley and Christie Mountain had areas with deep accumulations of ponderosa pine needles (up to 15 cm).

Pre-Fire Fuel Treatments

Prescriptions

Treatment prescriptions were not available for the Ormond Lake, Hat Creek, or Skookumchuck areas. Except at Christie Mountain and Nazko, prescriptions that were available were more about the management of stand structure and did not necessarily provide all the details one might like to see regarding fire management. None of the prescriptions available for any of the sites in this study discussed wildfire intensity targets, rate of spread targets, the potential for crown involvement, or 90th percentile fire weather indices. The treatment prescription available for the Nazko site was from 2015 and included the area in the wildfire as well as adjacent hills and riparian areas (an area of 212 ha). This prescription was a good example of planning for larger fuel treatment areas. The objective of the fuel treatment was to reduce crown and ground fuel availability and stand continuity through a combination of mechanical and manual thinning, piling, burning, and, in some areas, pruning. The treatment in TU3, where the wildfire occurred, was to a) remove dead standing trees and remove standing live trees to achieve a stand density of 500 conifer stems/ha, b) pile and burn fine woody debris, and c) prune branches on live trees to a height of 3m when crown base was less than 2m. According to the prescription, there were only 200 stems/ha >12.5 cm dbh and 800 stems/ha 7.5 to 12.5 cm dbh prior to treatment in this unit. The area (17.8 ha) was purportedly treated in the fall of 2018.

The prescription for the Christie Mountain fire was also a good example of a more recent prescription (2014) in the Ponderosa Pine biogeoclimatic unit. It was similar in most respects to the Nazko prescription except that the treatment area was smaller (only 9 ha in total in six small separate pieces), and only half the number of mature trees were to be retained. The stated goal was *to improve public safety through a reduction in fuel loading* (standing and surface fuel) *within the wildland urban interface to improve survivability of adjacent structures and to provide defensible space within which wildland firefighters could operate during an interface wildfire*. The prescription called for leaving no more than 5-20 tonnes of surface fuel per ha as large CWD and 200 to 300 stems/ha greater than 12.4 cm dbh. Large trees (>40cm dbh) and deciduous trees were to be left, as well as some of the smaller conifer regeneration. All other trees were to be felled, piled, and burned, except stems >30 cm in diameter, which would be left untreated as CWD. Residual trees in all treatment units were to be pruned to 2m on flat ground and ~3m on slopes over 15% if safe to do so. The prescription also called for a re-assessment in 3 to 5 years to evaluate the need for a maintenance treatment.

Treatment Field Observations

In general, treatments that were completed were small linear features resulting in relatively low canopy closure, wide spacing, and reasonably low levels of surface fuels. Treatment type, timing, objectives, and implementation levels at each site are captured in table 4. Additional detail for the Nazko and Christie Mountain sites is provided in the text following table 4 (as examples). Comments on treatment efficacy are provided in the section on Predicted Versus Observed Fire Behaviour With And Without Fuel Treatment after a discussion of fire chronology and development and suppression efforts. These latter two categories are discussed first because they are important factors impacting treatment efficacy.

Table 4: Summary of treatment type, timing, and objectives at the Thinning study sites.

Location	Wildfire Year	Treatment Year	Treatment 1	Treatment 2	Treatment Area (Ha)	Objective	Implementation
Nazko	2019	2018	Thin/Prune	Pile Burn	4	Reduce crown and ground fuels and fuel continuity.	Good in sec.s, partially implemented elsewhere.
Ormond Lake	2018	2011	Thin/Prune	Pile Burn	3	Not available.	Treatment not effectively implemented.
Williams Lake	2017	~2015	Thin	Pile Burn	2	Intermediate age stand thinning.	Complete but only thinning/ removal phases.
Hanceville	2017	2012	Thin/Prune	Pile Burn	6	Reduce wildfire hazard and laddering potential. Improve safety and access.	Treatment partially implemented.
Lees Corner	2017	2012	Thin/Prune	Pile Burn	6	Reduce wildfire hazard and laddering potential. Improve safety and access.	Treatment partially executed.
Hat Creek	2017	2012	Thin/Prune	Pile Burn	22	Not available.	Treatment partially implemented.
Lytton	2014	2012, 2018	Thin/Prune	Pile Burn	8	Remove forest fuels in close proximity to communities to increase safety.	Partially implemented. Debris piles not all burned.
Garnet Valley	2017	2016, 2017	Thin	none	>20	Treat ingrowth and ungulate habitat and enhance cultural heritage values.	Treatment only partially implemented.
Christie Mountain	2020	2015	Thin	Pile Burn	11	Improve public safety through reduced fuel loading. Create defensible space.	Partially implemented.
Skookum chuck	2017	~2016	Thin	none	2	Reduce stocking to an open forest structure (in the adjacent area).	Complete but only thinning/ removal phases.

A field evaluation of the Nazko site, conducted in 2019, about one month after the wildfire, revealed that treatment implementation was incomplete in some sections. About 5 ha were thinned, partially pruned, manually and mechanically piled, piles were burned, and then the area interacted with wildfire (figure 5). In other areas, that stand was thinned and piled and burned but had no wildfire interaction (figure 6). Some sections of the treatment area were thinned and piled, but piles were not burned, and then the area interacted wildfire (figure 7), and others sections were thinned, piled, not burned, and had nointeraction with wildfire (figure 8)

Figure 5: Area of thinning, pruning, piling, burning, and wildfire.

Figure 6: Thinning pile burning, no wildfire.

Figure 7: Section thinned, piled, then wildfire.

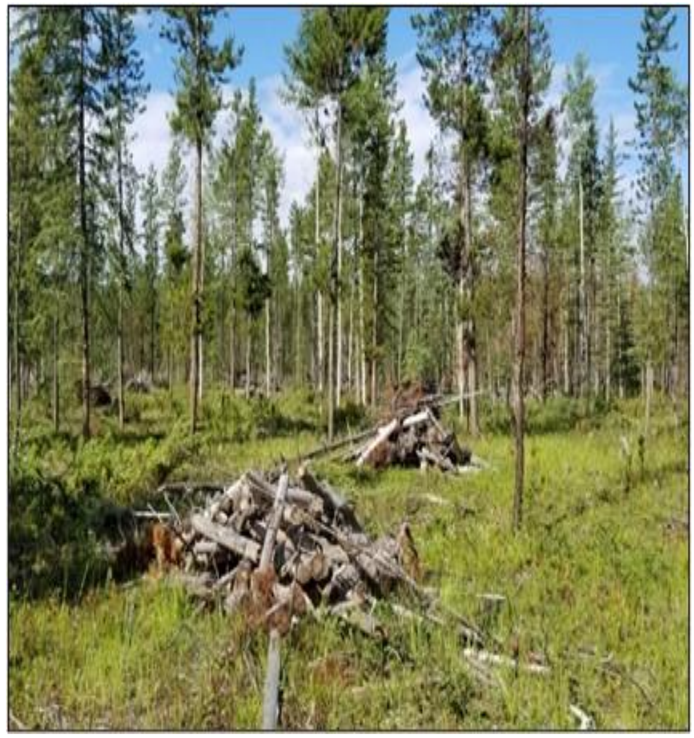


Figure 8: Section thinned, piled, not burned, no wildfire.

Figure 9: An area with larger, unburned piles left close to leave trees.

It was unclear whether the piles in the area that did interact with wildfire were actually burned before the wildfire. Unburned piles were 1.5 - 2.0m tall by 3.5m across in the area immediately adjacent to the wildfire, but in other areas in this treatment unit, piles were larger at 4 to 10m across and up to 3m high. In general, piles were too large and placed too close to leave trees (figure 9). Based on field observations, where the treatment was fully implemented, it resulted in a more open stand (crown spacing of 2 to 10m), lower levels of dead surface fuel, higher canopy base height, tree crowns with slightly higher crown bulk density, a discontinuous fuel distribution, and higher levels of flashy fuels like juniper, grasses, and herbs (the latter being important when they are in a cured state).

Theoretically, this type of treatment would reduce critical surface fire intensity, thus reducing the potential for torching, the possibility of an active crown fire, and the potential for spotting, but in some circumstances, because of flashy fuels and increased wind, it could increase spread rate. In areas where the piles had not yet been burned and/or pruning was not completed, most of these treatment benefits would not be realized. Additionally, the potential for torching would increase, spotting potential would increase, and localized fire intensity would increase.

At the Christie Mountain site (figures 10 and 11), treatment was reasonable but more pruning and reducing thickets of intermediate-sized Douglas-fir in some spots could have better reduced fuel conditions. Per Rory Colwell, Fuels Superintendent for the B.C. Wildfire Service (pers. comm. 2020), there is a trade-off in these types of stands between having a shaded overstory that is too dense, resulting in more needle litter, more ladder fuel, increased crown bulk density and continuity, and attendant increased risk of an active crown fire, versus a stand that is too open allowing grasses and herbs to build, potentially increasing spread rates. The stand type at the Christie Mountain fire is typical of many stands in the C7 fuel type (ponderosa pine/Douglas-fir). These stands often have a lower density of mature trees, but it is important to maintain a balance between overstory conditions, understory ladder fuels, woody surface fuels, and grasses, herb, and litter layers. Per Rory Coldwell and Brad Martin, Senior Wildfire Officer – Prevention, NW Fire Centre (pers. comm. 2020), one way to maintain this balance is to have more frequent maintenance treatments than in some other stand types in order to address the needle litter build-up and establishment of grasses and other fine fuels.

Figure 10: Aerial view of a treatment area that was burned in the Christie Mountain wildfire.

Figure 11: Ground view of a treatment area that was burned in the Christie Mountain wildfire.

At other sites in the study, treatment outcomes were similar to what was observed at Nazko and Christie Mountain. In some areas where the stand was older, no pruning was done because the canopy base height was already greater than 3m. In all other areas, except Garnet valley, pile burning had been completed. Crown espacement following treatment at all sites varied widely from 1m to 20m (see figures 12, 13 and 14). Espacement in the C7 fuel type was generally at the wider end of the spectrum. Canopy closure at all sites was less than 50% but more typically 5 to 25%. In all cases, post-treatment, woody surface fuels were relatively low and dispersed, but flashy fuels such as grasses, fireweed, and herbs were moderately abundant with 15 to 100% cover. It was not uncommon for treatments to be only partially implemented, and, at most sites, the treatment was a small, linear strip that had little opportunity to influence fire behaviour. The Nazko site was better in this respect because it was wider and contributedto a patchwork of discontinuity rather than a narrow strip or small patch.

Figure 12: Crown spacing in treated (top half) and untreated areas (bottom half) in a C7 fuel type at the Lytton site.

Figure 13: Crown spacing and closure at the Skookumchuck study area in southeastern B.C - 10 to 15m crown spacing and 10% crown closure in the treated area.

Figure 14: Crown spacing and closure at the Skookumchuck study area in southeastern B.C - 0 to 6m spacing and 35% crown closure in the untreated area.

Fire Weather And Wildfire Development

Fire Weather

Preceding sections have focussed on the fire environment at the thinning study sites including, most notably, topography, fuels, and fuel treatments. Weather conditions are also a fundamental driver of fire behaviour and fuel treatment outcomes. Hudak et al. (2011)[2], citing Bessie and Johnson (1995), state that weather and topography affect fire behaviour and can, in some cases, render the most robust fuel treatments useless. Similarly, Fernandes and Botelho (2003)[3] state that in extreme fire weather conditions, most fuel management treatments will have little to no overall effect. Beverly et al. (2020)[4] suggest that under low to moderate fire weather conditions, fuel treatments will likely be successful at reducing fire behaviour. However, under high or extreme fire weather, the effects of fuel treatments (thinning and pruning) in Boreal forest fuel types will not achieve the same reduction in fire intensity and rate of spread.

Fire weather indices at the study sites in this project are summarized in table 5. Fine fuel moisture code values (FFMC) were similar for all the fires, although somewhat lower in the northern two fires (Nazko and Ormond Lake). Relative humidity, wind speed, duff moisture code (DMC), drought code (DC), initial spread index (ISI), and buildup index (BUI) were all highly variable. Danger classes were similar and a good reminder that other factors such as fuel type, wind, and topography play a critical role in fire behaviour. The relatively low values at the Nazko site are not surprising, given that the wildfire occurred in spring conditions at a northern latitude when the BUI was low (77).

Table 5: BC weather station data for the Thinning study sites under active wildfire conditions.

Location	Fire Number	Fire Year	Air Temp (deg C)	RH	Wind Spd (km/hr)	Wind Direction	Precip (mm)	FFMC	DMC	DC	ISI	BUI	FWI	Danger Class
Nazko	**C10205**	**2019**	**25**	**21**	**13 to 17**	**230to340**	**0**	**91**	**59**	**283**	**12**	**77**	**34**	**3**
Ormond Lake	R11498	2018	22.5 - 30.5	35	9 to 14	247	0.2	90	70	401	9	98	29to36	4 to 5
Williams Lake	C20729	2017	30 (23)	15	9 to 11	0	0	96	149	444	16	162	45to51	5
Hanceville	C50647	2017	25	27	5	192	0	95	293	805	11	307	43	5
Lees Corner	C50647	2017	25	27	5	192	0	95	293	805	11	307	43	5
Hat Creek Plot45	K20637	2017	27	17	4	300	0	96	178	1152	12	256	44	4
Lytton	K70270	2014	33	30	30	190	0	97	150	738	18	199	57	5
Garnet Valley	K52024	2017	24	21	12	201	0	93	243	938	12	295	44	
Christie Mtn	K51287	2020	30-34	18	8	252	0	96	117	696	15	170	40to50	
Skookumchuck	N21451	2017	28	22	12	160to270	0	95	241	699	16	259	54	

As can be seen in table 5, fire weather was not extreme at the Nazko site during the wildfire. This site was one of only two sites in a pine (or pine/spruce) fuel type in the study. Because of this, and the fact that treatments and prescriptions were recent (treatment in 2018) and more reflective of current practices, it is a good candidate for a more detailed analysis of fire behaviour (provided in the following section). Another good reason for choosing this site was that the fire weather index (FWI) at the time was only 34, generally meaning a higher likelihood that the treatment could modify fire behaviour. Similarly, more detailed analysis on fire behaviour is also provided in the following sections for the Christie Mountain site because it is a good representative of the other study sites (all of which were C7 fuel types - Douglas-fir/ponderosa pine) and because it was also recently treated (2015), had a detailed prescription, and suppression actions (2020) were known.

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[2] Hudak et al. 2011. Review of fuel treatment effectiveness in forests and rangelands and a case study from the 2007 megafires in central Idaho. USA. RMRS-GTR-252. Fort Collins, CO.
[3] Fernandes and Botelho. 2003. A review of prescribed burning effectiveness in fire hazard reduction. International Journal of wildland fire, 12(2), 117-128.
[4] Beverly et al. 2020. Stand-Level Fuel Reduction Treatments and Fire Behaviour in Canadian Boreal Conifer Forests. Fire, 3(3), 35.

Wildfire Development And Suppression: Nazko

On May 9, 2019, at approximately 15:37, wildfire C10205 was ignited by a downed powerline in the community of Nazko. It was reported to the Cariboo Fire Centre at approximately 16:03. Personnel from BCWS and local residents undertook initial suppression action and managed to keep the fire contained to approximately 4.0 hectares. Data from the Nazko weather station revealed that BUI was low (77), FFMC was low to moderate (88 to 92 from 13:00 to 22:00), the temperature at 16:00 was 25^{o} C, and 10-minute wind speeds were moderate (9 to 17 km/hour, 14 km/hour at 16:00). In the same time frame, suppression personnel reported peak gusts between 25 and 30 km/hr. The terrain in the area was relatively flat, so no adjustments to account for slope or aspect were required.

Ignition occurred at the northern end of the unit at a powerline adjacent to a small lake and swamp system. According to personnel on site, the fire spread ~60m in less than 20 minutes during the acceleration rate of spread phase and, from 15:58 until 17:06, travelled a further 190m (250m in total). Once it reached an equilibrium rate of spread, it covered 190m in a little more than an hour, under the influence of the north wind, for an equilibrium rate of spread of 2.8 m/min (190m/68min). Based on post-fire field observations, it was probably an intensity class 3 fire (moderate vigour surface fire with head fire intensity of 500 to 2000 kW/m) and occasional torching. After 17:06, suppression efforts were in full swing and would have affected fire behaviour beyond what could be attributed to fuel treatments alone. Although not reported by suppression personnel, post-fire field observations revealed that some spotting had occurred up to 60m away. It is unknown whether there were unburned debris piles in the area of the wildfire that would have exacerbated the potential for spotting.

Suppression action was taken quickly on the small Nazko fire consisting primarily of machine-built guards and manual mop up. Figures 15, 16, and 17 show that fire line construction was relatively heavy but not always effective. The fire was contained the first day and largely extinguished the day after. Air support, planned ignitions, and water lines were not used.

Figure 15: Example of a fireguard that was effective.

Figure 16: Example of a less effectivefireguard.

Figure 17: Overview of the Nazko fire and cat guards.

Wildfire Development and Suppression: Christie Mountain

The Christie Mountain wildfire was quite different from the Nazko fire and more typical of some of the catastrophic fires seen in recent years in B.C. (figures 18 and 19). This fire was caused by a lightning strike on Aug. 18th, 2020, halfway up a gully on Christie Mountain above the Heritage Hills Estate near Penticton. It burned over a few weeks, growing to 6807 ha in size. The west edge of the fire was in the wildland-urban interface, adjacent to a subdivision, in an area that was rated as high to extreme in the BCWS provincial strategic threat analysis.

Figure 18: Overview of the Christie Mountain Fire, Sept. 2nd, 2020.

Fire weather indices on August 18th were much higher than at Nazko, with a buildup index more than twice as high (165), a drought code 2.5 times higher (696), and air temperature 1.5 times higher (34o C). FFMC was 96, ISI was 16, and 10-minute wind speeds were about 9 km/hour. August 18th was a day with substantial fire growth, and spotting distances seen in air attack photos that day were ~ 200 to 300m[5]. Although one home was lost to the fire, the damage

[5] Dana Hicks. Short Range Fire Growth Projection for K51278, Christie Mountain. Aug. 19th, 2020. Unpublished report.

could have been worse if it weren't for low fuel levels, winds blowing upslope away from the interface area, and suppression actions.

Suppression action at the Christie Mountain fire was relatively aggressive with ground crews, sustained air support, and support from structural firefighters. Of particular note, a planned ignitions were conducted from the bottom of the hill near the residential subdivision within the study area. A narrow gravel road (~ 8m wide) also played a role in preventing fire spread at this location. The fire was substantially out by early September.

Figure 19: Wildland urban interface at the Christie Mountain study site.

Fuel Treatment Efficacy – Predicted and Observed

In this project, we focused on using a paired plot approach to compare areas that were treated and burned in a wildfire with areas that were not treated but were burned as a way to determine if treatments had an impact. We also briefly investigated the use of predictive models as a way of explaining observed wildfire outcomes. Both approaches have value and drawbacks. Many wildfire analysts use modelling but commonly warn that models are often very sensitive to input assumptions/variables and scale Beverly et al. (2020)[6]; Fernandes and Botelho (2003)[7]; Prichard et al. (2018)[8], Hinckley and Wallace (2012)[9]. Conversely, while fire behaviour models are not necessarily reliable at a cut block level, with case studies

[6] Beverly et al. 2020. Stand-Level Fuel Reduction Treatments and Fire Behaviour in Canadian Boreal Conifer Forests. Fire, 3(3), 35

[7] Fernandes and Botelho. 2003. A review of prescribed burning effectiveness in fire hazard reduction. International Journal of wildland fire, 12(2), 117-128

[8] Prichard et al. 2018. Evaluating the influence of prior burn mosaics on subsequent wildfire behavior, severity, and fire management options. https://www.firescience.gov/projects/14-1-02-30/project/14-1-02-30_final_report.pdf

[9] Hinckley and Wallace. 2012. U.S. Fish and Wildlife Service. Fuel treatments reduce wildfire suppression cost: Merritt island national wildlife refuge

and paired plots, there are few examples and many variables involved, making it difficult to achieve statistical precision. In the next two sections, we explore the impacts of treatment using both approaches at the Nazko site and the Christie Mountain site. These two sites were chosen because they are reasonable representatives of current treatment protocols good supporting data existed for both. Information from other sites in the study was sometimes added to help further reinforce a particular finding or conclusion.

Fuel Treatment Impacts on Fire Behaviour: Nazko

At the Nazko South site, we evaluated the use of the tables in the Canadian Forest Fire Behaviour Prediction System[10] to identify how the fire would have behaved if it were not treated, specifically with respect to rate of spread and intensity based on a C3 fuel type. Table 5.1 of the Field Guide for Fire Behaviour Prediction indicates that, in an untreated C3 fuel type, with an initial spread index (ISI) of 7 and a BUI of 77, the fire would have spread approximately 60m (2m/min) from ignition time (15:37) until it was first discovered by BCWS staff at 15:58, 21 minutes later (based on the accelerating rate of spread for open fuels and surface fires in closed fuel types). The Canadian Forest Service document ST-X-3[11] (1992) states that 20 minutes is an average time for a fire to reach equilibrium ROS in an open fuel type. The predicted rate of spread, in this case, was very similar to that observed by suppression crews. Later in the day with higher ISIs (10 to 12), in a C3 fuel type, the equilibrium rate of spread is predicted to be 5m/min in the Field Guide for Fire Behaviour Prediction with an intensity class of 4. This compared to observed spread rates of about 3m/min and characterization of the wildfire by firefighters as a moderately vigorous surface fire with some torching. Rate of spread would be much higher if a C4 stand type (immature lodgepole pine) were used (14m/min), illustrating the sensitivity of the system to fuel types and the need for a precautionary approach when relying on fire models and calculators.

