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Unintended Effects of Fuel Thinning on the Microclimate in the Coastal Forests of Southwestern British Columbia, Canada

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Abstract: Prescriptions for fuels management are universally applied across forest types in British Columbia, Canada, to reduce fire behaviour potential in the wildland-urban interface. Fuel thinning treatments are assumed to reduce the potential for sustained ignition and crown fire initiation by reducing surface fuel loading. We hypothesized that these prescriptions are not appropriate for the coastal wet forests in the Whistler region of the province. Our study measured the efficacy of fuel thinning treatments in four stands located in the Whistler community forest. We examined several in-stand microclimate variables during snow melt in the spring and at the height of fire danger in late summer, at thinned and unthinned locations paired using GIS-analysis. We found that thinning increased the wildfire risk based on the differences between unthinned and thinned areas in the same forest stand.

Keywords: BC wildfires; climate change; conifer forest fuel complex; fire danger; fire weather; fuel moisture

1. Introduction

Building on the extensive culture of investigation and innovation in wildland fire science in Canada {1], we humbly add our research contribution to determining the effects of fuel thinning on the forest microclimate, and consequently, forest ecosystem sustainability. With the increased ingress of humans into the forest environment, through residential growth and recreational activities, there is less tolerance for wildfire. Governments have allocated significant tax dollars (CDN$5000 to CDN$7400 per hectare [2]) to fuels management in order to reduce wildfire risk. In municipalities like Whistler, British Columbia, Canada, with huge infrastructure investment, the cost of fuel thinning averages CDN$35000/ha (depending on the ability to offset costs through timber sales [3]); the consequences of wildfire are driving government response. Government response is misdirected at least partly because fire management terms have morphed from the original definition, leading to confusion and misuse (Appendix A).

By limiting our focus to forest fuels, we have lost site of the natural forest resilience as an important factor in mitigating fire behaviour. We are ignoring the link between reduced fire intensity and stand conditions of fuel moisture such as slower snow melt, water held in coarse woody debris (CWD) and low flammability of herbaceous perennial ground vegetation.

Fuel thinning was conceived in order to control the start and spread of crown fires [4,5] which are expected to increase in the future [1,6]. But crown fires are not common in coastal wet forests [7]. Crowning forest fires are associated with dense canopy conditions [8], yet fuel thinning dries out surface and ground fuels through effects of solar radiation [9–11] and increases in wind penetration which can in turn increase crown fire risk [12]. Fuel is one of but three factors (ignition agents and weather being the other two) that strongly influences wildfire activity [1,6,13]. Fuel thinning cannot mitigate fire severity under extreme fire behaviour [2,7], yet it is these extreme fire weather conditions that have triggered recent wildfires in the Pacific Northwest [7,14,15].

Fire danger assessment in Canada is undertaken using the Canadian Forest Fire Weather Index (FWI) System [16,17]. The FWI System is compromised of six components that integrate the effects of short- and long-term weather on potential fire behaviour. The Fine Fuel Moisture Code (FFMC), for example, is a numerical rating of the moisture content of the litter and other fine fuels of the forest floor surface and is thus an indicator of the relative ease of ignition of these fuels.

Our research set out to test the hypothesis that fuel thinning in the coastal forests of the Whistler region of British Columbia, Canada (Figure 1) increases the fire behaviour potential. Our research questions were:

Figure 1. Geographical location of the community of Whistler in southwestern British Columbia, Canada. Source: https://en.wikipedia.org/wiki/Whistler,_British_Columbia.

Does fuel thinning increase wildfire potential relative to the unthinned forest based on conditions associated with fire, namely: (a) in the spring (i.e., faster snow melt); (b) in late summer (i.e., drier fuels); and (c) in both seasons (i.e., increased wind speed, ambient air temperature, and solar radiation, and decreased soil moisture, and relative humidity)?

Does stand-level microclimate data give the same model-predicted risk of wildfire that the current regional climate data gives? Is the site with the greatest degree of fire danger consistent between the different measures? (section 3.2)

Does stand-level fuel moisture data give the model-predicted risk of fire that the current regional climate data gives? (section 3.3)

2. Materials and Methods

Sampling points were selected using a geographic information system (GIS) to exclude non-forested fuel types (e.g., wetlands, roads, lakes and infrastructure), and to pair thinned and unthinned locations by aspect, slope steepness, and forest type, while ensuring the sampling locations were at least 100 m apart (Figure 2). We sampled south-facing exposures with steep slopes which were expected to be the most affected by fuel thinning. Characteristics of the forest are detailed in Appendix B.