With respect to differences in wildfire behaviour in treated versus untreated areas at the Nazko site, there were only a couple of small spots that interacted with the fire that was not treated, making measured comparisons between the treated and untreated areas impossible. While the thinning, debris disposal, and pruning treatments at this site did result in more open stand conditions with a consequent decrease in fine fuel moisture content, slight increase in grass and herbaceous cover, potential decrease in relative humidity, and potential for increased wind speeds, these increased risk factors were offset by reduced dead woody fuels, reduced ladder fuels, increased crown separation, and decreased canopy bulk density (see figure 20). If there were unabated slash piles at the portion of the treated site that burned, short-range spotting could have been exacerbated because fire intensity and ember transport would have increased. Brad Martin (Senior Wildfire Officer – Prevention, NW Fire Centre, pers. comm. 2020) summarized treatment impacts at the Nazko site as follows:

1. The untreated stand would have burned more intensely than the treated stand because more fuel was available and continuous.
2. There would have been more torching/crown involvement if the stand were not treated because there would have been more ladder fuels. With more surface fuel, critical surface temperatures would have been reached more easily.
3. There would have been more short-range spotting because of the amount and distribution of surface fuels.

[10] Per the Field Guide to the Canadian Forest Fire Behavior Prediction System (Taylor and Alexander, 2016)

[11] Development and Structure of the Canadian Forest Fire Behavior Prediction System. Report ST-X-3. 1992: https://cfs.nrcan.gc.ca/pubwarehouse/pdfs/10068.pdf

Figure 20: Fire impact in the treated area at the Nazko site.

In addition to ameliorating fire behaviour, suppression personnel indicated that the thinning treatments improved access and increased visibility for suppression crews (because of reduced understory fuels), lowered risk with respect to danger trees, and improved response time. If air support were required on this type of site, treatment would also have resulted in better penetration and coverage of retardant or water drops.

Fuel Treatment Impacts on Fire Behaviour: Christie Mountain

Table 6 shows the actual ISI and BUI values from the Pentiction Weather Station near the Christie Mountain fire from Aug. 20th to the 24th (starting two days after fire ignition).

Table 6: Selected fire weather indicies for the Penticton weather station for the Christie Mountain Fire.

Date	ISI	BUI
Aug. 20th	10.8	174
Aug. 21st	15.6	179
Aug. 22nd	9.5	183
Aug. 23rd	9.0	187
Aug. 24th	6.4	189

The study site was located in a C7 fuel type, and, on the worst day, where the ISI was 16 and BUI was 179, the Field Guide for Fire Behaviour Prediction indicates an expected rate of spread of 7 m/min., an intermittent crown fire, and an intensity class of 5 (4000 to 10,000 kW/m). With an ISI of 6 or 7 and a BUI of 189, a low to moderately high vigour surface fire is expected with a rate of spread is 1 to 2 m/min., and an intensity class of 3 (500 to 2,000 kW/m). Using the same weather station data tempered by observed fire behaviour, BCWS issued a Fire Behaviour Forecast on Aug 20th, for Aug. 21st, predicting a rate of spread of ~6m/min for C7 fuel types but warned that with winds of 30 km/h, intermittent crown fire could occur in the C7 fuel types, with much higher spread rates on dry grassy slopes. Dana Hicks, a fire behaviour specialist with BCWS, simulated fire growth on Aug. 19th (when the fire was already ~1000 ha in size), projecting a wildfire size of 17,037 ha by the evening of Aug. 21st using the fire behaviour model

Prometheus[12.] Based on observations, including estimated spotting distances of 200 to 300m beyond the flaming front, Dana tempered this estimate t6000 to 6700 ha. As it turned out, the fire size after extinguishment was 6807 ha. This example once again illustrates the uncertainty and sensitivity of fire modelling and the need for knowledgeable modellers.

Figure 21: Douglas fir thickets at the Christie Mountain site.

Based on field observations at the study site, located lower on the slope on the west side of the fire, the predictions of a vigorous surface fire with intermittent crown fire at some points in the wildfire chronology were reasonably accurate. Many crowns were still green, while others were entirely consumed (about 10%) with up to 100% bole char, 100% duff consumption, and some spotting. The difference between treated and untreated areas in terms of fire outcomes was not striking, although there were more frequent thickets of Douglas-fir in some untreated areas (figure 21). The influence of suppression actions at this site (which included planned ignitions and air tanker suppression) was an added complexity when trying to differentiate fire behaviour in the treated and untreated areas.

Fuel Treatment Impacts on Fire Behaviour: Other Study Sites

At other thinning sites in the study that interacted with a wildfire, field measurements revealed that fire intensity in treated areas was generally lower than in untreated areas, spread rate was slower, and crown involvement was lower (see figures 22 and 23) for a visual example at the Williams Lake Airport site).

[12] Prometheus, produced by the Alberta Ministry of Agriculture and Forestry is a deterministic wildland fire growth simulation model based on the Fire Weather Index and Fire Behaviour Prediction sub-systems of the Canadian Forest Fire Danger Rating System. The model simulates spatially-explicit fire behaviour given heterogeneous fuel, topography and weather conditions. For more detail on Prometheus, see the case study on Broadcast burning.

Figure 22: Apparent burn intensity in the untreated area at the Williams Lake Airport site.

Figure 23: Apparent burn intensity in the treated area at the Williams Lake Airport site

Burn severity mapping (where available) corroborated these findings (see the example in figure 24), despite the fact that the scale of severity mapping is not meant to be used for areas as small as the fuel treatments (severity mapping was only available for 4 of the 10 study sites).

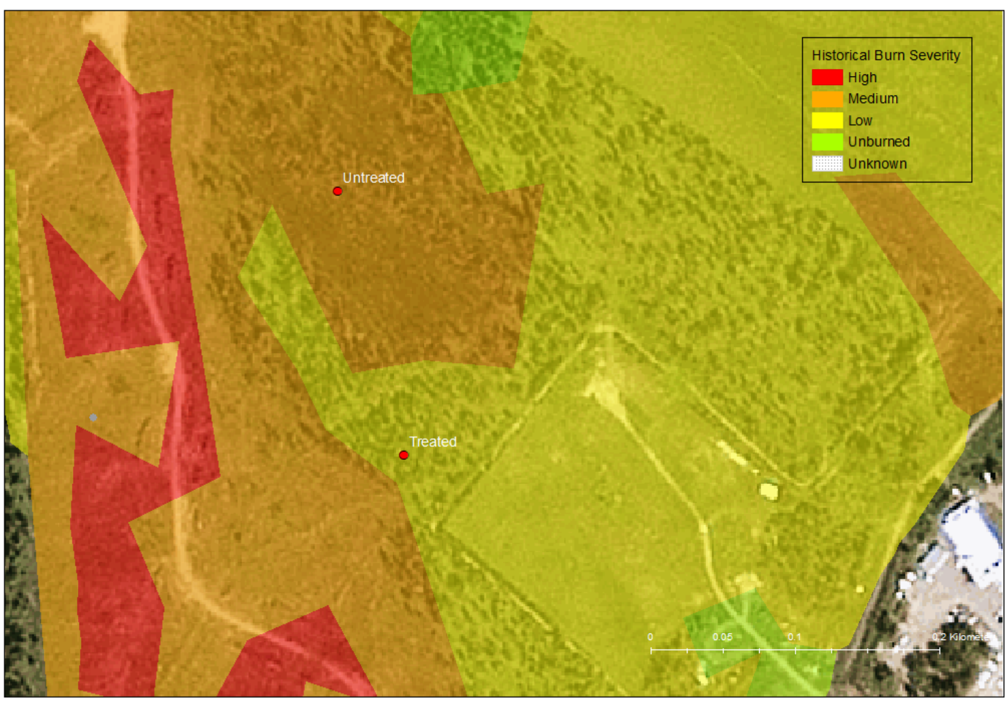

Figure 24: Burn severity mapping at the Williams Lake Airport site showing reduced burn severity in treated areas.

However, it did not appear that any of the treatment areas were large enough to be used for planned ignitions, large enough to hold the wildfire for an extended time, or have any large-scale influence on fire suppression or fire outcomes. While treatment clearly affected fire behaviour, its value was limited to the immediate area of the treatment. Also, at some sites, stand structure and fuel loading were **not** markedly different in the treated area versus the untreated area (notably Ormond Lake, Hat Lake, and Hanceville), possibly because treatments were either unnecessary, or they were under implemented.

Lessons Learned

Moody (2010)[13], in a synthesis of fuelbreak effectiveness in Canada's Boreal Forests, states that *the primary purpose for fuelbreaks is to change fire behaviour as it enters the fuel-altered zone resulting in limited, or slowed, fire spread, reduced flame lengths; and reduced probability of torching and independent crown fire. It can be used as an anchor point for indirect attack; it can facilitate the rapid construction of a fireline/firebreak by suppression forces, including sprinkler lines; it can provide safe access for ground suppression crews and possibly safe zones; it can allow greater penetration to surface fuels of fire retardants dropped from the air.* Typical fuel treatment objectives include reducing surface fuels, reducing ladder fuels, reducing fuel continuity, decreasing tree crown spacing and canopy bulk density, increasing canopy base height, and maintaining shade and understory moisture levels (either through retaining large, fire-resistant trees or creating fire resistant second-growth stands). Such measures are expected to reduce surface fire intensity, reduce flame length, reduce crown involvement, and reduce the chance of spotting. The treatments assessed in this case study often achieved many of these objectives, resulting in positive fire management outcomes, despite the small areas involved and under-implemented treatments.

Practical questions that fuel managers deal with when implementing this type of fuel treatment include such things as:

1. Where should fuel breaks be created?
2. How wide or what shape should be used?
3. How widely spaced should trees be?
4. To what height should branches and other ladder fuels be removed?
5. What types and how many tonnes of surface fuels can be tolerated?
6. What distribution of surface fuels is optimal?
7. How often does the fuel break need to be retreated?

This case study sheds light on some of these questions, for a particular set of fire weather conditions, fuel types, and topographic conditions, but there were not enough examples of wildfires interacting with these treatments to provide thresholds or answers to all these questions or for the full range of conditions that might be encountered in B.C.[14] Some insights for C3, C4, and C7 fuel types included that:

1. Treatment efficacy was consistent across a broad range of ecological conditions from the sub-boreal spruce moist, cool biogeoclimatic unit to the ponderosa pine very dry hot biogeoclimatic unit. This finding is consistent with Beverly et al. (2020)[15], who found, in an analysis of five different cases on the effects of fuel treatments on fire behaviour in the boreal forest areas of

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[13] Moody. 2010. Fuelbreak Effectiveness in Canada's Boreal Forests: A Synthesis of Current Knowledge. FP Innovations Internal Rpt.

[14] For a description of fuel management principles and some best practices see the newly updated B.C. Wildfire Service Fuel Management Practices Guide, 2020, and the FLNRO VanJam Strategic and Tactical Fire Management Plans (2015).

[15] Beverly, J. L., et al. 2020. Stand-Level Fuel Reduction Treatments and Fire Behaviour in Canadian Boreal Conifer Forests. Fire, 3(3), 35.

Northern Saskatchewan, Alaska, Northwest Territories, and Alberta, that some degree of fire intensity and/or rate of spread in fuel treated areas is decreased when compared to untreated stands.

2. Despite the use of short, thin (20 to 50m wide), linear strips, fire impacts (scorch height, tree mortality, and crown involvement) were still modified.
3. Treatments ameliorated fire behaviour on low slopes (< 30%) and on any aspect, but efficacy on steeper slopes is unknown since no treatment sites were located on anything steeper.
4. Treatments positively affected fire behaviour in C3, C4, and C7 fuel types even in relatively high-intensity fires (>2000 kW/m).
5. Increasing crown base heights to as little as 2m had a positive impact when combined with thinning and debris removal. At some sites, no pruning was performed, but in these cases, most tree crowns were naturally more than 3m above ground level.
6. In this study, thinning alone (with debris removal) did reduce tree mortality and crown involvement, but there was evidence that further gains can be made by reducing ladder and surface fuels. At the Skookumchuck site, merchantable trees were removed, but non-merchantable woody debris was not piled or burned, and at the Williams Lake Airport site, thinned materials were removed, but there was no treatment of ladder fuels, and yet the treated areas still had lower tree mortality and crown involvement than untreated areas. However, in a case study of megafires in central Idaho, Hudak et al. (2011)[16] indicated that surface fuel loading actually increased in thinned-only treatment stands, which counteracted any potential effects of reduction of ladder fuels, causing wildfire severity to remain mostly unaffected as compared to the untreated stands. Moody (2010)[17] states that removal of surface and ladder fuels may play a more important role in changing fire behaviour than thinning of overstory canopy fuels… and that extensive thinning does not reliably modify fire behaviour. Omi and Martinson (2009), in a meta-analysis of the literature on fuel treatment mitigation of wildfire fire intensity and severity, indicate that thinning treatments have demonstrated the most substantial reductions in wildfire severity, but only by those that produce substantial changes to canopy fuels (removing at least half), shift the diameter distribution towards larger trees, and are followed by broadcast burning.[18]
7. Crown espacement can be highly variable (clumpy) and still reduce crown involvement and tree mortality as long as there are frequent larger gaps (5 to 10m), canopy closure is less than 50% (more typically 25%) and leaving thickets of smaller stems that serve as ladder fuels (particularly in interior Douglas-fir stands) is avoided.
8. Fuel loading as high as 25 tonnes/ha did influence fire behaviour in terms of tree mortality and crown involvement as long as fuels were dispersed or patchy (~5 tonnes/ha was more typical). Moody (2010) provided some specific metrics for fuel treatments: crown closure should be less than 35%; surface fuel amounts less than 5kg/m^2; treatment should be about 1 kilometre from values, and non-fuel strips should be 10-30m wide.
9. In this study, it did not appear that any of the treatment areas were large enough to be used in suppression efforts (for example, to be used as anchor points, or for back burning, or to slow fire

[16] Hudak et al. 2011. Review of fuel treatment effectiveness in forests and rangelands and a case study from the 2007 megafires in central Idaho. USA. RMRS-GTR-252. Fort Collins, CO.
[17] Moody. 2010. Fuelbreak Effectiveness in Canada's Boreal Forests: A Synthesis of Current Knowledge. FP Innovations Internal Rpt.
[18] Omi and Martinson 2009. Effectiveness of Fuel Treatments for Mitigating Wildfire Severity: A Manager-Focused Review and Synthesis. JFSP Project Number 08-2-1-09.

progress to provide more time for suppression personnel), except at the Nazko South site (pers. comm., Andrew Flockhart, Wildfire Service, 2019) where treatment did provide better access and improved visibility. Safford et al. (2009), in a study of the effects of fuel treatments on fire severity in a mixed conifer forest in the Lake Tahoe Basin, indicate that thinning the forest canopy without strongly reducing surface fuels does not increase tree survival, although it may decrease some measures of fire severity.[19] They also suggest that 400–500 m is probably an absolute minimum for fuel treatment width at the wildland-urban interface (based on rates fire can move in extreme fire weather conditions).

10. Treatments were generally located where there was a heightened risk to human property and life, but it did not appear that they were necessarily strategically located to broaden their impact by including adjacent fire-resistant areas – their utility to date has been confined to a very small fraction of the area classified as a high or extreme threat in the provincial strategic threat analysis. Utzig (2019)[20], in assessing fuel treatments that might be used in the B.C.'s Kootenay region, indicates that because the area treated and the area affected by wildfire are only a small percentage of the landscape at any given time, the treatments may result in short-term reductions in area burned, but will likely have little effect on the overall fire regime over the long-term. Utzig also quotes Graham et al. (2004), who indicate that a landscape approach is more likely to have significant overall impacts on fire spread, intensity, perimeters, and suppression capability than an approach that treats individual stands in isolation. Reid (2010) stated that treating small or isolated stands (of Douglas-fir and ponderosa pine) *without assessing the broader landscape will most likely be ineffective in reducing wildfire extent and severity.*[21]
11. In some of the areas assessed in this study, there did not seem to be much difference between treated and untreated stands implying that treatment in these locations may not have been necessary or was not necessarily effectively implemented.

In summary, there is evidence that fuel treatments involving thinning, debris removal, and ladder fuel reduction are affecting wildfire behaviour in positive ways and that they are feasible at a larger scale. There are a number of areas in which fuel management practices, policy, and research could be augmented. Ways to accomplish this have been summarized in Section 4 Recommendations, together with the recommendations from the case study on Broadcast Burning.

3. BROADCAST BURNING

Historically, in B.C., prescribed fire has been used as a site preparation tool, following logging or, more recently, in ecosystem restoration treatments. BCWS suggests that the key objectives for the use of prescribed fire in British Columbia include:

1. creating and maintaining strategic fuel breaks both in the wildland-urban interface and the landscape
2. reducing understory fuels, restoring fire-maintained ecosystems

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[19] Safford et al. 2009. Effects of fuel treatments on fire severity in an area of wildland–urban interface, Angora Fire, Lake Tahoe Basin, California. Forest Ecol. Manage. doi:10.1016/j.foreco.2009.05.024.

[20] Utzig, G. 2019. Forest Fuel Treatments for the Southern West Kootenays: A Summary of Experiences in Other Places. Available at: https://www2.gov.bc.ca/assets/gov/public-safety-and-emergency-services/wildfire-status/prevention/fire-fuel-management/fuel_management _prescription_guidance.pdfafdas.

[21] United States Department of Agriculture. 2010. Cumulative Watershed Effects of Fuel Management in the Western United States, Symposium Proceedings. USDA, Rocky Mountain Research Stn, General Technical Report RMRS-GTR-231, Chpt 14.

3. improving wildlife habitat and domestic range
4. achieving reforestation objectives
5. meeting *Wildfire Act* and Wildfire Regulation requirements[22]

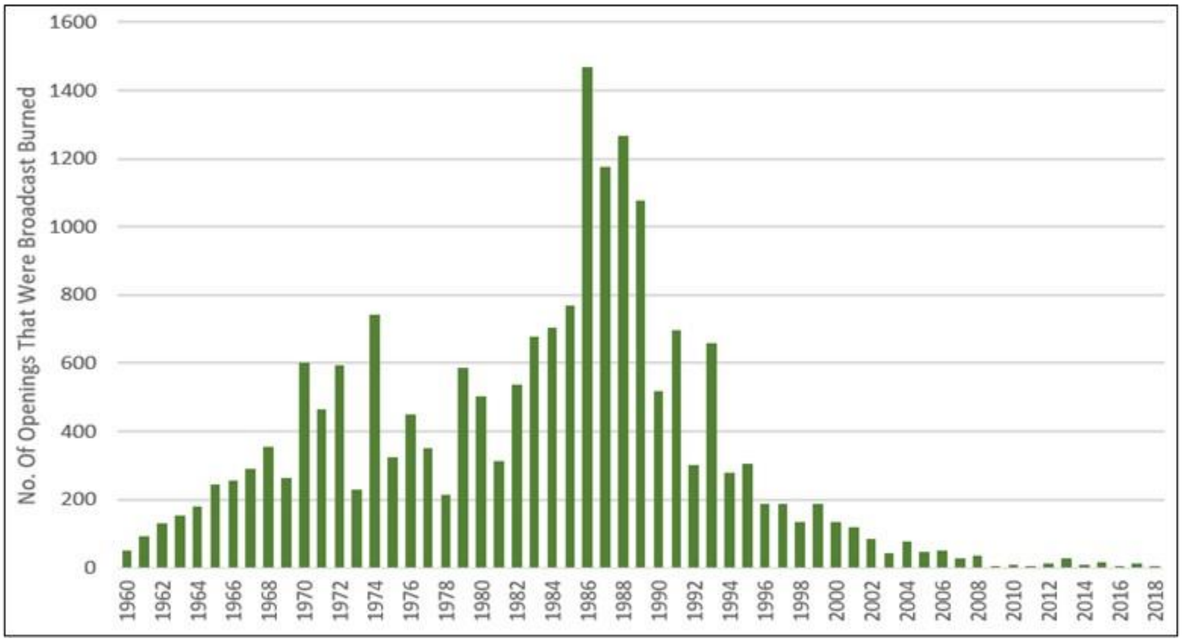


Figure 25: Number of broadcast burn treatments conducted in B.C (1960-2018).

Policy changes in the late 1980s, and a change in preferences by practicing foresters away from broadcast burning in B.C. because of potential liabilities associated with escape burns and smoke management issues, meant that relatively little broadcast burning was completed after about 1993. The graph in figure 25 shows a steady increase in the use of prescribed fire between 1960 and 1988, followed by a relatively rapid decline until 2002 with very little burning occurring after that (source: B.C. Government RESULTS database). As a result, there are few areas in B.C. where a recent wildfire (since 2012) has intersected with a broadcast burning treatment that occurred within the last 25 years. In a GIS analysis of the RESULTS database, in which we looked for instances in which a recent wildfire (2012+) intersected with prescribed broadcast burning, we identified 12 locations, only 5 of which appeared suitable for analysis. The seven areas that were rejected for inclusion in the study were either too small, the reported wildfire was actually an escaped burn resulting from the broadcast burn treatment, or there was no detail in RESULTS about the site.

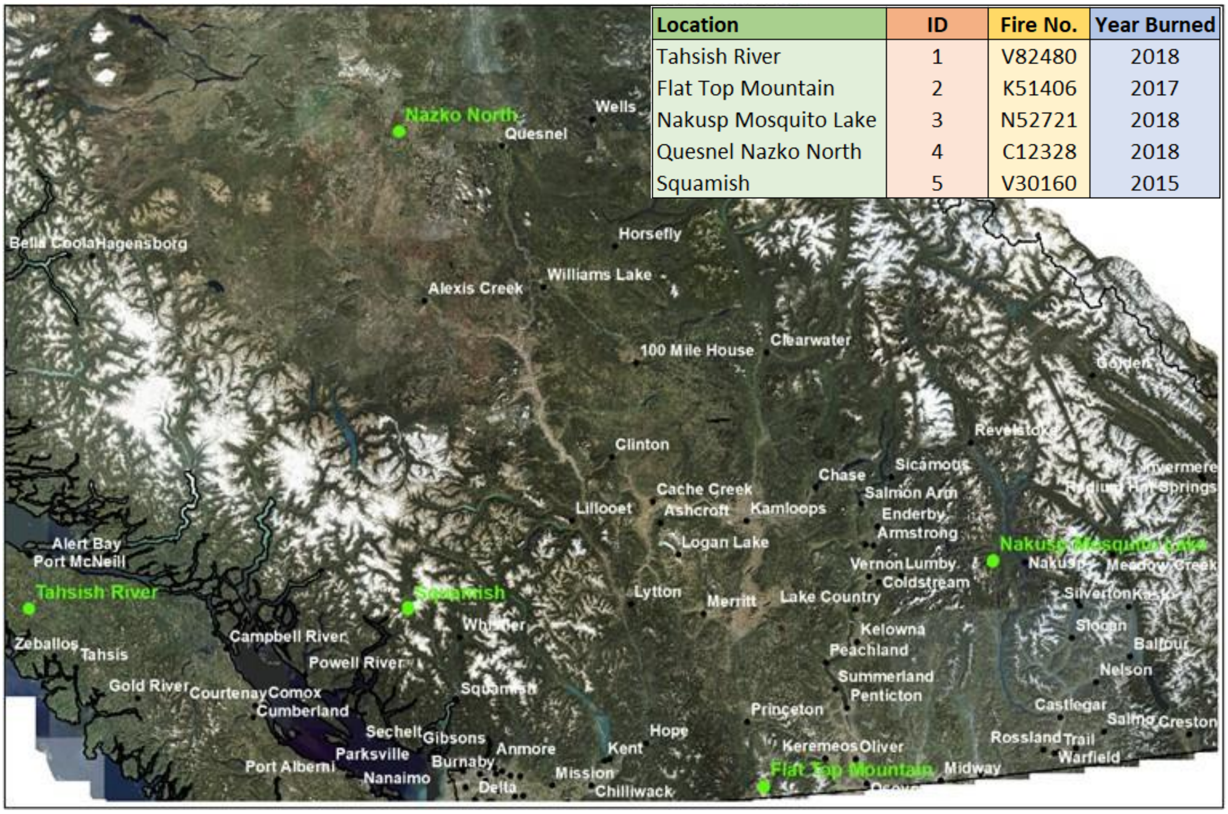
Stand and fire behaviour data were collected for at least two forest cover polygons at all five locations selected for the case study – a total of 13 – to ensure that both treated and untreated conditions were sampled. The methodology used to evaluate each sample site chosen for inclusion in the study was identical to that described in the case study for Thinning. All plot data for each site are provided in a Microsoft Excel spreadsheet titled CaseStudyData_bcBurn. As with the Thinning case study, the broadcast burning case study focuses on one benchmark site (Nakusp) augmented with data from the other

[22] https://www2.gov.bc.ca/gov/content/safety/wildfire-status/prevention/vegetation-and-fuel-management/prescribed-burning

broadcast burning sites to help illustrate the impact that site conditions, fire weather, or treatment differences affected treatment efficacy.

The Fire Environment

The locations of the five broadcast burn areas that interacted with wildfire in B.C. within the last eight years are shown in figure 26. Appendix I includes more detailed maps showing the location of each site relative to towns or other geographical features.



Location	ID	Fire No.	Year Burned
Tahsish River	1	V82480	2018
Flat Top Mountain	2	K51406	2017
Nakusp Mosquito Lake	3	N52721	2018
Quesnel Nazko North	4	C12328	2018
Squamish	5	V30160	2015

Figure 26: Geographic location of broadcast burning treatments (green placemarks).

These study sites were located in both B.C.'s interior and on the coast, spanning a range of biogeoclimatic zones, including the SBPSmk, the ICHmw2, the ESSFxc1 and dc2, the CWHms1 and ds1, and the CWHvm1. All five study sites were broadcast burn treatments located in clear-cuts that had been logged between 1988 and 2011. Data in the B.C. Government RESULTS database indicated that treatments had been conducted between 1988 and 2013. The Nakusp location (ICHmw2) was broadcast burned in 2005, 13 years before the wildfire in 2018 (figure 27). The relatively recent fire environment at this site made it easier to retrospectively evaluate fire behaviour, making it a good benchmark site for broadcast burn impacts on wildfire behaviour. The only site that was treated more recently (2013) was the Nazko north site - burned in a 2018 wildfire - but the treatment information for this location was incomplete.

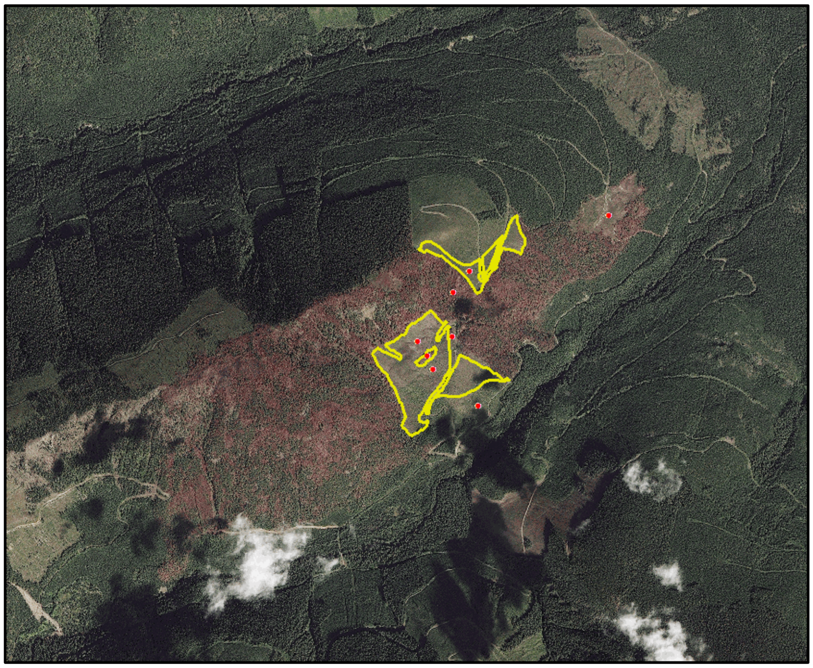


Figure 27: Overview of the Nakusp study site with broadcast burn boundaries (yellow outline) and plot locations (red dots).

Topography

Study sites tended to occur on undulating to gullied terrain and mid to lower slopes, with a variety of aspects. The elevation range was variable, with values as low as 455m at the Port McNeill site on Vancouver Island to 1840m at the ESSF site on Flattop Mountain in southern B.C. near the U.S. border. Except in one small area on a floodplain in the Elaho Valley near Squamish B.C., the percent slope was moderate to high (up to 50%), and so topography at these broadcast burns sites would have played a significant role in wildfire behaviour. Topography at the Nakusp site represented other areas reasonably well because it was mid-elevation, moderately steep (10 to 40%), with undulating terrain, and a southeast aspect.

Fuels And Pre-Wildfire Fuel Treatments

Except at the Nazko North site, the broadcast burn sites identified in this study were in moister subzones or at higher elevations where post-harvest slash levels are typically higher and more likely to be candidates for prescribed fire. All the sites had been logged and then broadcast burned with unknown levels of treatment success. Prior to the wildfire, they had all grown to become conifer plantations between 5 and 24 years of age (fuel type C6), however, expected fire behaviour in these stand types is heavily influenced by surface fuels left from the previous stand and is poorly represented in the CFS fire behaviour prediction system[23]. Based on field observations and VRI data, the post-harvest, pre-broadcast burn fuel types for the study sites were:

- Nakusp: S3 (Coastal Cedar/Hemlock/Douglas-fir), which approximates the fuel type for the interior wet belt[24].
- Nazko North: S1 (Lodgepole Pine Slash)
- FlatTop: S2 (Spruce/Balsam Slash)

[23] Source: https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/wildfire-management/fire-fuel-management/bcws_bc_provincial_fuel_type_layer_overview_2015_report.pdf

[24] Per the Field Guide to the Canadian Forest Fire Behavior Prediction System (Taylor and Alexander, 2016)

- Elaho: S3 (Coastal Cedar/Hemlock/Douglas-fir Slash)
- Port McNeill Tahsish: S3 (Coastal Cedar/Hemlock/Douglas-fir Slash)

It was not possible to obtain **pre-treatment** fuel loading on these broadcast burn sites because survey data or pre-treatment prescription data were not available and because broadcast burning and/or wildfire at the site consumed evidence of pre-treatment conditions. Similarly, there was only one plot (at the Tahsish River, Port McNeill) site that was treated but was not burned in the wildfire, making it difficult to determine **post-treatment** fuel loading. At the Nakusp and Flattop Mountain sites, however, there were nearby stands that were similar in some respects to the treatment areas, and these provided some insight into pre-treatment conditions. At the Nazko North site, there was a large area in the same stand that was not broadcast burned or burned in the wildfire, which also provided insight into pre-treatment conditions. These unburned areas are not perfect surrogates, however, since there were some differences in topographic location and stand structure, as well as fuel loading - as evidenced by the fact that they did not burn in the wildfire.

Another method to obtain an approximation of pre-treatment fuel loading is to use the photo guides available at the B.C. Government Wildfire Hazard Assessment And Abatement website[25]. These guides indicate that surface fuel loading for moderate levels of coastal western hemlock slash is about 150 tonnes/ha, and for moderate levels of western red cedar, it is 165 tonnes/ha. These values could approximate post-harvest, pre-broadcast burn fuel conditions at the Elaho River and Port McNeill sites, both of which are in the coastal western hemlock biogeoclimatic zone. When these sites were logged, these guides would have been reasonably representative of the utilization standards and logging practices at the time. The same guides indicate that B.C. Interior slash loading in an S1 fuel type is 20 to 30 tonnes/ha in the IDFdk (representing the Nazko North area), and for the S2 fuel type in the ESSFdc (representing the FlatTop Mountain site), it is typically about 53 to 63 tonnes/ha. Fuel loading in the guides for an S3 fuel type in the ICHmw (representing the benchmark Nakusp site) is indicated to vary from 30 to 120 tonnes/ha depending on the cedar and hemlock component. It is expected that for the Nakusp site, it would be closer to about 50 tonnes per ha. The photo guide values are similar to values for fuel loading after clearcut logging found by Kranabetter and Macadam (1998), who measured fuel loads on seven sites in Northwest B.C. They found that pre-broadcast burn slash loads varied from 44 to 109 tonnes/ha and that an average of 55% (34% to 75%) of the slash would be consumed by low to moderate-severity broadcast burns.[26]Detailed information on the fuel treatment prescriptions and implementation at the study sites was not available in the RESULTS database, vegetation resources inventory (VRI) database, or from licensees, and it is unclear, therefore, whether fire management objectives were achieved by broadcast burning. How much of the pre-treatment fuel was consumed in the broadcast burn at these sites is not precisely known. Based on the presence or absence of burned surface fuels and/or charcoal in the upper organic horizons in treated areas, it was evident that broadcast burning treatments were not always complete. A file note for the Flat Top Mountain site, for example, indicated that the broadcast burn was light intensity with a low rate of spread and pockets were left unburned, although hazard and slash reduction were successful enough to allow for easier planting. Partial success with broadcast burning is also implied by the shape of the RESULTS spatial files (figures 28 and 29) showing the area that was broadcast burned. In figures 28 and 29, cutblock opening boundaries are represented by white lines and the broadcast burn boundary is represented by yellow lines. The shape of the treatment boundary at

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[25] https://www2.gov.bc.ca/gov/content/safety/wildfire-status/prevention/for-industry-commercial-operators/hazard-assessment-abatement

[26] Kranabetter and Macadam. (1998). Ten-year Results from Operational Broadcast Burning Trial in Northwestern British Columbia. https://www.for.gov.bc.ca/hfd/pubs/docs/rr/rr15.pdf

these sites is not typical of broadcast burning, and it is also apparent that only part of the opening was completed.

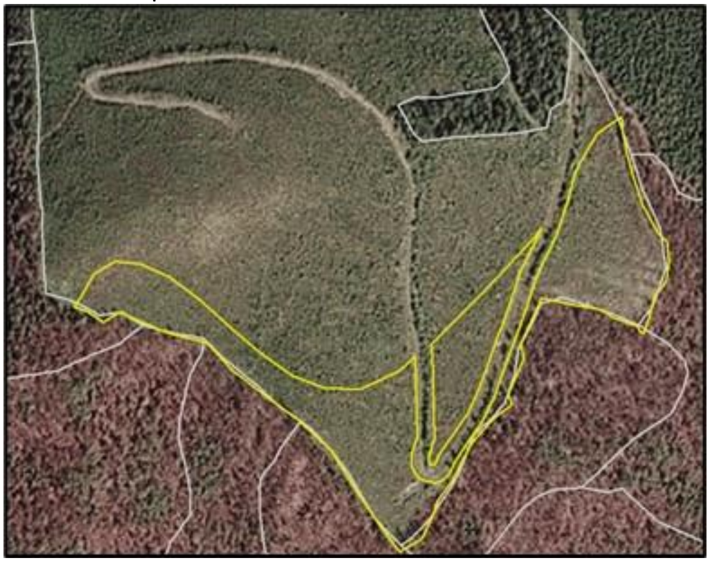

Figure 28: Broadcast burn boundaries (yellow lines – source: RESULTS database) juxtaposed against the VRI opening polygon (white lines) at the Nazko Site.

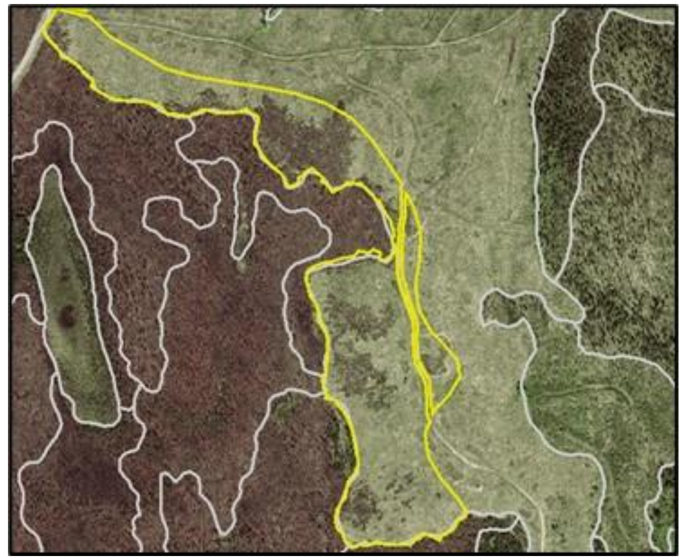

Figure 29: Broadcast burn boundaries (yellow lines – source: RESULTS database) juxtaposed against the VRI opening polygon (white lines) at the Nazko Site 2.

Wildfire Chronology and Development

Overview

Wildfires in this study occurred in 2015 (the Elaho Valley), 2017 (Flat Top Mountain), and 2018 (Nazko North, Nakusp, and Port McNeill). In early August 2018, an unstable air mass blanketed much of B.C., causing widespread thunderstorm activity and lightning strikes across the province, contributing to one of the worst fire seasons in B.C. history (2119 fires totalling more than 1.3 million ha burned)[27]. During the month of August, there were at least 565 separate wildfires. One of these, N52721, started west of the Nakusp benchmark site, where two openings had been broadcast burned in 2005 (figure 30). The fire started on the 11th of August, 2018 (the same day the fire at the Port McNeill site started) and continued burning throughout the month of August and into September but did not grow to more than about 350 ha.

Based on Sentinel Playground imagery (https://apps.sentinel-hub.com/sentinel-playground/), this fire spread from a lightning strike in the west and ran 1.4 km before Aug. 18th to reach the southwestern treatment area.

[27] Source: https://www2.gov.bc.ca/gov/content/safety/wildfire-status/about-bcws/wildfire-statistics/wildfire-averages

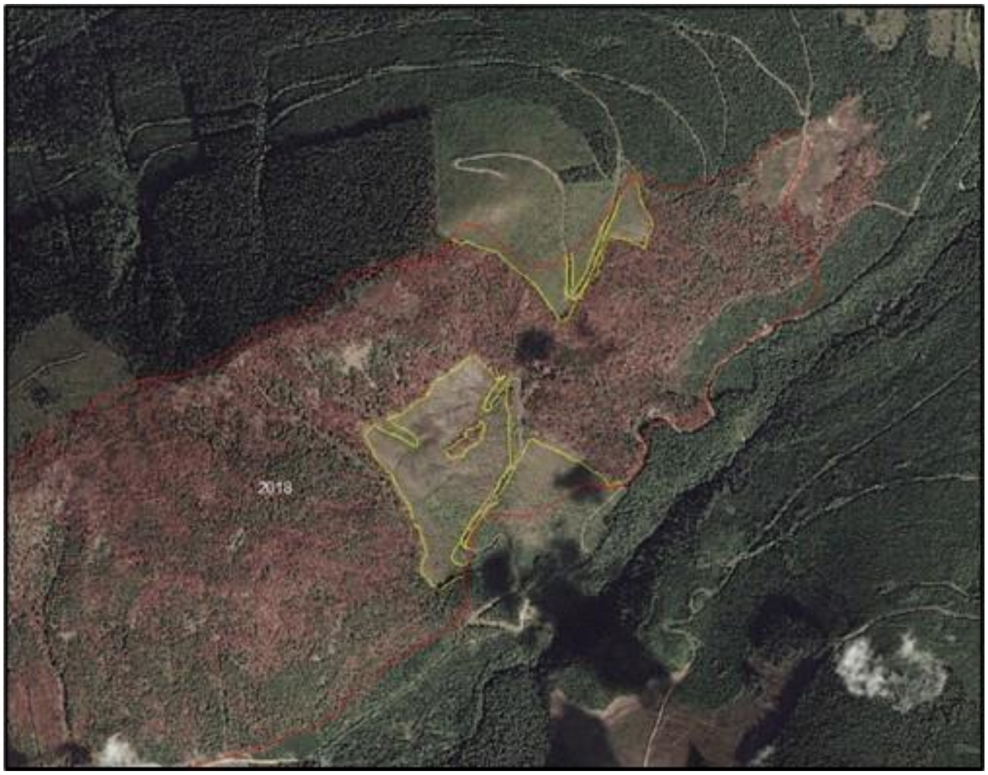

Figure 30: Broadcast burned areas at Nakusp (yellow outline) within fire N52721 (red outline).

After Aug. 18th, the wildfire made another 410m run, reaching the northeastern treatment area by August 21st (figure 31, left), held there for a couple of days before burning on the southern flank (figure 31, middle), and then progressed toward the untreated cutblock in the study, further to the northeast (figure 31, right).

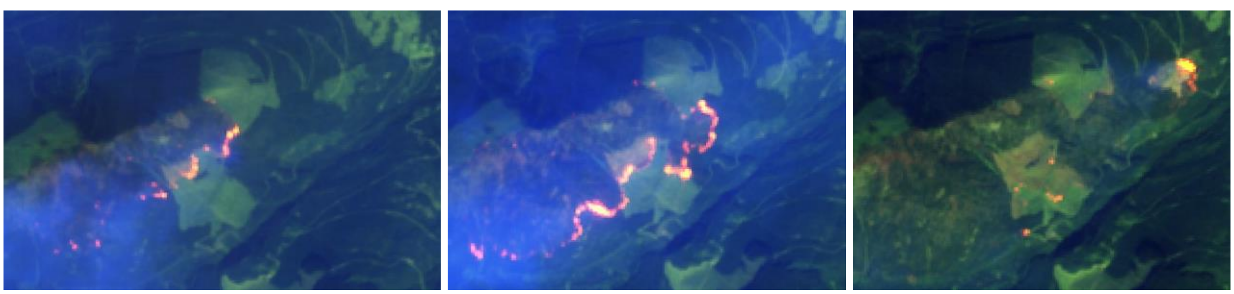

Figure 31: Progression of fire N52721 from west to east on Aug 21st (left), Aug 23rd (middle), and Sept 5th (right).