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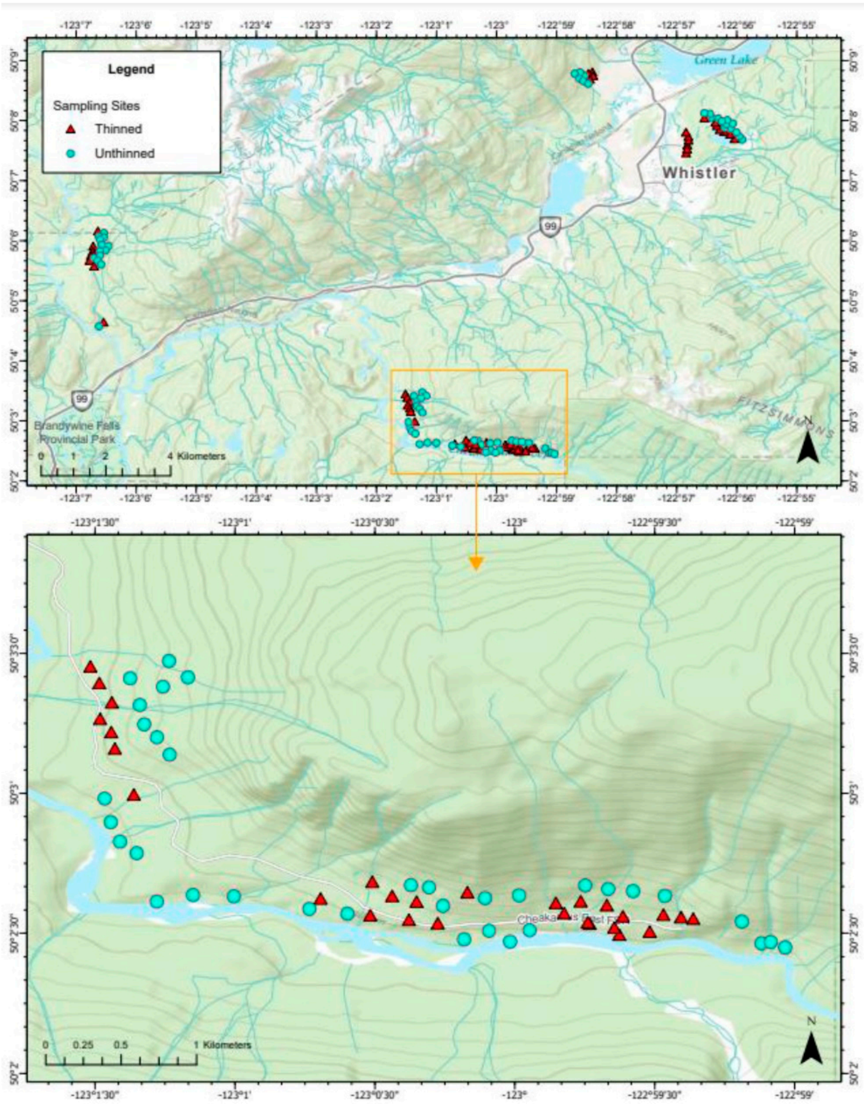

Figure 2. Example of GIS-derived sampling points (thinned and unthinned) in Cheakamus, one of the four areas sampled in Whistler's coastal forest area.

We replicated sampling at four sites in Whistler's coastal forest (i.e., Alpine, Lost Lake, Cheakamus, and Callaghan) in two seasons of the year: (1) spring – during snow melt as an indicator of wildfire risk (April); and (2) late summer – during the period of highest fire danger (i.e., the latter part of July to early August). We sampled at 99 point-

locations in the spring ($n = 44$ in thinned and $n = 55$ in unthinned locations) (Table 1). More points ($n = 111$) were accessible in late summer ($n = 52$ in thinned and $n = 59$ in unthinned locations) than in the spring (Table 1). We avoided sampling within 24-h of a recent rainfall event and sampled across sites as close in time as possible given availability of volunteer field assistants.

Table 1. Sampling design and sample size by treatment and season.

Season	Treatment	Site			
		Alpine	Lost Lake	Cheakamus	Callaghan
Spring	Thinned	4	13	19	8
	Unthinned	6	13	22	14
Late summer	Thinned	4	15	25	8
	Unthinned	6	12	28	13

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At each point, lab-calibrated equipment (Table 2, Figure 3) was used to measure ambient air temperature, relative humidity (RH), wind speed and direction, solar radiation, and soil moisture. In the spring, we included snow depth and snow cover. In late summer, we included fuel moisture, classification of fuel by volume, and digital photos of tree canopy closure and ground fuel (organic matter, CWD, cover).

Figure 3. Field measurement of microclimate (left), soil moisture and fuel data (right).

Table 2. Data collected and the expected direction of effect due to fuel thinning. Each variable is listed with its units and instrument accuracy where relevant. Solar radiation measurements were taken at waist height (110 cm above ground) and Kestrel variables (ambient air temperature, RH and wind speed) from tripod height (134 cm above ground).