Fire Weather

The two Active Fire Weather Stations most relevant to the Nakusp site, which is on a southeast aspect at an elevation of 1260m in the ICHmw2 biogeoclimatic unit, are Falls Creek and Curwen Creek. Falls Creek is only 19 km from the study site but is a west aspect at an elevation of 790m and close to Upper Arrow Lake, although it is in the same biogeoclimatic unit. Curwen Creek is a southeast aspect at 1286m and also in the same biogeoclimatic unit. Weather station data for these two stations for August 18th, 20th, 24th, 27th and Sept. 5th are shown in table 7.

Table 7: B.C. active weather station data for Falls Creek and Curwen weather stations near Nakusp B.C in 2018.

Date	Temp	R/H	Wind Spd	Wind Dir	Precip (mm)	FFMC	DMC (daily)	DC (daily)	ISI	BUI (daily)	FWI	Danger Class
Curwen												
Aug 18	16.1	66	0	38	0	87	48	283	2.9	67	10.2	3
Aug 20	23.0	35	7	27	0	90	53	296	6.0	73	18.7	4
Aug 24	13.3	57	6	245	0	88	64	324	4.5	86	16.5	4
Aug 27	15.1	63	8	244	5.2	56	43	326	0.5	65	1.0	3
Sept 5	20.3	35	4	77	0	84	17	325	2.4	30	5.1	2
Falls Creek												
Aug 18	19.7	65	2	245	0	87	62	432	3.2	92	13.2	4
Aug 20	23.4	45	8	253	0	89	67	446	5.2	97	19.8	4
Aug 24	20.6	39	12	266	0	90	78	474	7.9	111	28	4
Aug 27	19.3	45	10	278	6.8	66	50	464	0.9	79	3.8	3
Sept 5	17.9	41	7	237	0	86	28	469	3.3	48	9.1	3

Temperatures and relative humidity on the days the wildfire interacted with the Nakusp study site were moderate. Winds were from the southwest most of the time during the fire and were not strong. The BUI was relatively high, but initial spread rates were low to moderate because of lower wind. A significant rain event on August 27th reduced fire weather indices, but by early September, conditions were dryer again (despite better overnight recovery). Fire weather at the Nakusp site was relatively moderate compared to other study sites (except Port McNeill, which was similar). Measured indices at 13:00 PDT for selected days at the other study sites are shown in table 8 (dates were selected based on when the fire passed near the study site (as seen on sentinel-hub) and/or BCWS reports and maps where available).

Table 8 :B.C. active weather station data for selected dates at other sites.

Location	Date	Wthr Stn	Temp	R/H	Wind Spd	Wind Dir	Precip (mm)	FFMC	DMC (daily)	DC (daily)	ISI	BUI (daily)	FWI	Danger Class
Nazko	12-Aug-18	Nazko	21.4	32	12	356	0	91.3	82	693	9.2	126	32.9	4
Flat Top Mtn	30-Aug-17	Allison Pass	26.5	16	14	273	0	96.9	379	819	23.3	378	67.8	5
Elaho	30-Jul-15	Forecast #38	31.9	14	9	277	0	96.5	91	543	16.5	128	48.2	n/a
Port McNeil	24-Aug-18	Port Hardy	19	56	11	330	0	85.6	44	467	7.1	71	20.8	4

Temperatures, relative humidity, wind speeds, fine fuel moisture content, and drought codes were generally higher at these other sites than at the Nakusp site, with a consequent increase in fire danger (fire weather index). This was borne out during field analysis of wildfire intensity on these sites.

Observed Fire Development

Based on imagery on successive days in Sentinel-Hub, ignition was upslope at the east end of the final wildfire boundary. Smoke patterns showed that wind was coming across the slope from the southwest most of the time (figure 33) during the fire (consistent with the weather station data). Effective wind speed was not likely as high as one would expect for the slopes of 10 to 40% at this site because of the cross-slope vector.

Figure 32: Sept. 4th photo of the Nakusp fire revealing low wind and a head fire moving across the slope (photo credit: Marsel Adam).

Based on an ISI of 7 and a BUI of about 80 (both values at the high end of the diurnal range – see table 8) in the days leading up to the rain event, the equilibrium rate of spread in the conifer plantations (2m crown base height), where the broadcast burning had taken place, would be 7 to 8 m/min (420m per hour in a closed forest type like the C6 plantation) and intensity class 4; resulting in an intermittent crown fire[28]. In a multi-cohort interior Douglas-fir fuel type (stands adjacent to the cutblocks), this would correspond to a probability of sustained ignition of 91%.

In actuality, the spread rates predicted with an ISI of 7 and a BUI of about 80 did not occur. Based on Sentinel-Hub imagery, by Aug. 18th, the wildfire had reached the southwestern cutblock that had been broadcast burned, and from Aug. 18th to the 21st, it spread about 500m through C5 and C2 timber types to reach the upper, northeastern cutblock. Within the southwestern treated cutblock, during that same time period (Aug. 18th to 21st), the fire only spread 200m, and between Aug. 21st and Sept 2nd, it only spread an additional 400m within the cutblock. None of these advances would be considered to be aggressive fire behaviour. The more important question, however, is whether there was a difference in spread rate between the cutblocks that were broadcast burned and the unburned cutblock. Again, based on the limited imagery available in Sentinel-Hub, it appears that between Sept. 5th and Sept. 7th (a period where there was reasonable satellite imagery), spread distance in the treated southwestern cutblock was about 50m whereas during the same period in the untreated cutblock with similar pre-wildfire stand age, structure, and topography, it was 160m.

Suppression Actions

As already noted, in August of 2018, there were more than 500 fires burning in B.C. and suppression resources were likely at their limits. The suppression response at the Nakusp site was apparently limited as there were no fire reports available for this fire other than a location map for a cat guard (orange line in figure 33).

[28] Per the Field Guide to the Canadian Forest Fire Behavior Prediction System (Taylor and Alexander, 2016).

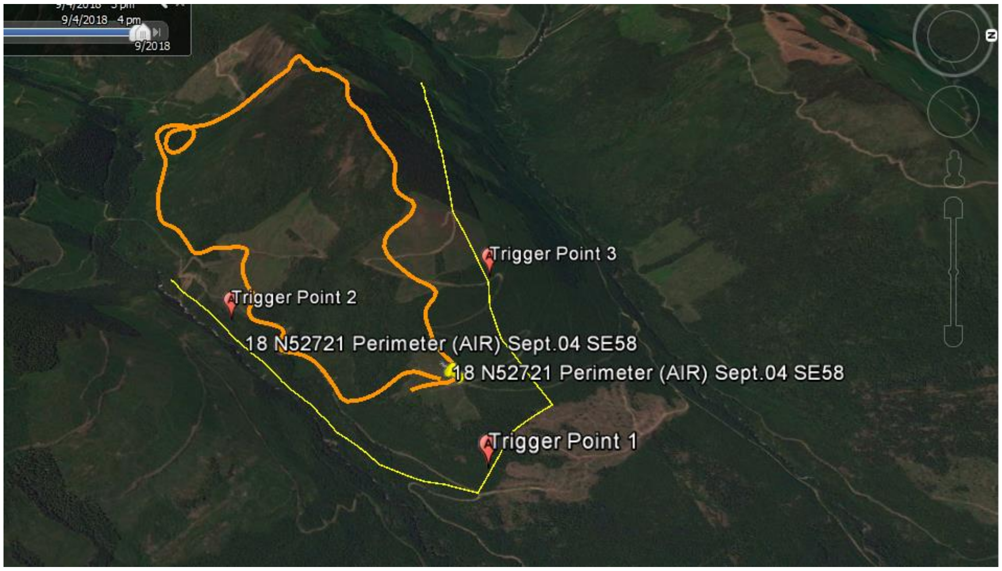

Figure 33: Location of the cat guard on the Nakusp wildifre (N52721)

Construction timing for this guard is unknown. Because the map is oriented with east up, it is difficult to relate the position of the guard to the fire perimeter, but it appears that the guard closely aligned with reported broadcast burn boundaries, and, based on Sentinel-Hub imagery, it held for a few days in both the treated and untreated cutblocks but was eventually breached in the untreated blocks and the northeastern treated block.

A similar situation occurred at the 2018 Nazko North fire (C12328), where a fireguard, built to contain the southern progression of the fire towards the town of Nazko, was located close to the 2013 broadcast burn boundary (grey line in figure 34). In this instance, the line did not appear to be located at the interface between the broadcast burn and untreated area, presumably because the line locator did not perceive there to be any differences in fuels in the area that was broadcast burned, and because of an existing trail/road that could be used on some parts of the line. An ignition was also planned for a 438 ha area north of the study site, but this did not impact fire behaviour in the study area. This fire, occurring in the same month and year as the Nakusp fire, was well resourced with 24 personnel, four helicopters, and eight pieces of heavy equipment at a point when the fire was 75% contained.

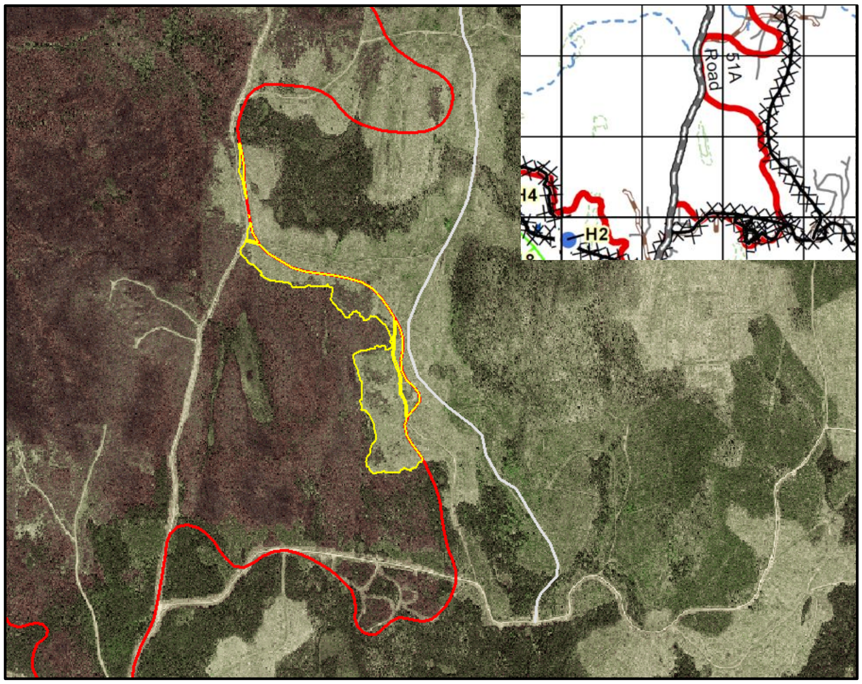

Figure 34: Fire boundary (red line), 2013 broadcast burn boundary (yellow line), and 2018 fireguard boundary (grey line) on fire C12328 (Nazko North). Inset: guard location (crosshatch line) from the incident operations map.

Figure 35: Nazko Fire 1. Photo credit: Rory Colwell.

Figure 36: Nazko Fire: 2 Photo credit: Rory Colwell.

Based on wildfire reports, suppression efforts at the other study sites in this project were also better resourced than at Nakusp. There was a full suppression response at the Elaho fire in 2015 and also in Port McNeill in 2018 during a very busy fire year when suppression resources were in high demand. At the Flat Top Mountain fire in 2017, also a big year for wildfire, a full response and sustained action approach was planned, but remote location, challenging terrain, and limited resource availability meant heavy equipment was not used, and there was limited ground action. There was no information in BCWS files for any of these fires that indicated that suppression actions directly affected wildfire outcomes in the broadcast burn areas.

Fuel Treatment Impacts

Except at the Nakusp benchmark site, it was not clear that the broadcast burn treatments significantly changed fire behaviour. Table 9 below characterizes surface and standing fuels at the study sites in treated versus untreated areas after the wildfire. One might logically expect that fire severity on sites that had not been broadcast burned would be higher, with more bole scorch and crown consumption, fewer live trees, more duff consumed, and a shift from shrubs to herbs. Conversely, a treated area could be expected to have less scorch and crown consumption, more live trees, more duff, and lower herb cover. Except at the Nakusp site, data in table 9 do not corroborate this thinking, showing that:

1. fire severity was similar to, or more severe, on sites that had been broadcast burned versus those that hadn't based on Wildfire Service fire severity mapping (not available for the Elaho site), drone imagery, and field observations (see also figures 37 and 38). This finding is at odds with Prichard and Kennedy (2014)[29], who found that clearcutting and broadcast burning had the greatest difference from no treatment in terms of the reflectance classification (burn severity) in mixed conifer stands in Washington State when imagery was obtained one year after the wildfire.
2. there was little difference in the number of surviving plantation trees
3. there was no clear trend in shrub and herb cover in treated versus untreated areas
4. there was little difference in duff levels after wildfire in areas that were broadcast burned versus those that weren't
5. residual woody fuels were similar in treated and untreated areas after the wildfire (theoretically, post-wildfire fuel levels could be the same with an effective broadcast burn and less severe wildfire versus no broadcast burn and a more intense wildfire)

[29] Prichard and Kennedy. 2014. Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event. Ecological Applications, 24(3), 2014, 571–590.

Table 9: Post-wildfire stand conditions in areas that were broadcast burned areas (treated) versus untreated areas.

Site	Wildfire Severity*	L3 and L4 Species Comp	Live L3 and L4 sph	L3 and L4 Height (m)	Crown Closure	Shrub % cover	Herb % cover	Duff Depth (cm)	Fuel % cover (>12.5 cm)	Fuel % cover (<12.5 cm)	CWD (Tonnes/ Ha)
Nazko Untreated	Unburned	Pl	1000	1.2	2	20 to 30	65 to 90	2 to 5	1	6	10
Nazko Treated	Low	Pl(Sx)	0 to 1000	1.2	0 to 2	7	85	1	0	5	10
Nazkup Untreated	High (Mod)	CwLw	<200	3 to 7	0	18	50	0 (1)	1	2	4
Nazkup Treated	Mod	Lw (Cw, Pw, Fd)	600	2 to 6	5	40	15 to 25	1	3	2	7
Flat Top Untreated*	Unburned (Low)	Sx(Pl, Bl)	3000	3 to 11	70	30	6	1 to 2	2	2	65
Flat Top Treated	Mod	Pl	<100	2 to 5	<1	0	75	0	2	0	65
Elaho Untreated	High	Fd	<10	12	0	40	12	0	7**	10**	30**
Elaho Treated	High	Fd	<10	8	0	30 to 75	15	0	1	6**	230***
Elaho Fldplain Treated	Mod	FdCw	<100	8	1	70	40	0 to 13	2	7	20
Tahsish Rv Untreated	Mod (Low)	FdCwHw	200	10	2	20	30	0 to 13	5	6	100
Tahsish Rv Treated	Mod (High, Low)	FdCwHw	<100	10	1	2	5	0	4**	14**	35

* refers to severity values produced by B.C. Min. FLNRORD using the normalized difference vegetation index (NDVI) or observed values where these were not available.
** wildfire did not penetrate this stand.
*** surface woody fuel loading was primarily a result of blowdown of wildfire-killed trees from the previous plantation.
**** high coarse woody debris values were a result of a few very large stems (1 m diam) left after original logging.

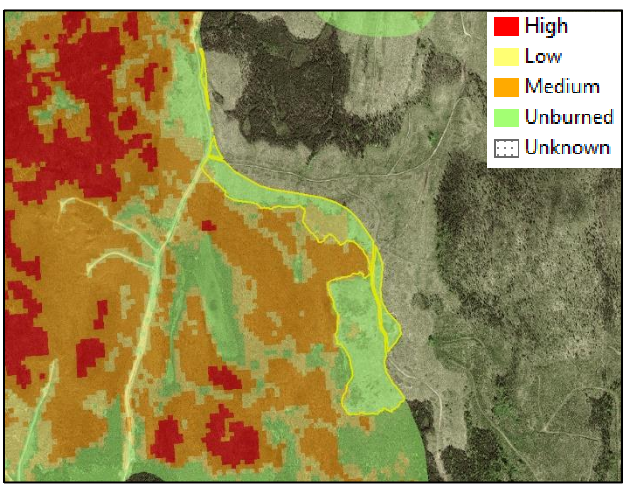

Figure 37: Wildfire severity at the Nazko site. Yellow outline is the area within a plantation that was broadcast burned and affected by wildfire.

Figure 38: Drone imagery at the Elaho site after the wildfire showing the difference in burn severity after broadcast burning (east of the yellow line) versus the area that was not broadcast burned (west of the yellow line).

In figure 37, the area that was in the plantation and was broadcast burned had a low to moderate burn severity following the spotty wildfire, but the part of the plantation that was not broadcast burned (east of the yellow line in figures 37), did not burn in the wildfire at all. As noted in the preceding section, there was a fireguard east of this site, but the wildfire did not reach it. In figure 38, fire severity in the area that was broadcast burned (right of the yellow line in the image) was higher than in the area that was not broadcast burned (left of the yellow line). At the Nazko North site, the wildfire fire did not reach the broadcast burned area until after Aug. 22nd, shortly before it was extinguished less than five days later. This was likely due primarily to rain events on Aug. 25th (3.2 mm) and the 27th (2.8mm). The reason the wildfire did not penetrate further into the plantation may have been due to the timing of the rain event and the prevalence of higher levels of flashy fuel in the broadcast burned area (versus shrubs in the rest of the cutblock).

At the Flat Top, Elaho, and Tahsish (Port McNeill) sites, variables such as stand structure before the wildfire, topography, and time since treatment appeared to be more important factors than the broadcast burning treatment. As can be seen in table 10, the stands at these three sites were older, with much higher crown closure, on steeper slopes, and except for the Tahsish site, were experiencing higher fire weather indices.

Table 10: Pre-wildfire stand conditions, topography, and treatment timing in relation to the year of the wildfire.

Location	Tree Species	Stand Age	Stand Ht (m)	%Crown Closure	Aspect	% Slope	Treatment Year	Wildfire Year	FWI
Nakusp	**Lw(Cw,Fd)**	**7**	**3**	**15**	**SE**	**15-35**	**2005**	**2018**	**20**
Nazko North	Pl(Sx)	5	1.2	7	W	3-8	2013	2018	33
FlatTop Mtn	Pl	15	3.5	52	NE	35-50	2000	2017	68
Elaho Rv	Fd(Cw)	24	8	30	SW	20-60	~1991	2015	48
Tahsish	Fd,Cw,Hw	24	10	90	E&W	10-40	~1992	2018	21

Post-treatment fuel buildup, particularly of flashy fuels (grasses and herbs, needle litter, and fine branches), was likely a contributing factor to the lack of fuel treatment efficacy at these sites. It is also possible that broadcast burning will simply not be effective with higher intensity fires if a resistant stand structure has not developed. Based on field observations and plot data collected we collected at various locations across the province, it appeared that closed canopy, second-growth stands (generally 20 to 40 years old) of hybrid white spruce, lodgepole pine, and sub-alpine fire were highly fire-resistant even in a high-intensity fire event. However, at the FlatTop Mountain site, the stand was too young and open to be fire-resistant, and at the Elaho site, it had been 24 years since treatment, the plantation was borderline in terms of crown closure, it was on a steeper south-facing slope (more prone to carrying a fire), and it was a Douglas-fir plantation, a stand type that appears to be less resistant than spruce, pine, and subalpine fir types. At the Port McNeill site, which was also broadcast burned more than 25 years before the wildfire, the treated area that burned in the wildfire was old enough to be fire-resistant, but it was also a Douglas-fir plantation on open, ridged, karst topography and was not highly fire-resistant. A stand in this same broadcast burned block with a similar stand structure and age but a different species mix (western hemlock and amablis fir), and which was located on a lower slope, seepage site, did not burn. At the Port McNeill site, species composition, crown closure, and slope position were controlling factors.

At the benchmark broadcast burn site near Nakusp, the impacts of the 2005 broadcast burning on 2018 wildfire outcomes were most like what might be expected. Key measures of wildfire impact are summarized in Table 11. Pre-wildfire stand age, species, structure, and topography were very similar in the broadcast burned area and untreated area, yet the wildfire in the untreated stand was more intense, included some crown involvement, killed more trees, and consumed more duff and woody debris (figures 39, 40 and 41).

Table 11: Measures of wildfire impacts at the Nakusp study site based on field data collected in 2020 in treated and untreated areas

Plot Type	Fire Intensity Class	Crown Burn Percent	Bole Char Ht. (m)	% Duff Consumption	Surviving Trees (Stems/Ha)	
Untreated Area	4	50	3.0	100	<50	
Treatment Complete	3	20	0.2	95	600	

In the northeastern block, where the broadcast burn appeared to be incomplete, burn intensity was even lower, but the pre-wildfire stand in this block was more fire-resistant because it was denser (1200 to 2000 stems/ha vs 1000), crown closure was higher, and the stand was taller (4 to 8m tall versus 2 to 6m). Low burn impacts in that stand might have had more to do with stand structure than broadcast burn treatments.

Figure 39: Stand condition two years after the wildfire at the Nakusp site in the untreated area.Stand condition two years after the wildfire at the Nakusp site in the untreated area.

Figure 40: Stand condition two years after the wildfire at the Nakusp site in the southwest block that was broadcast burned.

Figure 41: Drone image highlighting low post-wildfire stand mortality in the southwest broadcast burned area at Nakusp.

In summary, based on the few examples available in this study, broadcast burning did not appear to significantly alter wildfire behaviour except at the Nakusp study, where wildfire impacts were clearly lower on treated areas relative to the untreated area when topography, stand structure, and fire weather was similar. Some of the reasons broadcast burning did not appear to be as effective on some sites include:

1. Fire weather – in hot, dry, windy conditions (90th percentile or beyond), it is very difficult to achieve an intensity class less than 4 (<4000 kW/m). Beverly et al. (2020)[30], for example, suggest that under low to moderate fire weather conditions, fuel treatments will likely be successful at reducing fire behaviour. However, under high or extreme fire weather, the effects of fuel treatments (i.e. thinning and pruning in their example) in Boreal forest fuel types will not achieve the same reduction in fire intensity and rate of spread. Hudak et al. (2011)[31] state that, under extreme fire conditions, it's likely that fuel management treatments will have minimal effects on mitigating wildfire intensity/severity.
2. Quality of treatment – incomplete, spotty, or low surface intensity broadcast burning may not reduce surface fuels enough to impact fire behaviour. Prescribed fire can reduce horizontal fuel continuity (shrub, low vegetation, woody fuel strata), which in turn disrupts the growth of surface fires, limits their intensity, and reduces the potential of spot fire ignition. In addition, by reducing fine fuels, duff, large woody fuels, and rotten material, their continuity changes the fuel energy stored on the site and potentially reduces both fire intensity and burn severity (Reid, 2010)[32].
3. Time since treatment - although there was insufficient data to provide detail on how long broadcast burning might be effective in changing wildfire behaviour, burning that had occurred more than 20 years before the wildfire did not have any influence on wildfire outcomes. At the Nakusp site, 13 years after treatment, some treatment effect was still noticeable. After about 20 years, there is good evidence that stand structure could be a more important factor than broadcast burning in reducing wildfire impacts.
4. Ecosystem condition - treatment is unlikely to be as effective or last as long in ecosystems where high levels of herbaceous species, grass, and tree litter are likely to develop quickly after treatment (mesic to fresh sites with less shrub development).

Predicted Versus Observed Fire Behaviour With and Without Fuel Treatment

In this project, we used a paired plot approach to compare areas that were treated and burned in a wildfire with areas that were not treated but were burned as a way to determine if treatments had an impact on wildfire behaviour. Low numbers of interactions between wildfires and broadcast burn treatments, time since treatment, size of treatment areas, and quality of treatments made comparisons difficult, however, and so we also conducted a preliminary analysis of other methods to evaluate treatment efficacy. These included the Critical Surface Fire Intensity (CSFI) worksheet, Prometheus, and Canfire. A brief synopsis of these methods and their utility in understanding the impacts of broadcast burning is provided below.

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[30] Beverly et al. 2020. Stand-Level Fuel Reduction Treatments and Fire Behaviour in Canadian Boreal Conifer Forests. Fire, 3(3), 35.
[31] Hudak et al. 2011. Review of fuel treatment effectiveness in forests and rangelands and a case study from the 2007 megafires in central Idaho. USA. RMRS-GTR-252. Fort Collins, CO.
[32] United States Department of Agriculture. 2010. Cumulative Watershed Effects of Fuel Management in the Western United States, Symposium Proceedings. USDA, Rocky Mountain Research Stn, General Technical Report RMRS-GTR-231. Chpt. 14

More detailed analyses associated with this synopsis are contained in Appendix II - Analysis Of The Utility Of Fire Behaviour Prediction Tools.

The Critical Surface Fire Intensity Worksheet

The critical surface fire intensity worksheet is a stand level spreadsheet tool produced by BCWS that can be used to calculate fire intensity (kW/m), surface fire flame length, and critical surface fire intensity for initial crown combustion, all useful variables when predicting the efficacy of fuel treatments. Inputs include live crown base height, date of ignition, latitude and longitude to get foliar moisture content (FMC) using the BCWS Foliar Moisture Content Calculator, the surface fuel loading (not including duff) in kg/m^2, fuel type, and equilibrium rate of spread (ROS) based on expected fire weather indices (ISI and BUI) for the fuel type involved. The tool is useful primarily in determining spread rate and whether the surface fire intensity will exceed the critical intensity required to result in some degree of crown involvement. With respect to broadcast burning, one could use it to compare spread rate and surface fire intensity for a given location and fire weather condition, when no fuel treatments have been conducted, versus after treatment. It could also be useful in helping determine how often to treat a firebreak to achieve the desired fuel load for a given spread rate and surface fire intensity targets.

In this project, we used the CSFI calculator to simulate spread rate and critical surface fire intensity using:

1. fuel loads before broadcast burning and actual fire weather indices at the time of the wildfire,
2. fuel loads after broadcast burning and actual fire weather indices, and
3. fuel loads before broadcast burning and average 90th percentile fire weather indices for this location over the last 20 years determined from the BCWS 90th percentile Fire Weather Index Calculator[33].

Because there was no way of knowing pre-wildfire fuel loading, we used fuel load surrogates (see appendix II) for input into the calculator.

Despite its promise, the simulations revealed that there are several limitations with the calculator and/or the sources of input data when trying to determine appropriate fuel loading:

1. Surface fuel load values before treatment will need to be measured, and a basis for estimating fuel loading after treatment will also be necessary if wildfire impacts before and after treatment are to be compared.
2. The calculator uses the Canadian Forest Fire Behaviour Prediction System fuel types and associated ISI and BUI values which, in B.C., are not well calibrated for several fuel types, including conifer plantations (Brad Martin, Senior Wildfire Officer – Prevention, NW Fire Centre, pers. comm. 2020), black spruce stands (Beverly et al. 2020), B.C. coastal forests and interior cedar hemlock stands (Taylor and Alexander, 2016), and treated stands which don't fit any of the fuel types post-treatment (Beverly et al. 2020).
3. Results from the CSFI are directly dependant on Bryam's formula (1959)[34] for quantifying fire intensity, a widely accepted metric for fire behaviour. However, this formula appears to be highly sensitive to the initial spread rate, sometimes providing values that are not even on the same scale as the CSFI table for critical surface fire intensity thresholds (where the maximum value is <4000 kW/m).

[33] https://wps-web-prod.pathfinder.gov.bc.ca/percentile-calculator/

[34] Byram, George M. 1959. Combustion of forest fuels. Pages 61-89 In: Davis, K. P., editor. Forest fire: control and use. New York, NY: McGraw-Hill.

4. Using the 90^{th} percentile fire weather indices predicted with the Fire Weather Index Calculator could be useful in planning treatments but must be used with caution given that, in this test, it led to values for predicted head fire intensity and rates of spread that were far higher (5x) than both the 2020 BC Wildfire Service Head Fire Intensity (HFI) mapping available from DataBC's BC Data Catalogue, and observed conditions.
5. The CSFI calculator states that fuel treatments should target an outcome that keeps surface fire intensity to less than 2000 kW/m, presumably because intensities less than 2000 kW/m can be suppressed by direct ground attack. Per Brad Martin (Senior Wildfire Officer – Prevention, NW Fire Centre, pers. comm. 2020), an intensity where conventional suppression methods, including air resources, have a reasonable chance of success is more like 4000 kW/m.

In the most plausible scenario in this analysis of the CSFI worksheet, where the area had been broadcast burned with a resulting fuel load of 2.2 kg/m^2 and actual fire weather indices were used, surface fire intensity was simulated to be less than the threshold (meaning crown fire was unlikely) and the rate of spread was low at 0.3m/min. Broadcast burning provided a positive fire management outcome in this case, but such conclusions must be used cautiously, especially when fire weather indices are approaching the 90^{th} percentile. It is best used as a tool to explore the relative impacts of varying fuel loads on fire intensity and possible crown fire (i.e. treatment versus no treatment). The absolute values for fuel load required to make a difference in wildfire behaviour should be treated with caution. Additionally, in the case of young plantations, knowing whether there is potential for crown fire is not as important as rate of spread values that can be obtained directly from the Canadian Forest Fire Danger Rating System. A final limitation of the calculator is that it is not spatially explicit and does not account for the heterogeneity of fuels and their interaction across a landscape. For that type of analysis, tools like Prometheus or Canfire are required.

Prometheus And Canfire

Prometheus[35] and Canfire[36] are landscape-level tools that have great potential for evaluating the impacts of fuel treatments on wildfire behaviour and would be very helpful in answering questions such as how big treatments should be or how frequently they should be done. Prometheus is a deterministic wildland fire growth simulation model that simulates spatially explicit fire behaviour given heterogeneous fuel, topography and weather conditions. According to Natural Resources Canada, the web-based version of CanFIRE is set up to calculate fire behaviour and fire effects for an individual stand and can be used to run various hypothetical scenarios for prescribed burn planning or to estimate expected wildfire behaviour and impacts quickly.

In this study, simulations using both models were initially proposed to test the efficacy of broadcast burning in changing wildfire behaviour. By looking at treated versus untreated scenarios, it was hoped that differences in the rate of spread, intensity, probability of crown fire, and fuel consumption could be identified and then compared to field observations. Prometheus, however, does not allow for detailed characterization of fuel types beyond the simple fuel types described in the Canadian Forest Fire Behaviour Prediction System, making it impossible to use the model to do fuel treatment analysis. BCWS modellers also warn that Prometheus fire growth simulations are sensitive to some variables and may not

[35] http://firegrowthmodel.ca/prometheus/overview_e.php
[36] http://www.glfc.forestry.ca/canfire-feucan/index.cfm?lang=eng

reflect the actual size and shape of fires (Dana Hicks[37], 2020; Dan Perrakis[38]). Beverly et al. (2020)[39] , in an evaluation of different fuel treatment strategies, data inputs, and methodologies for modelling/testing the effects of fuel breaks (including both Prometheus and Canfire), also warns that there is great sensitivity to model assumptions when modelling fire behaviour.

Canfire provided more control in terms of input variables such as fuel loading, including litter, upper duff, lower duff, medium woody debris load, and coarse woody debris before and after treatment. Outputs include fuel consumption by fuel class, emissions, and a fire summary with, amongst other things, head

Fire Summary

Fire Behaviour

Showing 1 to 11 of 11 entries | Filter items

Behaviour Element	Behaviour Value
Crown fire?	No
Scorch Height	8.788 meters
Total Fuel Consumption	6.072 kg/m^2
Total Surface Consumption	6.072 kg/m^2
Final HFI	456.157 kW/m
Surface HFI	456.157 kW/m
Forest Floor Consumption	4.0573 kg/m^2
Dead Woody Debris Consumption	2.015 kg/m^2
Rate of Spread	0.917 m/min
Crown Fuel Consumption	0.000 kg/m^2

Figure 42: CanFIRE simulations with no broadcast burning using fuel loading data from Kranabetter and Macadam (1998) and actual fire weather indices from the Nakusp study site.

Fire Summary

Fire Behaviour

Showing 1 to 11 of 11 entries | Filter items

Behaviour Element	Behaviour Value
Crown fire?	No
Scorch Height	7.995 meters
Total Fuel Consumption	4.661 kg/m^2
Total Surface Consumption	4.661 kg/m^2
Final HFI	395.854 kW/m
Surface HFI	395.854 kW/m
Forest Floor Consumption	3.42768 kg/m^2
Dead Woody Debris Consumption	1.233 kg/m^2
Rate of Spread	0.917 m/min
Crown Fuel Consumption	0.000 kg/m^2

Figure 43: CanFIRE simulations with broadcast burning using fuel loading data from Kranabetter and Macadam (1998) and actual fire weather indices from the Nakusp study site.

fire intensity, rate of spread, and whether a crown fire is likely (figures 42 and 43).

However, as can be seen in figures 42 and 43, differences in outcome between no treatment and treatment, when FFMC codes were moderate, and wind speed was low, were relatively minor (456 versus 396 kW/m^2) for head fire intensity. When wind speed was increased to 20 km/hr, and FFMC was changed to 94 (90th percentile), the untreated stand was projected to have a head fire intensity of 18,586 kW/m, and the treated stand was projected to have a head fire intensity of 16,130 kW/m. This result was an order of magnitude different than the first scenario and calls into question the sensitivity of the model. The difference between treatment and no treatment was also relatively small in the second scenario and did not provide a compelling argument for broadcast burning. As was the case with CSFI and Prometheus, the main indicators of broadcast burn efficacy were limited to the surface intensity and the potential for crown involvement. When broadcast burning is done primarily in harvested clearcuts as a way to mitigate wildfire impacts in C6 fuel types, crown involvement is not a significant factor, and the utility of the

[37] Dana Hicks. Short Range Fire Growth Projection for K51278, Christie Mountain. Aug. 19th, 2020. Unpublished report.

[38] Dan Perrakis, Short Range Fire Growth Projection for V30160, Elaho River. June. 17th, 2015. Unpublished report.

[39] Beverly et al. 2020. Stand-Level Fuel Reduction Treatments and Fire Behaviour in Canadian Boreal Conifer Forests. Fire, 3(3), 35.

calculator and models, therefore, is really no better than simply using the Canadian Forest Fire Danger Rating System Field Guide to get a rate of spread and intensity class.

Lessons Learned

As was the case with the Thinning case study, there were not enough examples of wildfires interacting with broadcast burning treatments in this study to provide thresholds or answers to practical questions such as how much surface fuel can be tolerated, what distribution of surface fuels is optimal, how often does a fuel break need to be retreated, and how big does a treatment area have to be. Nonetheless, in thinking about how to achieve effective fuel management in the future, a number of insights bear mentioning. These form the basis for several recommendations in Section 4:

1. Since about 1993, there has been a dramatic decline in the use of broadcast burning in B.C. Since then, there have been very few instances in the province where a recent wildfire (2012 or later) has intersected with a broadcast burning treatment. In this study, we identified 12 such locations, only five of which were suitable for analysis. These findings support revisiting the use of broadcast burning in B.C and are consistent with recommendations in the Abbott/Chapman report (an independent review examining the 2017 flood and wildfire seasons)[40].

2. While there is some data from studies undertaken more than 20 years ago on pre and post-broadcast burn fuel conditions (e.g. Kranabetter and Macadam, 1998), logging practices and market conditions (which drive utilization) have changed significantly, and this type of data may not serve as a benchmark today. This is an important loss, given that all of the models and calculators used to predict fire behaviour are based on fuel levels.

3. It was evident in this study that the implementation of broadcast burning in the past was not always successful. Cochrane et al. (2102)[41] examined the effects of more than 72,000 ha of wildland fuel treatments in 14 large wildfires in the U.S. and concluded that the effectiveness of treatments will vary as a function of the type, amount, size, spatial distribution and intensity of treatments, time since implementation, ecosystem type, topography and weather conditions at the time, and geographic location of burning. Hudak et al. (2011)[42] , in a review of fuel treatment effectiveness in forest and rangelands in central Idaho, concluded that prescribed burning treatments varied in their effectiveness. Kelly Osbourne, fire and fuel management officer with BCWS (pers. comm, 2020), cautions that past treatments may not be reflective of current practices and that *B.C. is currently focusing on increasing training and support for the science-based application of prescribed fire on the land base in a targeted approach with clear objectives linked to fire behaviour outcomes.*

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[40] G. Abbott and M. Chapman. 2018. Addressing The New Normal-21st Century Disaster Management In BC. https://www2.gov.bc.ca/assets/gov/public-safety-and-emergency-services/emergency-preparedness-response-recovery/embc/bc-flood-and-wildfire-review-addressing-the-new-normal-21st-century-disaster-management-in-bc-web.pdf

[41] Cochrane et al. 2012. Estimation of wildfire size and risk changes due to fuels treatments. International Journal of Wildland Fire 2012, 21, 357–367. http://dx.doi.org/10.1071/WF11079

[42] Hudak et al. 2011. Review of fuel treatment effectiveness in forests and rangelands and a case study from the 2007 megafires in central Idaho. USA. RMRS-GTR-252. Fort Collins, CO.

4. Actual fire behaviour (spread rate and crown involvement) is not always consistent with fire behaviour predicted in the Canadian Forest Fire Danger Rating system. Understanding why this can occur is important when planning wildfire mitigation.

5. In this study, fire severity mapping using the normalized difference vegetation index (NDVI) approach used by BCWS was reasonably reflective of fire severity and crown consumption, scorch height, duff consumption, and tree mortality observed during field assessments. Cases where it might be less reliable are with a) slow-moving ground fires that smoulder and burn a substantial proportion of the duff but have little crown involvement, b) when dry litter layers or flashy fuels burn easily, but deeper duff layers are moist or frozen resulting in shallow burn depth and less infrared reflection, or c) less commonly, with high wind speed and a fast-moving crown fire that does not necessarily cause as much duff consumption (Brad Martin, Senior Wildfire Officer – Prevention, NW Fire Centre pers. comm. 2020).

6. Information from suppression actions, which could provide valuable learning on broadcast burn efficacy, is not normally available or is incomplete. Focusing on an efficient system to collect this information during or shortly after a wildfire is key. BCWS has already developed a tool (the Fire Behaviour Field Collection Form) that is meant to serve as a template for use by suppression forces (and others) during a fire event. This could be expanded to include key factors when a wildfire interacts with any kind of fuel treatment.

7. In the broadcast burn case study, there was no record that suppression efforts were influenced by fuel treatments, although Hudak et al. (2011) reviewed several case studies in which fuel treatments were effective at aiding fire suppression efforts.

8. Based on the few examples available in this study, it appears that there is some uncertainty about achieving fire management objectives with broadcast burning when treatments are driven by silviculture objectives rather than wildfire mitigation objectives. Past practices suggest that broadcast burning was not an easy tool to use because of the many variables involved, uncertainty about weather, and the potential magnitude and consequence of an escaped burn. Fernandes and Bothelo, in a review of prescribed burning effectiveness in fire hazard reduction (2003)[43], state that the variation of site factors (i.e. fire weather, indices) can greatly vary the fuel reduction efficacy of a burn, which makes using prescribed fire as a fuel reduction tool somewhat difficult to control directly. Formulating realistic fire behaviour objectives is critical, and clearly articulating the environmental and wildfire thresholds where the treatment is likely to be successful will help ensure that it is used in the right circumstances.

9. BCWS and the Canadian Forest Service have developed several predictive tools to help understand potential wildfire behaviour, although none of these proved to be very useful in this study. When broadcast burning is done primarily in harvested clearcuts as a way to mitigate wildfire impacts, success is measured based primarily on fuel continuity, potential fire intensity, and rate of spread - crown involvement is less important. The utility of the predictive calculators and models, therefore, may not be any more helpful than simply using the Canadian Forest Fire

[43] Fernandes and Botelho. 2003. A review of prescribed burning effectiveness in fire hazard reduction. International Journal of wildland fire, 12(2), 117-128.

Behaviour Prediction System Field Guide. With some changes, these models do have potential, particularly if pre-broadcast burn fuel condition has been collected.

10. Although the Forest Fire Behaviour Prediction System is a widely used and useful tool, there are some significant challenges in applying it to fuel treatment analyses in B.C. One of these is the lack of ability to adequately represent changes in stand structure and fuel loading associated with thinning or broadcast burning treatments. For example, changes in stand volume, canopy bulk density, stem espacement, or canopy base height with thinning and pruning treatments, or increases in fuel loading and ladder fuels that occur over time as a stand grows after clearcutting, or fuel loading reductions that occur with decomposition or broadcast burning. Another challenge is that the fuel types themselves don't always represent B.C conditions. For example, the need to use C5 (red and white pine) for interior Douglas-fir stands, C6 (conifer plantations) was also based on red and white pine, which doesn't occur in B.C., there is no fuel type for interior Douglas-fir or slash modifiers for different volumes resulting from different utilization levels or treatments, and C1 (spruce-lichen woodland) is an upland, well-drained type that doesn't represent the frequent black spruce bogs that occur in the B.C. interior. Of course, adding more fuel types and/or modifiers is a big undertaking, and to date, there has been little appetite to invest in filling in the gaps.

11. Small, thin, and irregular treatment areas such as those at Nakusp or Nazko North (or many of the Thinning fuel treatment areas) are less effective because the wildfire will have more opportunity for spotting or to find a different path through another fuel type. Barnet et al. (2016) found, for example, that larger treatments that interacted with wildfire between 1999 and 2013 on U.S Federal Lands were more effective at reducing fire impacts due to less edge effect and more interior area, and emphasize the need to find innovative ways to treat larger areas[44]. Reid (2010)[45] states that despite some modification of fire behaviour, there are no studies of small-scale treatments that demonstrate that spread or behaviour of a large fire was significantly altered - probably because the units were relatively small and were surrounded by areas containing vegetation favouring continued fire growth.

12. As was the case with the thinning/debris disposal/pruning treatments, the geographic location of a treatment unit as it relates to topography, resistant fuel types, and values at risk is important. Landscape-level planning will help identify where fuel reductions can be most useful, but if broadcast burning depends on the relatively random selection of blocks that are burned for other reasons (to meet abatement requirements or for silvicultural purposes, for example), then the treatment may not be helpful in terms of meeting wildfire management objectives.

13. Based on findings in this study, it appears that prescribed fire treatments, as they were implemented in the past, are less effective than treatments that aim to modify stand structure and surface fuels through thinning and debris disposal. However, prescribed fire, properly implemented, can reduce horizontal fuel continuity (shrub, low vegetation, woody fuel strata),

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[44] Barnett et al. 2016. Beyond fuel treatment effectiveness: characterizing interactions between fire and treatments in the US. Forests, 7(10), 237.