Direction of Effect with Higher Risk	Variable	Instrument
Increase	Solar radiation (W-m^{-2})	Extech Solar power meter; hand-held (110 cm above ground)
	Ambient air temperature (°C)	Kestrel 5500 with vane, tripod-mounted (134 cm above ground)
	Wind speed (m s^{-1})	Kestrel 5500; wind speed averaged over a x-min interval
Decrease	Relative humidity (%)	Kestrel 5500
	Snow depth (cm)	Snow ruler (mm)
	Snow cover (cm^2)	Snow ruler (mm)
	Soil moisture (%)	Extech MO750 Soil Moisture Meter (20-cm probe)
	Fuel moisture (%)	OHaus Scot II model balance (0.01 g), Excalibur 4-tray Dehydrator
	Canopy cover (%)	Olympus Tough TG4

In order to analyze fuel moisture, samples of surface materials were collected using a trowel to a 3-cm soil depth (Table 3). Each sample was put into a Ziplock plastic bag, labelled with site, date, and time on the outside and stored in a dark cupboard at a temperature of 20°C and 50% RH for up to 9 days. A measured volume (cm^2) of each sample was transferred to a half cup metal container and weighed (to a 0.01 g accuracy) before and after drying. Samples were dried at 74°C until the weight did not change (2.0 to 4.5 hours) using a 4-tray food dehydrator (Figure 4). Fuel moisture content was calculated as the quantity of moisture in the fuel (the difference in weight from initial to dried) and expressed as a percentage of the final weight when thoroughly dried.

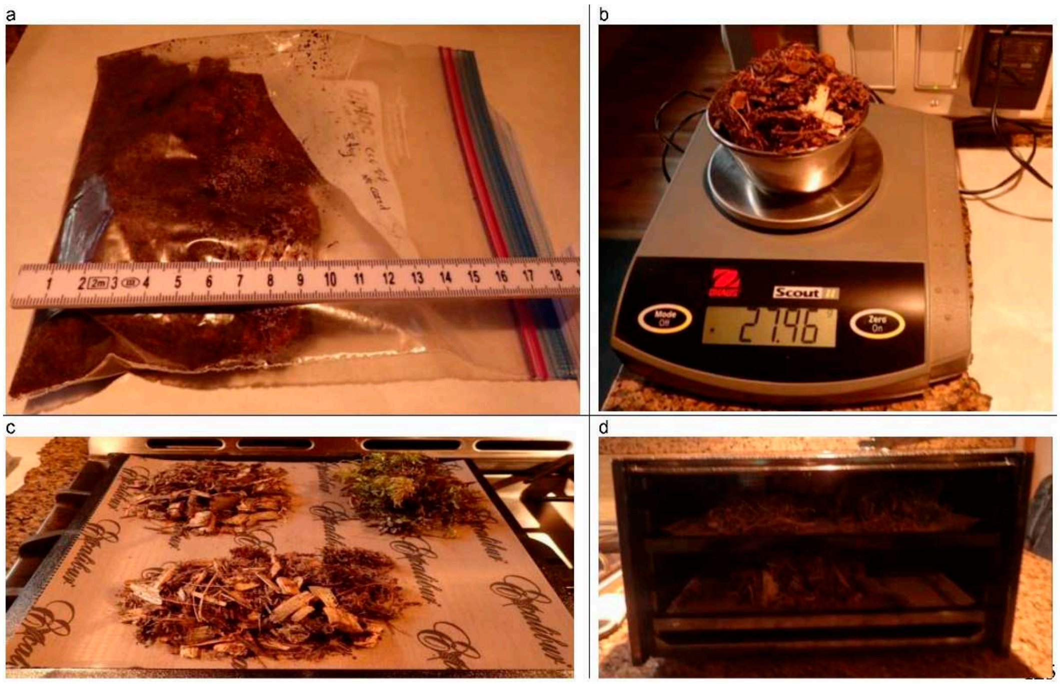

Figure 4. Drying method for soil moisture data, where (a) represents the volume (cm^{-3}), (b) represents the weight (g), (c) is the dehydration tray, and (d) is the dehydrator (Excalibar set at 74°C for 1.0-24 h).

Table 3. Number of ground fuel samples collected for fuel moisture content (15 per treatment; 30 total).

Treatment	Site			
	Alpine	Lost Lake	Cheakamus	Callaghan
Thinned	2	4	5	4
Unthinned	2	3	7	3

The proportion of each fuel component was estimated visually at the initial weighing (Figure 4) and again by photo analysis. Fuels were categorized as living plants, moss, CWD, needles/cones, chipped-wood, and bare ground/rock) to correspond with expected drying times.

Ground and canopy photos were taken at 78 sites (Table 4) and uploaded to a photo analysis software tool called *Image*J, where a grid (220 cells per image) was overlaid on every image and within each grid, the percent canopy cover (versus clear sky) and percent ground cover by fuel component were calculated (Figure 5). For each image (n = 156), invalid cells (i.e., not clear sky or not ground cover) were ignored and the portion of each valid cell tallied by grid-row for a total percentage per image ± variability across the rows. The average percent ground cover and percent canopy cover was compared by treatment and site. At Lost Lake, photos were only taken at thinned sites.