[45] United States Department of Agriculture. 2010. Cumulative Watershed Effects of Fuel Management in the Western United States, Symposium Proceedings. USDA, Rocky Mountain Research Stn, General Technical Report RMRS-GTR-231, Chpt 14

which in turn disrupts the growth of surface fires, limits their intensity, and reduces the potential of spot fire ignition (Reid, 2010). Other authors believe that using a combination of thinning and prescribed fire is the most effective at reducing crown fire initiation, spread, and severity (Hudak et al., 2011; Omi and Martinson (2009)[46].

4. RECOMMENDATIONS

Despite the lack of interactions between wildfires and fuel treatments like thinning/debris disposal/pruning or broadcast burning in British Columbia, there was sufficient evidence from the case studies undertaken in this project to make a number of recommendations. Some of these apply to any type of fuel treatment, while others are particular to a specific treatment.

1. With the magnitude and cost of wildfires in recent years and the possibility that the situation will get worse with climate change, there has been an increased focus on forest fuel treatments as a mitigative measure. Fuel treatments can be very expensive, however (thinning and debris disposal treatments in particular), and/or involve significant risks (broadcast burning near infrastructure for example), and there is an incomplete understanding of their impact on fire behaviour in B.C ecosystems. Up until 2020, manual thinning and debris disposal treatments conducted without any timber harvesting averaged $3839/ha (30 projects) and mechanical thinning treatments that didn't involve timber harvesting averaged $1853/ha (7 projects), according to a Forest Enhancement Society of BC (FESBC) Wildfire Risk Reduction Treatment Cost Summary[47]. This data suggests the need for increased investment in the science that underpins fuel treatment decisions and treatments. Some examples include:
    a. Conducting controlled burn experiments at, for example, 90th percentile weather indices to quantify the effectiveness of fuel treatments in fuel types that are most at risk. This might include such things as pre and post-burn fuel load measurements, fuel continuity mapping, in-stand heat flux sensors, photogrammetric flame heights, burn pins, drone-based infrared imagery, and drone-based high-resolution imagery of stand structure. If the experiments were conducted in an area already identified for fuel treatment during strategic planning, the research could address multiple objectives. Another approach might be to allow wildfires to burn through treatment areas, although relying on chance encounters would not provide information very quickly and could not provide the range of information that could be obtained in a controlled burn.
    b. Quantifying fuel treatment longevity and the need for fuel break maintenance on selected sites in the most commonly burned fuel types by describing and quantifying the build-up of fuels year over year. Barnett et al. (2016)[48] indicate that treatments are usually most effective one to three years after treatment, except for some slow regenerating forest types where treatments can be effective for up to 20 years. Utzig

[46] Omi and Martinson 2009. Effectiveness of Fuel Treatments for Mitigating Wildfire Severity: A Manager-Focused Review and Synthesis. JFSP Project Number 08-2-1-09

[47] Gord Pratt, FESBC Operations Manager. 2020. Unpublished. Forest Enhancement Society of BC (FESBC) Wildfire Risk Reduction Treatment Cost Summary. Projects Completed Between October 2016 and March 31, 2020.

[48] Barnett et al. 2016. Beyond fuel treatment effectiveness: characterizing interactions between fire and treatments in the US. Forests, 7(10), 237.

(2019)[49] stated that in his review of the literature, most of the studies indicated that treatments are expected to begin to lose effectiveness in 5 to 15 years and become generally ineffective after 20 years.

c. Quantifying the influence of prior burn mosaics on subsequent wildfire behaviour. At one of the potential study sites in this project, the Peta Fire, three wildfires overlapped in less than a decade (2013, 2014, 2018). Prichard et al. (2018) used a combination of fire modelling and burn severity mapping (using the relative differenced normalized burn ratio) on three large wildfires in southeastern B.C. and Washington State (2003, 2006, and 2007) and found there were impacts but suggested that better information on changes in burn severity, field validation, and some model improvements are required.[50] A better understanding of how location, size and age of past wildfires influence subsequent wildfire behaviour could be helpful in planning fuel breaks and wildfire suppression and in understanding fire intensity and spread, as well as the duration of effectiveness.
d. Quantifying the impact of repeated treatment. In the US, it is not uncommon, in ponderosa/Douglas-fir types, to undertake thinning and debris removal treatment, followed by under burning every 5 to 10 years. In B.C., we have rarely had an opportunity to do this (with the possible exception of ecosystem restoration burning).

These types of investments will not only improve our understanding of fuel treatment efficacy but also provide important training opportunities for suppression personnel and practitioners implementing fuel treatments.

2. Fuel and fire calculators and predictive models have much potential to help ensure fire data collection is more consistent and improve our understanding of how treatments impact fire behaviour. At a practical level, they can help corroborate and flesh out field observations, and they can be used to help determine how much fuel can be tolerated and, therefore, when maintenance might be required. BCWS has made significant strides in making some of these tools available. Based on the analysis in this study, there are a number of improvements that could be made, however, to make them more useful in assessing fuel treatment efficacy:
   a. In Canfire and Prometheus, more control over fuel loading levels and stand structure are required. Without the ability to characterize the difference in fuels before and after treatment, neither of these tools can be used to evaluate fuel treatments. Canfire provides some control over fuel loading and distribution but does not consider surrounding fuel types and spatial heterogeneity. Prometheus is not able to simulate differences in stand structure, using only the general fuel types in Canadian Forest Fire Danger Rating System. It does, however, model wildfire behaviour over a landscape (that the user defines) and would be a useful tool to use to explore questions such as how big a treatment area needs to be to significantly change fire behaviour/achieve fire management objectives. Prometheus requires some GIS skills, though, and is cumbersome to use compared to Canfire.

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[49] Utzig, G. 2019. Forest Fuel Treatments for the Southern West Kootenays: A Summary of Experiences in Other Places. Available at: https://www2.gov.bc.ca/assets/gov/public-safety-and-emergency-services/wildfire-status/prevention/fire-fuel-management/fuel_management _prescription_guidance.pdfafdas

[50] Prichard et al. 2018. Evaluating the influence of prior burn mosaics on subsequent wildfire behavior, severity, and fire management options. https://www.firescience.gov/projects/14-1-02-30/project/14-1-02-30_final_report.pdf

b. Most of the models and calculators are based on the considerable data available and formulae that are the basis for the Canadian Forest Fire Danger Rating System. This information is currently the best available for most parts of Canada but is nonetheless insufficiently detailed to differentiate between stand structure and fuel loading in areas that have been broadcast burned or thinned versus those that have not been treated. It would be useful if further work could be completed to create a more robust characterization of B.C. fuel types, complete with some stand structure modifiers.
c. The critical surface fire intensity worksheet is a useful tool for determining spread rate and whether a surface fire will result in some degree of crown involvement. The advantage of this tool is that it accounts for wind, fuel moisture content, and recent weather, and the user can input measured fuel loads, thus accounting for differences in treatment. However, the calculator appears to be very sensitive is to high ISI. More work seems to be needed to validate formulae for a broader range of inputs. It would also make sense to integrate the fine fuel moisture content calculator directly into this spreadsheet.
d. With some changes and some rigour by fuel managers in collecting appropriate input data, fire behaviour tools could prove to be very useful. Consideration should be given to providing more training in the use of these tools.

3. Effective fuel management starts with having good data on fuels. Pre-and post-treatment data on fuels and fire weather conditions are important, as is fire behaviour information in treated areas during suppression actions that interact with fuel treatments. Such data were challenging to locate in the examples evaluated in this study. FP Innovations, on behalf of the B.C. Wildfire Service and Yukon Wildland Fire Management has developed some tools that might help ensure such information is obtained (for example, the Rapid Response Kit: Data Collection Methods For Documenting Encounters Between Wildfires and Forest Fuel Treatments (Mar. 2017)[51], the Fuels Management Field Collection Form (2016)[52], and the Fire Behaviour Field Collection Form (Mar. 2016). The next steps for BCWS could include more training in the use of these forms and a mechanism (such as a dedicated team within BCWS that can be deployed to selected wildfires during an incident to collect the data, as an example) to help advance the use of these tools.

4. The B.C. Wildfire Service Fuel Management Practices Guide (2020) has detailed descriptions of the principles of fuel management, as well as some good examples of fuel treatments, but would benefit from the inclusion of key metrics for treatment success such as surface fire fuel loads or surface fire intensity targets and rate of spread for various fuel types, terrain, and fire weather conditions. Incorporating a table with easy to refer to limits/thresholds/targets that build on the principles in the Guide could prove helpful.

5. Fuel assessments and treatments, like other land management treatments, need to be reported in a provincial database like RESULTS and include enough information to make it possible to evaluate treatment efficacy (pre-treatment site conditions, as well as particulars about the treatment, including environmental conditions at the time of treatment, treatment

[51] https://wildfire.fpinnovations.ca/173/TR2017N33.pdf
[52] https://wildfire.fpinnovations.ca/164/FieldDataForm_FuelsManagement_v2.pdf

methods, fire metrics if applicable, and treatment results). New guidance for reporting "*projects involving wildfire risk reduction that produce a land-based plan and/or completed activities on the ground*" was released by the Provincial Government in the fall of 2020. Details on program requirements are outlined in Section 19 of the RESULTS Information Submission Specifications-GF[53]. A new shell opening will be required for these activities if tenure is not issued. Tenured wildfire risk reduction activities must be reported using the Results Information Submission Specifications-LS with changes outlined in Table 27 of the RISS-GF. A spatial submission is also required. It is recommended that BCWS ensures that the Results Submission Specification includes data that will allow a retrospective evaluation of fuel treatment efficacy.

6. Treatment prescriptions must consider the full suite of fire management and other land use objectives described in strategic fire management plans as well as other higher-level plans to help ensure the best locations are chosen, and those fuel treatments will not conflict with other forest management goals. On some sites in this study, it was not clear that higher-level plans were considered.

7. A modern approach to forest fuel management goes beyond thin, linear fuel breaks whose greatest utility is in their use as an anchor point for backburning. There needs to be a cohesive land management strategy that identifies priority areas for fuel management treatment but also capitalizes on opportunities to allow wildfires to burn through treatment areas (i.e. in low-risk scenarios) to quantify the effectiveness of the fuel management activity (Barnett et al., 2016)[54]. Broader thinking will include creating landscape-level fuel discontinuity and fire-resistant stands by, for example, reducing fuels through timber harvesting, broadcast burning after logging, thinning and debris disposal in strategic locations, underburning in some areas, establishing a network of fire-resistant second-growth stands (pine, spruce, and subalpine fir that are 20 to 40 years old), encouraging deciduous stands in some areas, and tying treatments into naturally resistant features. One of the key factors that Thompson et al. (2013)[55] found in a modelling analysis of the impacts of fuel treatments on wildfire costs in Oregon was that results were contingent on large-scale implementation of fuel treatments across the landscape. Reid (2010)[56] states that fire behaviour under extreme fire weather may involve large areas of fuels, multiple fires, and spotting, so a "firesafe" landscape needs to populate hundreds to thousands of hectares with strategically located fuel treatments. While this landscape-level approach means bigger treatment areas will be required, it could also mean less maintenance as the geographic locations of fire-resistant areas shift over time, and it could result in lower suppression costs in the long run.

[53] https://www.for.gov.bc.ca/pscripts/his/apb/index.asp?DE=Y&RecordID=3625

[54] Barnett et al. 2016. Beyond fuel treatment effectiveness: characterizing interactions between fire and treatments in the US. Forests, 7(10), 237.

[55] Thompson et al. 2013. Quantifying the Potential Impacts of Fuel Treatments on Wildfire Suppression Costs. J. For. 111(1):49–58. http://dx.doi.org/10.5849/jof.12-027

[56] United States Department of Agriculture. 2010. Cumulative Watershed Effects of Fuel Management in the Western United States, Symposium Proceedings. USDA, Rocky Mountain Research Stn, General Technical Report RMRS-GTR-231. Chpt. 14

8. A key feature of landscape-level fuel management is getting timber harvesting licensees involved. Timber harvesting has more impact on landscape-level stand structure and fuel load than any other single factor. The location and type of harvesting and other land management treatments that licensees employ, therefore, should reflect fuel and wildfire considerations if landscape-level fire management objectives are to be achieved. There is an economic imperative associated with this approach as well. As noted above, fuel treatments involving thinning and debris disposal are expensive, and it would be beneficial, when possible, to undertake this type of activity when stand structure/merchantability supports some cost recovery in the form of logs or bioenergy products. In Gord Pratt's[57] Wildfire Risk Reduction Treatment Cost Summary, for example, when manual or mechanical thinning and debris disposal treatments are done in conjunction with harvesting, average costs per hectare dropped by 30 to 60%. Examples of ways licensees could assist in the achievement of landscape fire management objectives include, during the planning process, locating harvesting in areas where there is a higher potential for a running crown fire or where, 20 years into the future, a wide area of fire-resistant second-growth close to key values will be created; or using treatments such as improved utilization, broadcast burning, and trenching (mechanical site preparation) to reduce fuel loading and break up fuel continuity at the site level which could provide silviculture benefits as well as fire management benefits. A combination of incentives and regulations could be used to encourage these outcomes. An example of an incentive might be recognizing the increased costs associated with achieving fire management objectives. Another example would be to look at possible changes to the Wildfire Act and Regulation to create risk zones that are based not just on proximity to infrastructure but also on wildfire risk areas and to develop fuel hazard thresholds that are lower in these risk zones and more closely aligned with fire intensity targets.

Some other practical recommendations that one might consider:

1. Ensuring that fuel treatments reflect landscape conditions (best identified in a strategic fire management plan) as well as conditions at the treatment site.
2. Creating larger fuel breaks that have more chance of changing fire behaviour (based on modelling and an examination of surrounding fuel types).
3. If using linear treatments in areas subject to higher prevailing wind speeds, aligning them to control fire spread on the flank because fuel breaks oriented perpendicular to the direction of fire spread are unlikely to be wide enough to prevent spotting across the treatment (Romero and Menakis, 2104)[58].
4. Ensuring that thinning treatments include debris disposal (~30% of areas examined in this study had unburned debris piles).
5. Maintaining firebreaks through repeat treatment based on desired fire intensity thresholds. This is particularly important in ecosystems with frequent fire occurrences. Moody (2010)[59], in an

[57] Gord Pratt, FESBC Operations Manager. 2020. Unpublished. Forest Enhancement Society of BC (FESBC) Wildfire Risk Reduction Treatment Cost Summary. Projects Completed Between October 2016 and March 31, 2020.

[58] Romero and Menakis. 2014. Mountain Fire Fuel Treatment Effectiveness Summary. USDA, Pacific SW Region, Final Version Nov. 2014. USDA, Pacific SW Region.

[59] Moody. 2010. Fuelbreak Effectiveness in Canada's Boreal Forests: A Synthesis of Current Knowledge. FP Innovations Internal Rpt.

analysis of fuelbreak effectiveness in Canada's boreal forests, states that repeating treatments to maintain fuel conditions that mitigate wildfire severity is important. Prichard and Kennedy (2014)[60] , in an analysis of fuel reduction treatments and burn severity in the 2006 Tripod Complex fires (similar environmental conditions as the southern interior of B.C.), state that treatments may need to be repeated more frequently (2–10 years) in more productive ecosystems with flammable shrub and/or understory tree layers that could be released by thinning and prescribed burn treatments.

6. Providing more fire management field trips/demonstrations and office-based training for anyone involved in forest fuel and wildfire management.
    a. Building on the FP Innovations work on data collection methods in their Rapid Response Kit, it would be valuable to create a formalized process to collect fire weather data, fuel loading information, and fire behaviour data on selected fires in real-time to test data collection tools and further our understanding of fuel treatment efficacy.
    b. It was evident in many of the recent fires that more research is required to understand the impacts of silviculture treatments on fire behaviour: stands aged 20-40 years can be quite resistant to wildfire, even in the most extreme circumstances, but more research is required to understand the mechanisms at play (for example, microclimate, close canopy with less wind penetration, less understory fuel, less ladder fuel).

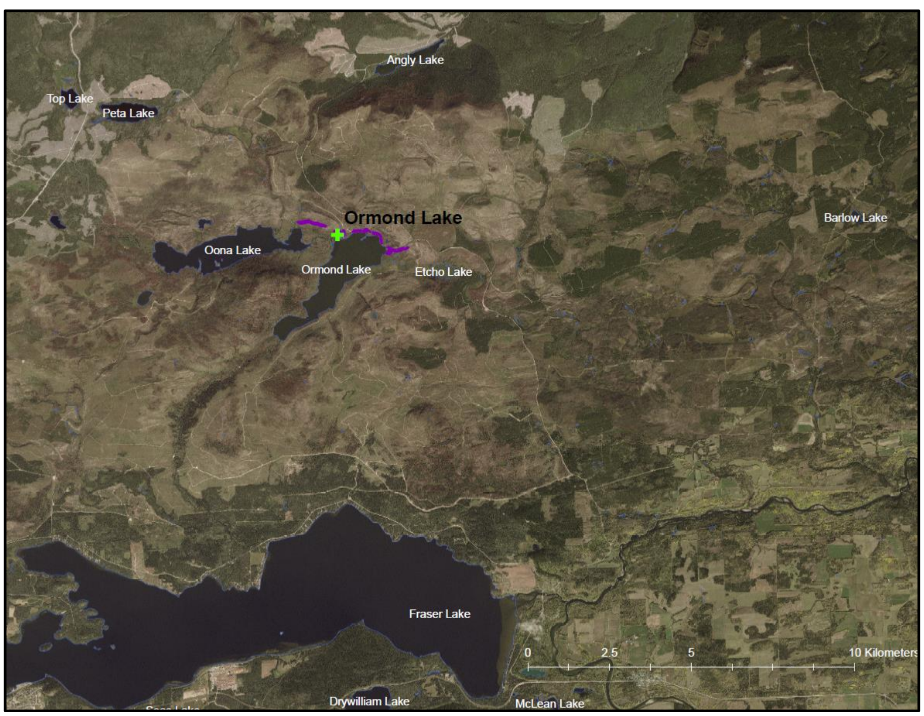
For further information on BC Wildfire Service fuel management programs, contact Kelly Osbourne, Fire and Fuel Management Officer, 778-974-4902, kelly.osbourne@gov.bc.ca.

[60] Prichard and Kennedy. 2014. Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event. Ecological Applications, 24(3), 2014, 571–590.

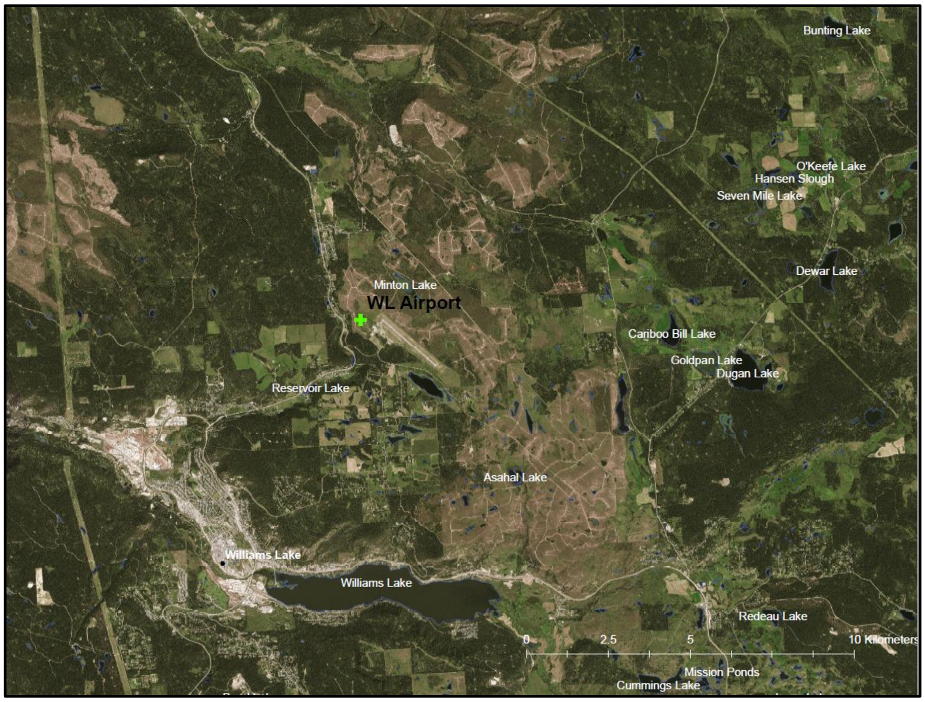
Appendix I – Study Site Location Maps

Thinning Case Study Sites

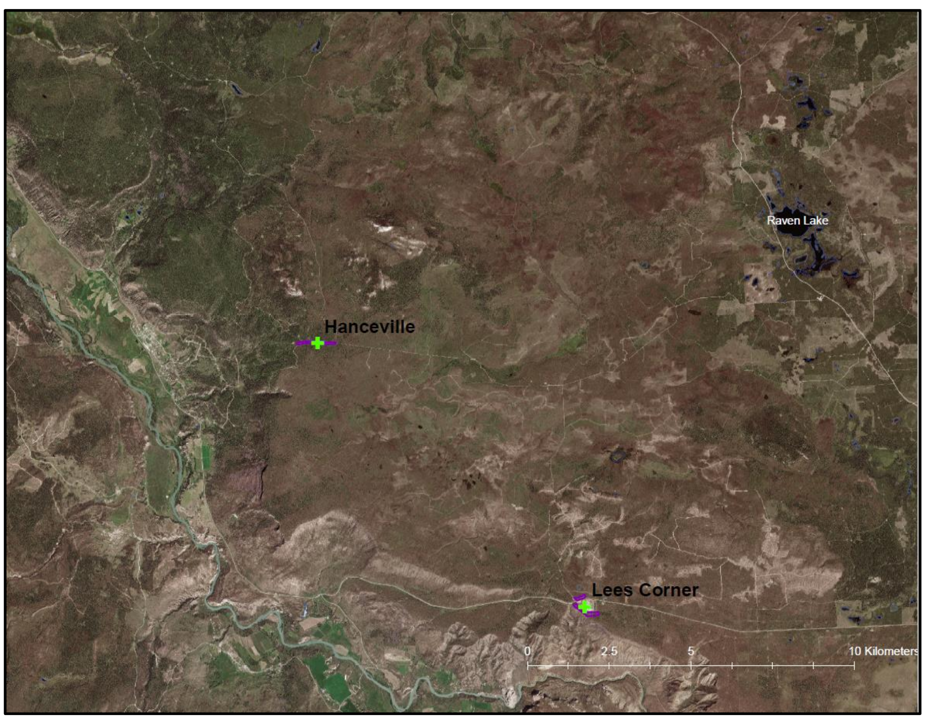
Nazko



Ormond Lake

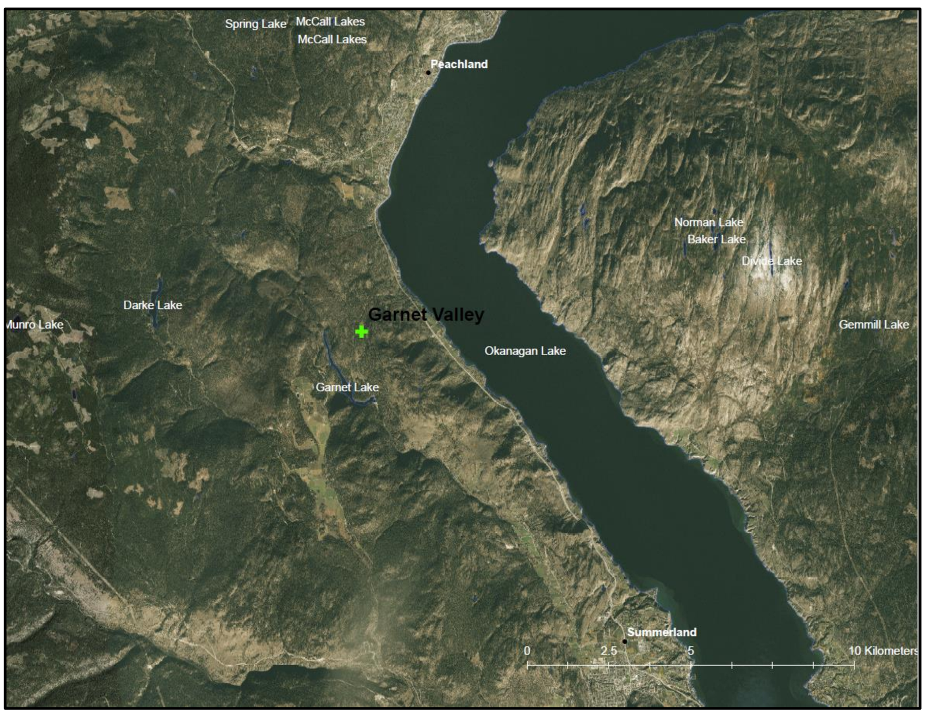


Williams Lake

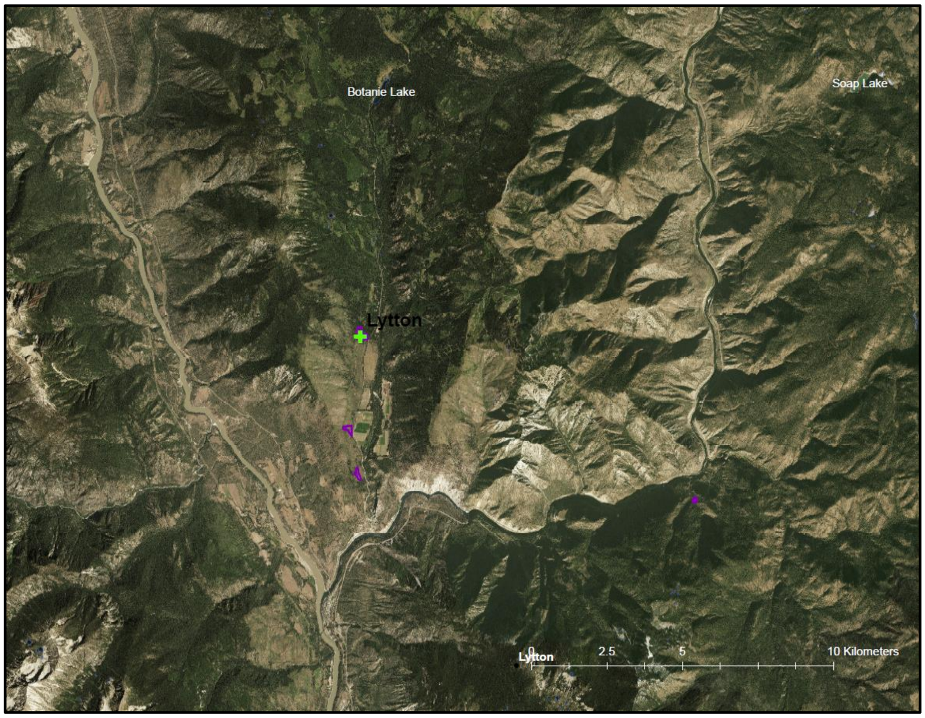


Hanceville and Lees Corner

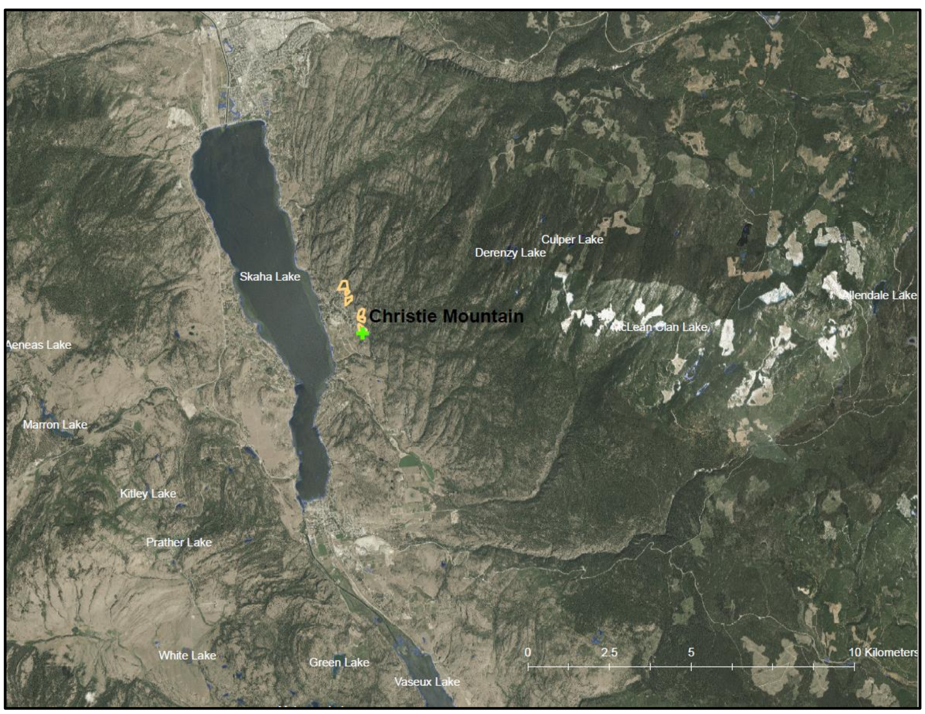
Hat Creek



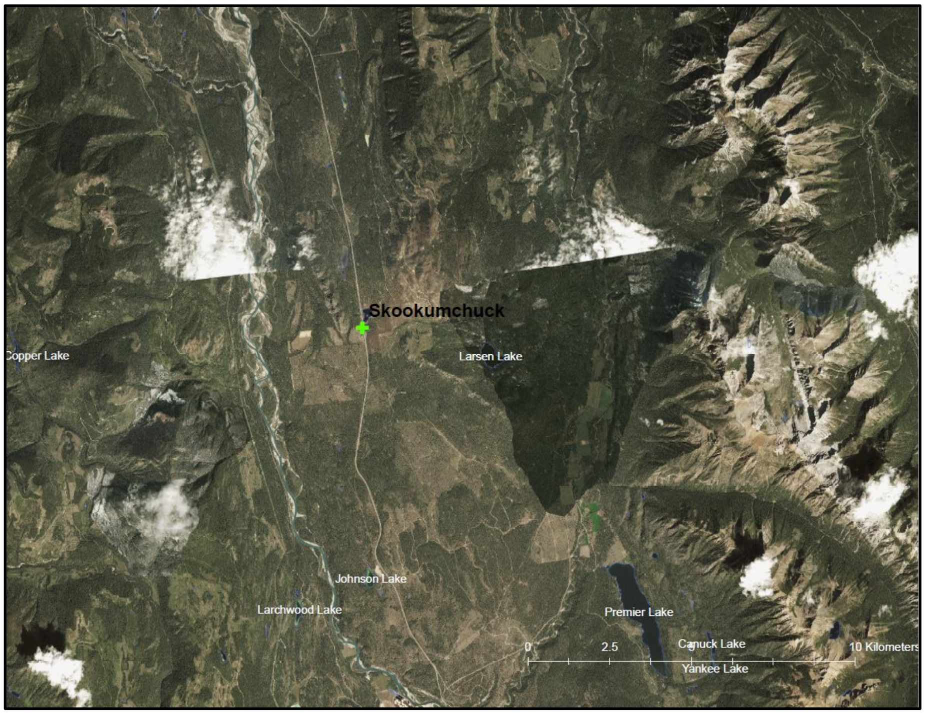
Garnet Valley



Lytton

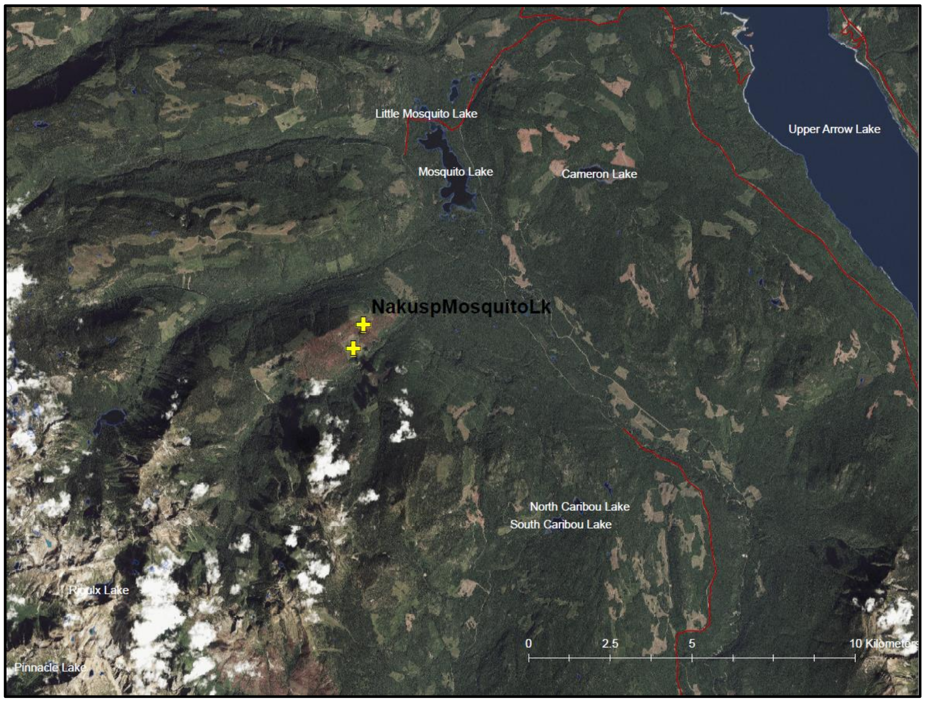


Christie Mountain

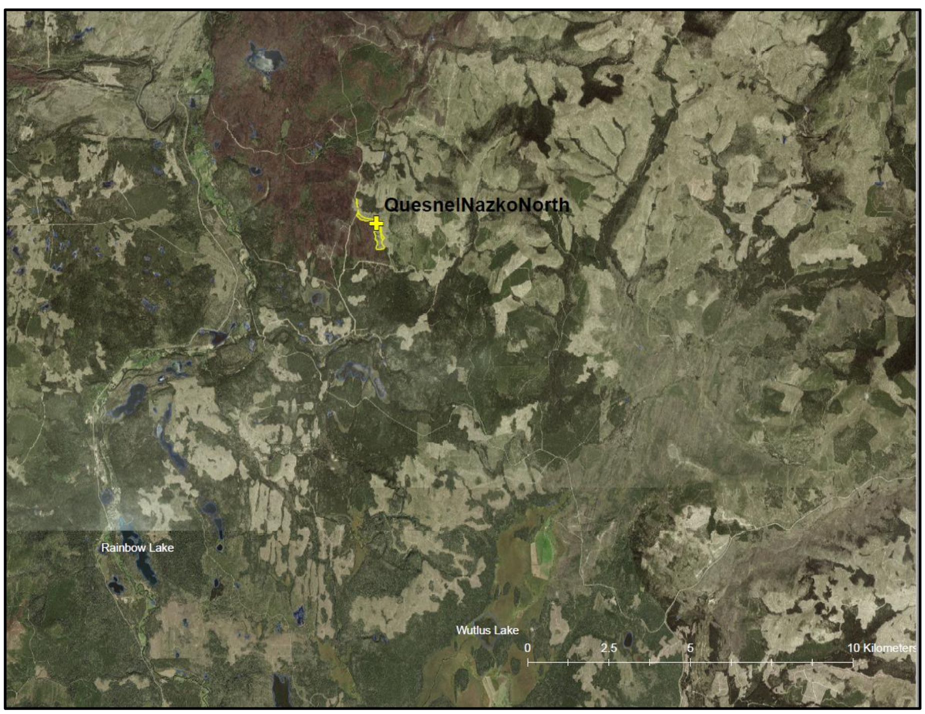


Skookumchuck

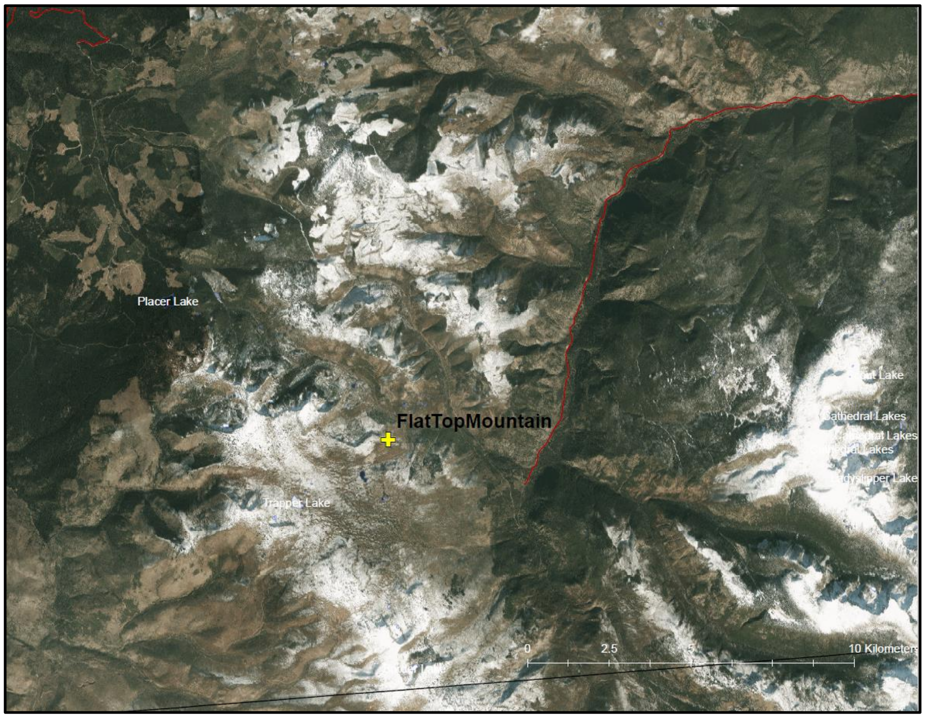
Broadcast Burning Case Study Sites



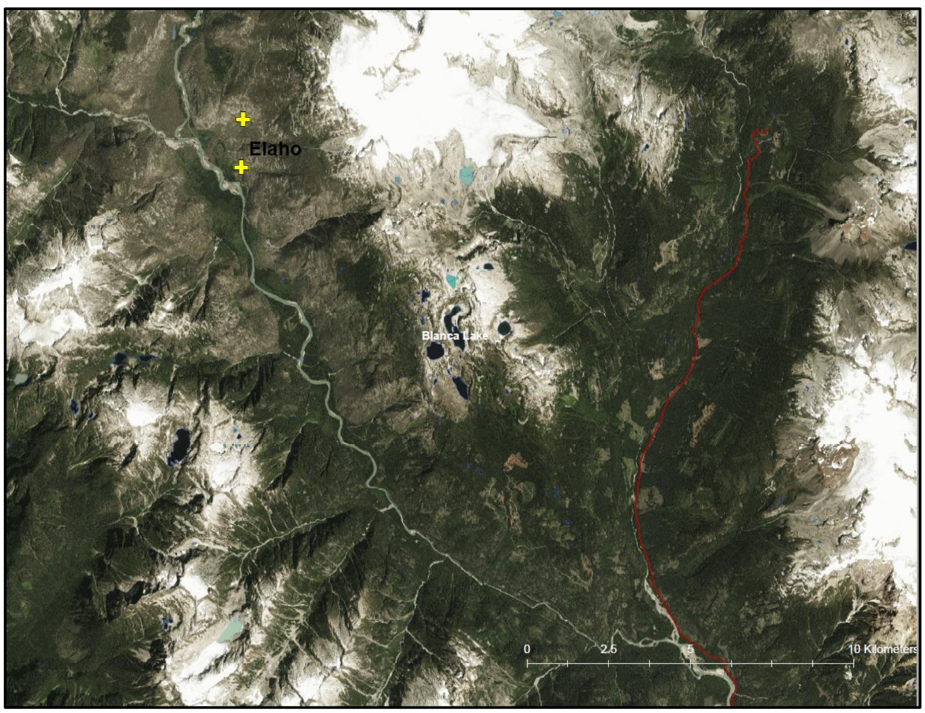
Nakusp



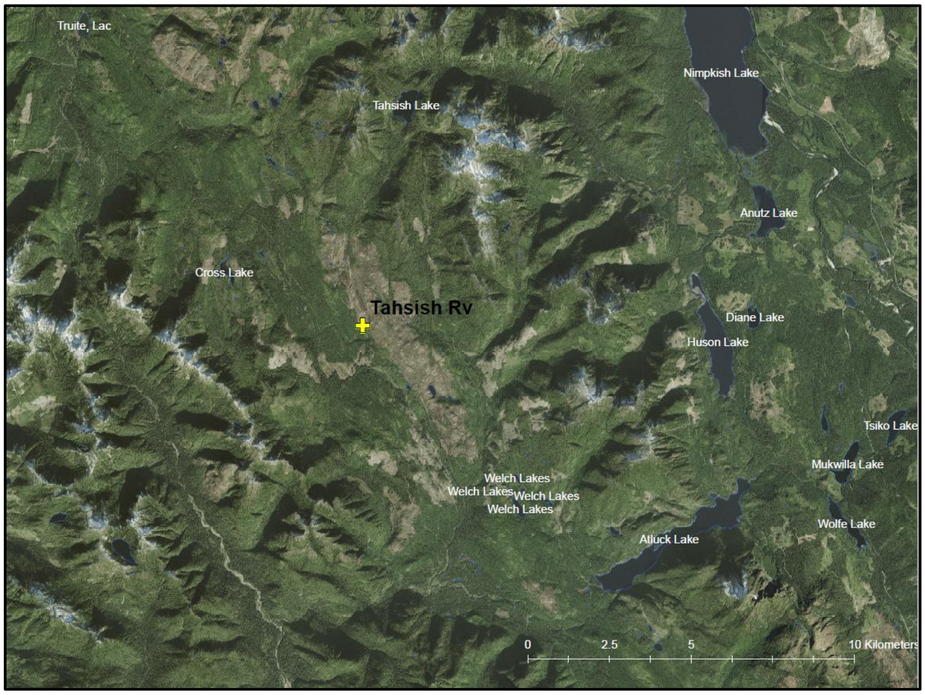
Nazko North



Flat Top Mountain



Elaho River



Tahsish River (Port McNeill)

Appendix II – Analysis Of The Utility Of Fire Behaviour Prediction Tools

Critical Surface Fire Intensity Worksheet

BCWS has developed a number of tools for predicting fire behaviour. One of the most useful for fuel treatment design is the Critical Surface Fire Intensity (CSFI) Worksheet. The CSFI worksheet is based on Van Wagner's Conditions For The Start And Spread Of Crown Fire (1977)[61] and Bryam's 1959 work on Combustion Of Forest Fuels[62]. Outputs from the calculator include fire intensity (kW/m), surface fire flame length, and critical surface fire intensity for initial crown combustion. An estimation of lethal scorch height can also be derived. Inputs include live crown base height, date of ignition as well as latitude and longitude to get foliar moisture content (FMC) using the BCWS Foliar Moisture Content Calculator, the surface fuel loading (not including duff) in kg/m^2, fuel type, and equilibrium rate of spread (ROS) based on fire weather information (ISI and BUI) for the fuel type involved. The tool is useful primarily in determining spread rate and whether the surface fire intensity will exceed the critical intensity required to have some degree of crown involvement. With respect to broadcast burning, one can compare spread rate and surface fire intensity for a given location and fire weather condition when no fuel treatments have been conducted versus after treatment.