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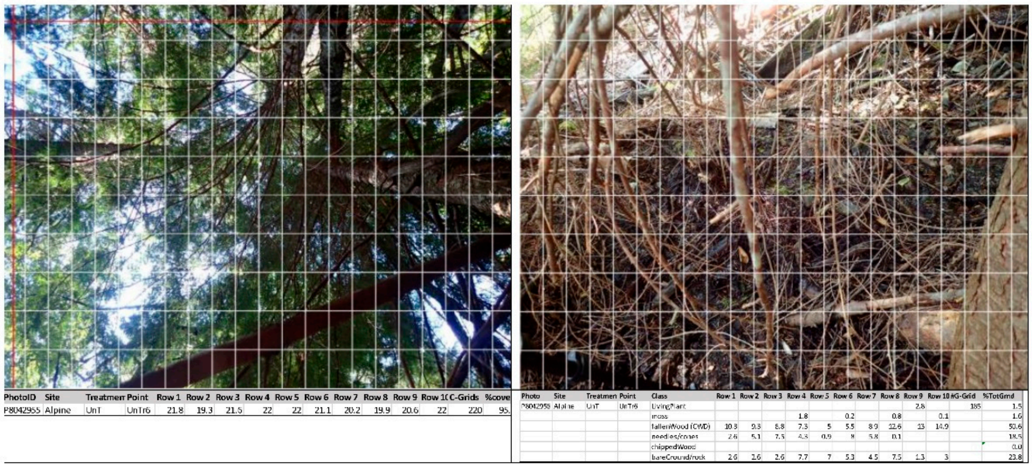

Figure 5. Example grid overlay for *Image* analysis with the accompanying excel data for the (**left**) unthinned canopy and (**right**) ground views at the Alpine site.

Table 4. Canopy cover and ground cover photo analysis (78 sampling locations; 34 in thinned, 44 in unthinned). A canopy and a ground photo were taken at each site for a total of 156 photos.

Treatment	Site			
	Alpine	**Lost Lake**	**Cheakamus**	**Callaghan**
Thinned	4	4	18	17
Unthinned	6	0	25	22

3. Results

3.1. Fuel thinning effect on microclimate

All microclimate variables changed in the direction of an increase in wildfire potential for both seasons (Tables 5 and 6). The average increase (absolute value) across all parameters was 58% (unthinned to thinned) in the spring and 37% in late summer. Unthinned points received 12% of the solar radiation measured at thinned stand locations.

Table 5. Data used in assessment of the effect of thinning or lack thereof on microclimate variables in the spring (UnT = unthinned; T = thinned; Avg. = average; SD = standard deviation; and *n* = sample size).

Direction Change	Variable	UnT Avg.	T Avg.	% Change	UnT SD	T SD	UnT *n*	T *n*
Increase	Solar radiation (W-m^{-2})	26.4	213.5	78.0	141.3	15.4	55	44
	Avg. temperature (°C)	9.1	10.8	8.6	1.1	0.5	55	44
	Avg. wind speed (m-s^{-1})	0.2	1.0	68.1	0.6	0.2	55	44
Decrease	Relative humidity (%)	73.6	61.4	-9.0	5.5	7.9	55	44
	Soil moisture (%)	4.6	2.4	-32.1	1.0	1.7	55	44
	Avg. snow depth (cm)	7.8	0.0	-100.0	0.0	8.3	55	44
	Snow cover (cm^2)	4.9	0.0	-100.0	0.0	3.8	55	44

Table 6. Data used in assessment of the effect of thinning or lack thereof on microclimate (T = thinned in late summer (UnT = unthinned; T = thinned; Avg. = average; SD = standard deviation; *n* = sample size).

Direction Change	Variable	UnT Avg.	T Avg.	% Change	UnT SD	T SD	UnT *n*	T *n*
Increase	Solar radiation (W-m^{-2})	23.3	485.4	90.8	3.5	330.0	67	46
	Avg. temperature (°C)	25.2	26.7	3.0	3.4	1.8	67	46
	Avg. wind speed (m-s^{-1})	0.2	0.7	63.4	0.1	0.5	67	46
Decrease	Relative humidity (%)	44.9	40.0	-5.8	14.2	13.7	67	46
	Soil moisture (%)	1.6	1.3	-10.8	1.3	1.3	67	46
	Fuel moisture (%)	33.3	23.7	-16.8	10.4	13.4	67	46

Fuel moisture declined an average of 18% from unthinned to thinned stands, consistently across all four sites. No snow remained in thinned forest at the time of spring sampling, and in thinned stands in late summer, we found field-detectable soil moisture only at the points with decaying wood chips. At the untreated sites, 71% of those with field-detectable moisture had coarse woody debris.

Photo analysis of canopy and ground cover images showed thinned areas had 27.05% less canopy and that ground cover did not change appreciably (16.25 versus 16.34%; Tables 7 and 8). Comparisons could not be made at Lost Lake with photos taken only at thinned sites. Living plants weren't significantly different in thinned versus unthinned stands. There was no apparent change in prescription or interpretation of the prescription by the contractor who carried out the thinning operation (Table 9). However, canopy cover is significantly more variable (16.9%) across thinned sites, than it is at unthinned sites (4.9%). Irrespective of year of treatment or contractor, Whistler canopy removal is beyond that of "Moderately-Thinned" prescriptions (Table 9).

Table 7. Effect of thinning on canopy cover, expressed as a percent of each image taken above the sampling point, then averaged for each site and totalled across sites for each treatment. Photo samples were not taken at Lost Lake.

Treatment	Site			Total % Canopy
	Alpine	Cheakamus	Callaghan	
Thinned	66.6	60.4	63.6	63.5
Unthinned	96.5	88.8	94.1	93.2
Difference	-18	-19	-19	-19

Table 8. Effect of thinning on ground cover by fuel components, expressed as a percent of each image taken above the sampling point, then averaged for each site and totaled across sites for each treatment.

Treatment	Fuel Component	Site		
		Alpine	Cheakamus	Callaghan
Thinned	Living plants	14.43	38.96	18.96
	Moss	0.78	5.32	1.64
	Coarse wood debris	25.17	27.86	26.64
	Needles/cones	24.71	5.90	4.21
	Chipped wood	0.00	0.05	4.03
	Bare ground/rock	34.35	18.91	44.98
Un-thinned	Living plants	1.51	37.88	17.36
	Moss	1.57	16.72	8.72
	Coarse woody debris	50.59	29.50	22.18
	Needles/cones	18.54	4.20	10.04
	Chipped wood	0.00	0.02	0.01
	Bare ground/rock	23.84	7.67	43.68

Table 9. Reduction in canopy cover ("T – UnT" = "Thinned – Unthinned") by year of fuel thinning and contractor employed.

Site	Reduction in % Canopy Cover (T - UnT)	Year	Contractor
Alpine	-29.9	2021	3
Callaghan	-30.5	2017-1019	1
Cheakamus	-28.4	2019-2021	2
"Lightly-Thinned"	-12.0		
"Moderately-Thinned"	-20.0		

There were other unintended effects beyond microclimate changes associated with the increased wildfire risk. At the Cheakamus and Callaghan thinned areas, we observed an increase in unauthorized trails used by both motorized and non-motorized vehicles thereby leading to increases in potential human-caused ignition potential. Evidence of reduced resilience in the forest environment was also observed in the form of bark damage on tree boles as well as soil erosion (Figure 6).

Figure 6. Reduced forest resilience in thinned areas: tree bole damage (**left**), and soil erosion (**right**).

3.2. Site most suspectible to the threat of wildfire

The site most susceptible to the threat of wildfire is defined as the driest, warmest, and windiest site, combined across treatment. Dryness is a combined factor of low RH, low soil moisture and either less snow remaining in the spring or less fuel moisture in late summer. Warmest is a combined factor of ambient air temperature and solar radiation. Windiest is measured directly as highest average wind speed. Given that each factor is recorded in different units, the factors are first converted to rank order across sites and then the combined rank for each site compared (Table 10). The site most susceptible was Callaghan in the spring and Lost Lake in late summer. To analyze for the microclimate effects of fuel thinning, the site most susceptible was compared to before and after thinning for dryness, heat and wind (Table 10); the overall change was an increased risk (+4 Alpine, -3 Lost Lake, +2 Callaghan, -1 Cheakamus).

Table 10. Summary of site susceptibility to the threat of wildfire factors**.** The four sites (A = Alpine, LL = Lost Lake, Cal = Callaghan, and CCF = Cheakamus community forest) were ranked from the highest (4; in yellow) to lowest (1) for each microclimate variable in the spring and the late summer (i.e., the height of fire danger) at thinned versus unthinned sampling points.

			Spring				Late Summer			
Treatment	**Ranking**	**Variable**	**A**	**LL**	**Cal**	**CCF**	**A**	**LL**	**Cal**	**CCF**
Untreated	Driest overall	RH	4	1	3	2	2	4	1	3
		Soil Moisture	4	3	2	1	1	4	2	3
		Snow/Fuel	3	4	1	2	3	4	2	1
	Warmest overall	Temperature	3	2	4	1	1	4	2	3
		Solar radiation	1	2	4	3	2	4	1	3
	Windiest overall	Wind avg	1	1	3	4	4	4	1	4
Treated	Driest overall	RH	1	3	4	2	4	3	1	2
		Soil Moisture	2	3	4	1	4	3	2	1
		Snow/Fuel	4	4	4	4	4	3	2	1
	Warmest overall	Temperature	2	3	4	1	3	4	1	2
		Solar radiation	4	1	3	2	2	4	1	3
	Windiest overall	Wind avg	1	4	2	3	4	2	1	3
		Total ranking across treatment	30	31	38	26	34	43	17	29

3.3. Stand-level wildfire risk models

3.3.1. Microclimate

We input our data from the unthinned sampling points for each of the four sites separately to compare with the Canadian Forest Service stand-level model for wildfire severity rating [16] for the year of our data collection, August 2021, to determine which site was most at risk and to what extent local microclimate data effected the predicted wildfire risk. We repeated this analysis for thinned points compared with the regional August 2021 wildfire rating in order to examine whether or not thinning increases fire risk based on this model.