In this project, we used the CSFI calculator in 3 scenarios for the Nakusp site: 1) no broadcast burning and fire weather indices available from the wildfire event, 2) broadcast burning and fire weather indices from the wildfire event, and 3) no broadcast burning using average 90th percentile fire weather indices for this location over the last 20 years determined from the BCWS 90th percentile Fire Weather Index Calculator[63]. Because there was no way of knowing pre-wildfire fuel loading, we used the following fuel load surrogates for input into the calculator:

1. a study by Kranabetter and Macadam involving seven sites in various BEC units in the Skeena region in which pre-broadcast burn slash loads varied from 44 to 109 tonnes/ha with an average of 55% (34 to 75%) being consumed by low to moderate severity broadcast burns. In this study, most of the fine slash (< 3 cm) and intermediate slash (3–7 cm) were consumed (91 and 72%, respectively) by the broadcast burn.
2. Published values for fuel loading in the B.C. Government photo guides are available at https://www2.gov.bc.ca/gov/content/safety/wildfire-status/prevention/for-industry-commercial-operators/hazard-assessment-abatement. As noted in the section on Fuels And Pre-Fire Fuel Treatments, these guides indicate that surface fuel loading for B.C. Interior slash loading in an S3 fuel type in the ICHmw (representing the benchmark Nakusp site) could vary from 30 to 120 tonnes/ha depending on the cedar and hemlock component.

Based on these two sources, it is expected that pre-broadcast burning fuel loading would be about 50 tonnes/ha (5 kg/m^2) for the Nakusp site. If 55% of this could be expected to burn in a prescribed fire, post-broadcast burn fuel loads would be about 22 tonnes/ha (2.2 kg/m^2). Crown base height in the plantations at the time of the wildfire would have been <1m based on field observations, and foliar moisture content from the Foliar Moisture Content calculator at the time of the wildfire would be 120.

Using fire weather data from Curwen Creek and Fall Creek fire weather stations (e.g. see figure 44 for an example for Curwen Creek), typical ISI, BUI, and FFMC values might be 3, 73, and 76 respectively (likely

[61] https://www.nwcg.gov/publications/pms437/crown-fire/initiation-propagation
[62] Byram, George M. 1959. Combustion of forest fuels. Pages 61-89 In: Davis, K. P., editor. Forest fire: control and use. New York, NY: McGraw-Hill.
[63] https://wps-web-prod.pathfinder.gov.bc.ca/percentile-calculator/

lower if broadcast burning took place in late September or October). The 90th percentile Fire Weather Index Calculator indices for these same weather station locations, over a 20-year window, were much higher at 10.5, 80, and 93, respectively, for ISI, BUI, and FFMC.

Fire Weather System

2018/08/18 for CURWEN CREEK

View Min/Max Data

Guide to abbreviations

Wx Zone	Station	Status	Temp.	RH	Wind Dir.	Wind Sp.	Precip.	Grass Cure	FFMC	DMC	DC	ISI	BUI	FWI	Dgr. Cl.
22	CURWEN CREEK	act	16.1	66	38	0	0.0	*	87.2	48	283	2.9	67	10.2	3

Figure 44: Fire weather indices at the Curwen Creek weather station near the Nakusp study site during the 2018 wildfire. Results from the three Critical Surface Fire Intensity simulations are shown in figures 45 to 47.

(Van Wagner 1977)	
To find:	
Critical Surface Fire Intensity	214.2
Enter:	
Foliar Moisture Content (%)	120
and:	
Live Crown Base Height (m)	1
Surface Fire Flame Length (Byram 1959)	
To find:	
Surface Fire Flame Length (m)	8.25
Enter:	
Fire Intensity (kW/m)	25500.0
Surface Fire Intensity based on Flame Length (Alexander 1982)	
To find:	
Surface Fire Intensity	20418.75
Enter:	
Flame Length	8.25
Crown Scorch Height (Van Wagner 1973)	
To find:	
Lethal Crown Scorch Height (m)	128.48
Enter:	
Fire Intensity (kW/m)	25500.0
or to find:	
Fire Intensity (kW/m)	25357.1886
Enter:	
Lethal Crown Scorch Height (m)	128
Wildfire Intensity (I = HWR) Bryam	
To find:	
Wildfire Intensity	25500.0
Enter	
Weight of the fuel (kg/m^2)	5
and	
Rate of Spread (m/min)	17

Figure 45: Predicted fire intensities in a C6 fuel type at the Nakusp site using pre-broadcast burning fuel loads and fire weather indices from the 90th percentile Fire Weather Index Calculator

(Van Wagner 1977)	
To find:	
Critical Surface Fire Intensity	214.2
Enter:	
Foliar Moisture Content (%)	120
and:	
Live Crown Base Height (m)	1
Surface Fire Flame Length (Byram 1959)	
To find:	
Surface Fire Flame Length (m)	1.29
Enter:	
Fire Intensity (kW/m)	450.0
Surface Fire Intensity based on Flame Length (Alexander 1982)	
To find:	
Surface Fire Intensity	499.23
Enter:	
Flame Length	1.29
Crown Scorch Height (Van Wagner 1973)	
To find:	
Lethal Crown Scorch Height (m)	8.71
Enter:	
Fire Intensity (kW/m)	450.0
or to find:	
Fire Intensity (kW/m)	449.329596
Enter:	
Lethal Crown Scorch Height (m)	8.7
Wildfire Intensity (I = HWR) Bryam	
To find:	
Wildfire Intensity	450.0
Enter	
Weight of the fuel (kg/m^2)	5
and	
Rate of Spread (m/min)	0.3

Figure 46: Predicted fire intensities in a C6 fuel type at the Nakusp site using pre-broadcast burning fuel loads and indices from fire weather stations during the wildfire.

(Van Wagner 1977)	
To find:	
Critical Surface Fire Intensity	214.2
Enter:	
Foliar Moisture Content (%)	120
and:	
Live Crown Base Height (m)	1
Surface Fire Flame Length (Byram 1959)	
To find:	
Surface Fire Flame Length (m)	0.88
Enter:	
Fire Intensity (kW/m)	198.0
Surface Fire Intensity based on Flame Length (Alexander 1982)	
To find:	
Surface Fire Intensity	232.32
Enter:	
Flame Length	0.88
Crown Scorch Height (Van Wagner 1973)	
To find:	
Lethal Crown Scorch Height (m)	5.04
Enter:	
Fire Intensity (kW/m)	198.0
or to find:	
Fire Intensity (kW/m)	198.121657
Enter:	
Lethal Crown Scorch Height (m)	5.04
Wildfire Intensity (I = HWR) Bryam	
To find:	
Wildfire Intensity	198.0
Enter	
Weight of the fuel (kg/m^2)	2.2
and	
Rate of Spread (m/min)	0.3

Figure 47: Predicted fire intensities in a C6 fuel type at the Nakusp site using post-broadcast burning fuel loads and indices from fire weather stations during the wildfire.

Figures 45 to 47 shows that the critical surface fire intensity to potentially get crown involvement in a C6 plantation with a crown base height of 1m or less is 214 kW/m. In the first scenario, using 90th percentile indices, expected fire intensity (25,500 kW/m) for a fuel load of 5 kg/m^2 far exceeds the critical surface fire intensity, and rate of spread calculations based on an ISI of 10.5 and BUI of 80 in a C6 fuel type would be very high at 17m/min (based on the Canadian Forest Fire Danger Rating System). In the second scenario, with 5kg/m^2 fuel load (i.e. no treatment) and ISIs during the wildfire, fire intensity also exceeds the critical surface fire intensity, but the rate of spread is much lower at 0.3m/min. In the third scenario, where the area has been broadcast burned (fuel load of 2.2 kg/m^2), surface fire intensity is less than the threshold (meaning crown fire is unlikely), and the rate of spread is still 0.3m/min. Broadcast burning is predicted in this case to provide a positive fire management outcome. In these scenarios, it is assumed that the fuel loading that existed after the broadcast burning in 2005 would be the same as in 2018 when the wildfire occurred. While this is unlikely to be true because of decomposition and vegetation regeneration, and added debris as the stand ages, it is expected that the net level of woody fuel will not have increased significantly in these stands.

Another way this calculator could be used would be to determine, for a given fire weather condition, what level of fuel loading is required to ensure no crown fire involvement. In the Nakusp example, it would be 2.4 kg/m2 (corresponding to a 52% reduction in fuel load) to ensure fire intensity is below the threshold for crown involvement. It also implies that maintenance levels should be such that fuel loads are kept below 2.4kg/m^2, although in a young plantation, the importance of a crown fire is not as high as it is in an older fuel type. The CSFI calculator states that fuel treatments should target an outcome that keeps surface fire intensity to less than 2000 kW/m presumably because, as some literature suggests, intensities less than 2000 kW/m can be suppressed by direct ground attack. Per Brad Martin (Senior Wildfire Officer – Prevention, NW Fire Centre, pers. comm. 2020), an intensity where conventional suppression methods, including air resources, have a reasonable chance of success is more like 4000 kW/m. At the Nakusp site, if the spread rate were 17m/min, a fuel load of less than 0.4 kg/m2 would be required to ensure fire intensity would be less than 2000 kW/m.

Results from the CSFI are directly dependant on Bryam's (1959) formula for quantifying fire intensity, a widely accepted metric for fire behaviour. However, as can be seen in figure 48, this formula appears to be highly sensitive to the initial spread rate, sometimes providing values that are not even on the same scale as the CSFI table for critical surface fire intensity thresholds (where the maximum value is <4000 kW/m). Another way to test the validity of results from the calculator is to use the 2020 BC Wildfire Service Head Fire Intensity (HFI) mapping available from DataBC's BC Data Catalogue. This data layer represents daily peak burning head fire intensity for a small number of days (~1-15) in an average year based on the fuels identified in the provincial inventory layer (as of 2017), assuming 90th percentile fire weather. It represents generally accepted fire intensity thresholds for ground-based suppression[64]. Figure 26 shows the HFI values for the Nakusp site. The southwest cutblock is classified as category 4, which is equivalent to 4000 to 6000 kW/m (maximum possible value is category 10, which is >100,000 kW/m). So, while the calculator produces a value for the 90th percentile fire weather ISI that is within the scale of the HFI mapping, it is still fivex higher than the mapped HFI, and it was not consistent with observed or mapped fire severity on this site or observed spread rates.

[64] Per metadata in the BC Data Catalogue for this layer.

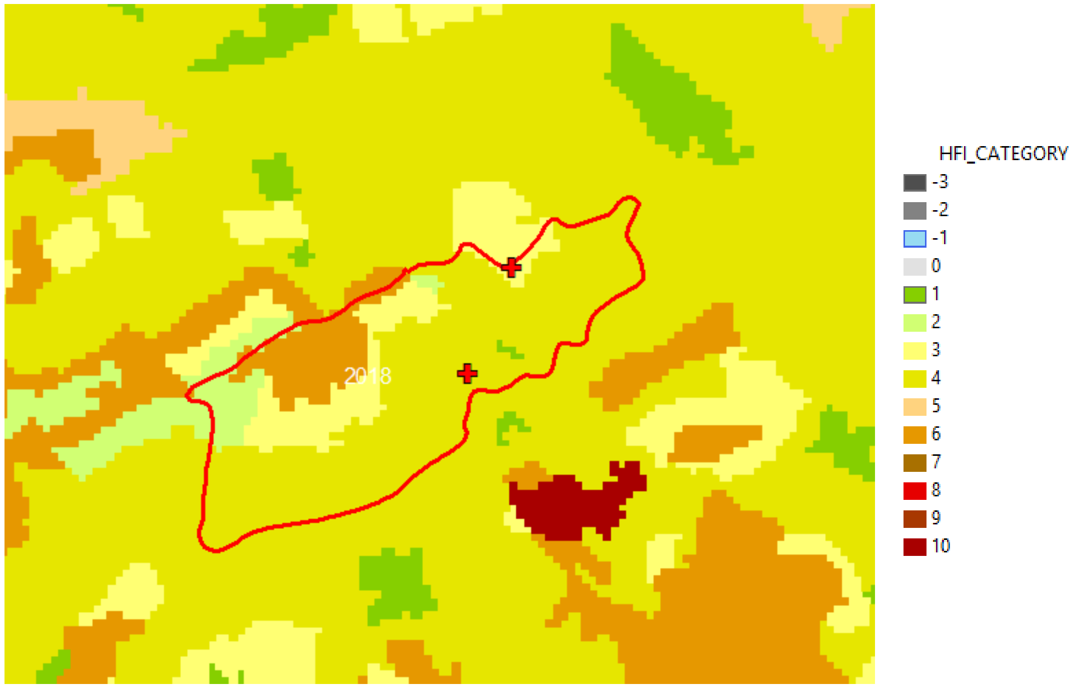


Figure 48: Head Fire Intensity values for the Nakusp study site showing an expected HFI of 4000 to 6000 kW/m based on 2017 inventory data (when the fuel type was C6).

It appears that the Critical Surface Fire Intensity Worksheet must be used with caution when fire weather indices are approaching the 90th percentile, given how sensitive the calculator is to high spread rates. As a tool to explore the relative impacts of varying fuel loads on fire intensity and possible crown fire (i.e. treatment versus no treatment), it has some value, but the absolute values for fuel load required to make a difference in wildfire behaviour should be treated with caution. Additionally, in the case of young plantations, knowing whether there is potential for crown fire is not as important as the rate of spread values that can be obtained directly from the Canadian Forest Fire Danger Rating System. Another limitation of the calculator is that it is not spatially explicit and does not account for the heterogeneity of fuels and their interaction across a landscape. A tool like Prometheus is required for this type of analysis.

Prometheus

The Alberta Ministry of Agriculture and Forestry is the custodian of the Wildland Fire Growth Simulation Model known as Prometheus. Prometheus is a deterministic wildland fire growth simulation model based on the Fire Weather Index and Fire Behaviour Prediction sub-systems of the Canadian Forest Fire Danger Rating System. The model simulates spatially explicit fire behaviour given heterogeneous fuel, topography and weather conditions. All spatial outputs are compatible with Geographic Information Systems[65]. The software developers suggest that there are many applications for the software, including forecasting wildland fire growth and planning prescribed fire.

In this study, we initially proposed using Prometheus to test the efficacy of broadcast burning in changing wildfire behaviour. By looking at treated versus untreated scenarios, we hoped to identify differences in rate of spread, intensity, probability of crown fire, and fuel consumption and then compare these to field observations. The model, however, does not allow for detailed characterization of fuel types beyond the simple fuel types described in the Canadian Forest Fire Behaviour Prediction System. When fuel

[65] http://firegrowthmodel.ca/prometheus/overview_e.php

treatments are implemented, there are changes in stand structure (species shifts, number of stems/ha, size distribution, surface fuel loading, and crown base height, for example) that cannot be captured in the input tables used to run Prometheus, making it very difficult to use the model to do fuel treatment analysis. Other practitioners also warn that "Prometheus fire growth maps tend to portray near worst-case fire growth potential rather than average fire growth under similar conditions so fires may not achieve the size and shape shown in simulations…" (Dan Perrakis, a fire behaviour specialist and modeller, in an unpublished June 2015 fire growth analysis report for the Elaho fire).

While the tool has great potential for evaluating the impacts of fuel treatments on wildfire behaviour and would be very helpful in answering questions such as how big treatments should be or how frequently they should be done, its current utility is minimal for the type of fuel analysis required in this project. Brad Martin (BCWS Wildfire Prevention Officer, NW Fire Centre) feels that Prometheus could be a great tool, particularly for spatial visualization, if it were possible to recreate a fuel complex that accurately reflected post-treatment conditions. This is currently not possible, and so it was not used in this study.

The Canadian Fire Effects Model

In this project, we also considered using the web-based version of the Canadian Forest Service Canadian Fire Effects Model, CanFIRE. CanFIRE is a compilation of Canadian fire behaviour models that are used to calculate the immediate, physical effects of fire on stand characteristics[66]. According to Natural Resources Canada, the web-based version of CanFIRE is set up to calculate fire behaviour and fire effects for an individual stand and can be used to run various hypothetical scenarios for prescribed burn planning or to estimate expected wildfire behaviour and impacts quickly. In this model fire rate of spread is calculated using Canadian Forest Fire Behaviour Prediction System equations and related procedures (for example, foliar moisture content and BUI). Fuel consumption is calculated using Canadian Forest Service fuel consumption models, and fire intensity is calculated using those data and Byram's (1959) equation (I=hwr). The model requires the following inputs: stand type (slash, timber, or grass), slash type, area (Ha), drought code value, wind speed, fine fuel moisture content, build-up index, and forest floor depth, as well as fuel loading (kg/m^2) including litter, upper duff, lower duff, medium woody debris load, and coarse woody debris. Outputs include the fire weather inputs used, fuel consumption by fuel class, emissions (C, CH_4, CO_2, NMHC, and particulates), and a fire summary with, amongst other things, head fire intensity, rate of spread, and whether a crown fire is likely.

In this study, we ran two simulations using the web-based version of CanFIRE and pre and post-broadcast burning data on fuel loading from Kranabetter and Macadam (1998) combined with on-site data on duff depths and fire weather indices from the Nakusp study site (the same values used in the CSFI scenarios described above). Input parameters for each scenario are shown in table 4. In the first scenario, pre-broadcast burn fuel loads were used, and in the second scenario, post-broadcast burn fuel loads were used. Fuel reductions from the broadcast burning were assumed to be 55% and 29%, respectively, for slash and duff based on Kranabetter and Macadam (1998).

[66] http://www.glfc.forestry.ca/canfire-feucan/index.cfm?lang=eng

Table 12: CanFIRE input parameters for broadcast burn and no broadcast burn fuel loading at the Nakusp site.

Scenario	Stand Type	Slash Type	Area	DC	Wind Speed	FFMC	BUI	Duff Depth	Litter	Upper Duff	Lower Duff	CWD	MWD
Not Treated	Slash	S3	1 ha	283	5	87	67	5	1	4	4	5.6	2.6
Treated	Slash	S3	1 ha	283	5	87	67	5	1	3	3	2.4	1.6

Outputs from the modelling exercise are shown in figures 49 and 50.

Fire Summary

Fire Behaviour

Showing 1 to 11 of 11 entries | Filter items

Behaviour Element	Behaviour Value
Crown fire?	No
Scorch Height	8.788 meters
Total Fuel Consumption	6.072 kg/m^2
Total Surface Consumption	6.072 kg/m^2
Final HFI	456.157 kW/m
Surface HFI	456.157 kW/m
Forest Floor Consumption	4.0573 kg/m^2
Dead Woody Debris Consumption	2.015 kg/m^2
Rate of Spread	0.917 m/min
Crown Fuel Consumption	0.000 kg/m^2

Figure 47: CanFIRE simulations with no broadcast burning using fuel loading data from Kranabetter and Macadam (1998) and fire weather indices from the Nakusp study site.

Fire Summary

Fire Behaviour

Showing 1 to 11 of 11 entries | Filter items

Behaviour Element	Behaviour Value
Crown fire?	No
Scorch Height	7.995 meters
Total Fuel Consumption	4.661 kg/m^2
Total Surface Consumption	4.661 kg/m^2
Final HFI	395.854 kW/m
Surface HFI	395.854 kW/m
Forest Floor Consumption	3.42768 kg/m^2
Dead Woody Debris Consumption	1.233 kg/m^2
Rate of Spread	0.917 m/min
Crown Fuel Consumption	0.000 kg/m^2

Figure 50: CanFIRE simulations with broadcast burning using fuel loading data from Kranabetter and Macadam (1998) and fire weather indices from the Nakusp study site.

The CanFIRE results indicate that head fire burn intensity would be reduced by about 60 kW/m or 13% when FFMC codes are moderate and wind speed is low. A 13% difference in intensity between treated and untreated conditions may not be enough to have a significant impact on wildfire reduction objectives. When wind speed was increased to 20 km/hr, and FFMC was changed to 94 (90th percentile fire weather indices for the Curwen Creek weather station near the study site), the untreated stand was projected to have a head fire intensity of 18,586 kW/m, and the treated stand was projected to have a head fire intensity of 16,130 kW/m. Using this model, neither outcome provides a compelling argument for broadcast burning. As was the case with CSFI and Prometheus, the main indicators of broadcast burn efficacy are limited to surface intensity and the potential for crown involvement. When broadcast burning is done primarily in harvested clearcuts as a way to mitigate wildfire impacts in C6 fuel types, crown involvement is not a significant factor, and the utility of the calculator and models, therefore, is really no better than simply using the Canadian Forest Fire Danger Rating System Field Guide to get rate of spread and intensity class.