By applying the lmer function in the lme4 package in R [19], we found that the difference in mean soil moisture, ambient air temperature, and RH between thinned and unthinned stands was significant in the spring with approximate p-values of 0.000217, 9.40e-05, and 4.33e-08, respectively. There were no discernible differences in mean soil moisture, ambient air temperature, and RH in the late summer. The difference in mean solar radiation, average wind speed, and average cross wind between thinned and unthinned samples are significant in the spring and late summer (with approximate p-values for spring of 9.54e-07, 0.02101, 1.92e-09, and for late summer of 2.45e-07, 4.08e-06, and 2.45e-05, respectively).

Using local microclimate data, the models indicated an increased wildfire risk at the thinned sites compared to the unthinned sites, due to changes in mean soil moisture, ambient air temperature and RH in the spring and in mean solar radiation, and average wind speed in both the spring and late summer.

3.3.2. Fuel Moisture

We input our fuel moisture data from the unthinned stand locations into the Canadian Forest Fire Behavior Prediction (FBP) System [20] to compare with the August 2021 regional ease of ignition and flammability, in order to examine to what extent local fuel moisture data effects the predicted wildfire risk. We repeated this analysis for the thinned stand locations. This was done in order to compare with the regional August 2021 wildfire rating, in an effort to examine whether or not fuel thinning increases the risk of ignition and flammability based on this model.

We also calculated the initial rate of spread (RSI) according to the following general formula:

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$$\mathbf{RSI} = \boldsymbol{a} \times [\mathbf{1} - \mathbf{e}^{(-\boldsymbol{b}\times\mathbf{ISI})}]^{\mathbf{c}} \tag{1}$$

where a, b, and c are parameters specific to each fuel type found in the FBP System [20]. The fuel type in our study is best represented by FBP System fuel type C-7 (ponderosa pine/Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*]) where the a, b and c parameters are, respectively, 45, 0.0305 and 2.0. Figure 7 shows the boxplot of the fire rate of spread for the thinned and unthinned stands in late summer.

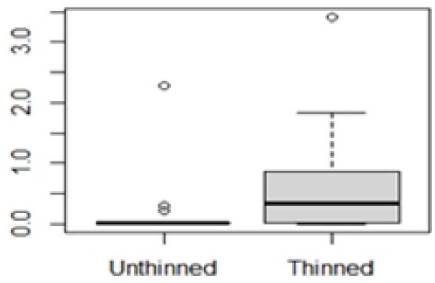

Figure 7. Fire spread rate potential in thinned and unthinned forest stands in late summer.

According to our data on ground slope (*GS*), the computed spread factor (*SF*) [20] is:

$$\boldsymbol{SF} = \boldsymbol{e}^{3.533\times(\frac{\boldsymbol{GS}}{100})^{1.2}} \tag{2}$$

Note that this equation is not recommended for use on slopes greater than 60% [20]. The zero wind rate of spread (***RSZ***) is then multiplied by the ***SF*** to produce the slope-adjusted zero wind rate of spread (***RSF***):

$$\boldsymbol{RSF} = \boldsymbol{RSZ} \times \boldsymbol{SF} \tag{3}$$

The ***ISF*,** representing the Initial Spread Index (*ISI*) and slope steepness influence and zero wind speed, is then calculated:

$$\boldsymbol{ISF} = \frac{\ln\,[1 - (\frac{100 - \boldsymbol{RSF}}{100 \times \boldsymbol{a}})^{\frac{1}{c}}]}{-\boldsymbol{b}} \tag{4}$$

where ***RSF*** is the zero wind rate of spread multiplied by the slope factor; ***a***, ***b***, and ***c*** parameters are fuel type specific rate of spread equation constants.

The next step in the procedure is to compute the slope equivalent wind speed (*WSE*). This is done as follows:

$$\boldsymbol{WSE} = \frac{\ln\,[\frac{\boldsymbol{ISF}}{0.208 \times \boldsymbol{f(F)}}]}{0.05039} \tag{5}$$

where *f*(*F*) is the moisture function inthe ***ISI*** equation:

$$\boldsymbol{f(F)} = 91.9 \times \boldsymbol{e}^{(-0.1386\times\boldsymbol{m})} \times [1 + \frac{\boldsymbol{m}^{5.31}}{4.93 \times 10^{7}}] \tag{6}$$

where *m* is the fine fuel moisture. The slope equivalent wind speed for the thinned and unthinned forest in late summer is shown in Figure 8.

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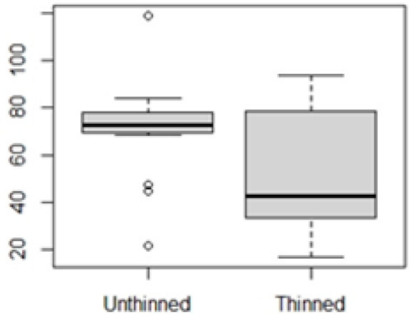

Figure 8. Slope equivalent wind speed for the thinned and unthinned forest stands in late summer.

To determine the net effective wind influencing the fire, the computed WSE value can be added to the observed wind speed. The difference in wind direction and slope direction is also used to add the two wind vectors together including observed wind and wind speed equivalent. According to the following set of equations, the vector addition is given by:

$$\boldsymbol{WSX} = [\boldsymbol{WS} \times \sin(\boldsymbol{WAZ})] + [\boldsymbol{WSE} \times \sin(\boldsymbol{SAZ})] \quad (7)$$

$$\boldsymbol{WSY} = [\boldsymbol{WS} \times \cos(\boldsymbol{WAZ})] + [\boldsymbol{WSE} \times \cos(\boldsymbol{SAZ})] \quad (8)$$

$$\boldsymbol{WSV} = \sqrt{\boldsymbol{WSX}^2 + \boldsymbol{WSY}^2} \quad (9)$$

$$\boldsymbol{RAZ} = \arccos\left(\frac{\boldsymbol{WSY}}{\boldsymbol{WSV}}\right) \quad (10)$$

where $\boldsymbol{WSX}$ is the resultant vector magnitude in the x-direction, $\boldsymbol{WSY}$ is the resultant vector magnitude in the y-direction, $\boldsymbol{WAZ}$ is the wind azimuth (direction), $\boldsymbol{SAZ}$ is the uphill slope azimuth, $\boldsymbol{WSV}$ is the net effective wind speed, and $\boldsymbol{RAZ}$ is the net effective wind direction. Figure 9 displays the boxplot of the net effective wind direction for the thinned and unthinned forest in late summer.

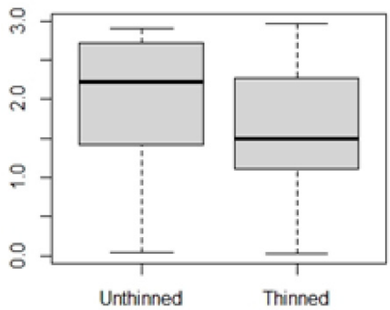

Figure 9. Net effective wind direction for the thinned and unthinned forest in late summer.

The fire behaviour model indicates that thinning increases the fire spread rate (Figure 7. Another index in the model related to fire spread, is the slope effect on wind where a steeper slope is expected to enhance spread. Figure 9 shows a greater slope effect because unthinned sites tended to be further from roads and in more extreme terrain.

The difference in mean fuel moisture between thinned and unthinned samples is not significant in late summer (approximate p-value of 0.3764; Figure 10). The fuel moistures at the thinned and unthinned locations of the same forest stand of the four sampled sites in late summer are displayed in Figure 10.

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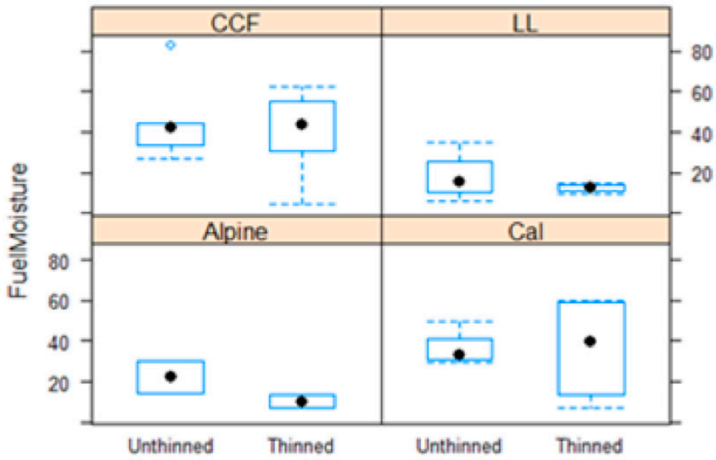

Figure 10. Fuel moistures at the unthinned and thinned locations of the same forest stand at the four sampling sites in late summer, where CCF is the Cheakamus Community Forest, LL is Lost Lake, and Cal is Callaghan.

4. Discussion and Conclusions

Our findings are consistent with others [e.g., 13,18,21,22] where thinning resulted in increased solar radiation, wind speed and ambient air temperature, and decreased RH and fuel moisture. As Whitehead and others [13] have found, the effects on RH and soil moisture were less pronounced in late summer at the height of fire danger. The importance of forest canopy in maintaining high fuel moisture levels was pointed out by Stickel [23] in as early as 1931. The level of increased wind speeds we found in thinned stands was similar to that observed by Bigelow and North [24] in order to increase the rate of fire spread using fire simulation modeling software (i.e., FMAPlus). Opening the forest stand results in a warmer, drier microclimate that creates a net increase in fire hazard [25]

Based on the photo analysis, none of the fuel thinning reduced the canopy cover to the threshold reduction of 27.05% that Gibos [10] noted for solar radiation levels needed to cause increased wildfire risk. Nonetheless, where the forest stands were thinned to below 50% (leaving 34-49% canopy coverage), the solar radiation levels reaching the ground surface were 39 to 65% higher than the unthinned places. The ground fuels in thinned forest areas were predominantly covered by bare ground/rock which were associated with higher wildfire risk. Pickering and others [21] found understorey vegetation to be important in mitigating fuel flammability. In our ground photo analysis, living plants weren't found to be affected by fuel thinning.

During peak burning conditions in daylight hours (i.e., 1300 to 1700 h local time) the south-facing site was on average 1.4°C warmer and had a RH 5.5% lower than the north-facing site. We did not conduct the model analysis proposed by Wotton [26]. However, given fuel moisture and response time of fuel is predicted from RH, and surface temperature is a function of ambient air temperature, wind speed and solar radiation, fuel thinning in Whistler's coastal forests has unquestionably increased fuel flammability.

We need to consider more than fuel in fire management strategies and go beyond a 'one size fits all' approach. The coastal, naturally regenerated forests of the Whistler region requires a different fire management strategy from the dry, fire-prone forests around Kelowna in southcentral British Columbia and the plantation forests around Fort St. John in northeastern region of the province. The humid conditions in British Columbia's southwestern coastal forests yield less frequent fires [27–31]. Fuel thinning prescriptions of today (i.e., selection thinning and crown thinning that maintain multiple canopy layers, along with individual tree selection systems) will not reduce the risk of crown fire occurrence except in the driest of ponderosa pine stands [32]. Silvicultural practices that involve the creation of high-density, even-aged stands of commercial conifer tree species have contributed to an increase in fire potential [33,34]. Similarly, unmanaged forests comprised of mature ponderosa pine (*Pinus ponderosa* Dougl. ex Laws), western white pine (*Pinus monticola* Dougl. Ex D. Don.), and western larch (*Larix occidentalis* Nutt.) tend to exhibit tall stems (with the crowns separated from the surface fuels) that are deep-rooted (which are more resilient to drought) and are self-pruned (and therefore lack bridge or ladder fuels), even in moderately dense stands [32].

An unexpected result from our study was the net effect of slope steepness on wind speed (both the slope equivalent wind speed and the net effective wind speed; Figure 8 and 9). This influence of slope on fire spread rate, due to the addition of wind vectors, provides further caution as to why fuel thinning, as a strategy for wildfire mitigation, is not appropriate in the extreme topography of ski resorts in southwestern British Columbia.

We need to separate risk from consequence. Fear is not an accurate guide. To accurately predict where a decrease in wildfire risk requires action, fire risk models require local, in-stand (not 6 m above), microclimate and local fuel moisture indices.

There is an opportunity to integrate FireSmart [35] efforts with fuel management in the wildland-urban interface and reduce harvesting of trees that are essential to mitigate climate change. Solar radiation and wind ingress to FireSmart thinned stands can be greater than fuel thinned stands. Research is needed on the potential for planting of native perennial herbaceous plants to retain climate resilient microclimate in the wildland-urban interface. Mitigating fire hazard with deciduous species provides protection [36]. However, perennial herbaceous plants would provide year-round, RH enhancing cover.

Gibos [10] found that a FireSmart thinned stand received 30% of the solar radiation and 30% of the wind measured in the open and was significantly warmer than all other stands during the peak solar radiation period of the day. In this study, unthinned locations in the stands received 12% of the solar radiation measured in the thinned portions of the stand in the spring and 5% in late summer. Gibos [10] found FireSmart thinned stands had wind speeds 18% higher than unthinned stands, compared to the 3-5 fold higher wind speed levels we observed at thinned versus unthinned locations within the stand.

Further work is required to quantify the increased risk of wildfire ignitions due to improved accessed by motorized vehicles (i.e., dirt bikes, quads and side by sides) [37].

What is the confounding effect of a change in prescription and contractor when it comes to fuel thinning? The digital photo analysis revealed considerable variation in implementation. Our stands were moderate to heavily thinned compared to those of Bigelow and North [24] who recorded a difference in canopy cover of 69±7% to 57±6% for lightly thinned stands and 49±8% in moderately thinned stands.

Our results also suggest that the recent provincial strategy to remove debris after thinning [38] will enhance the drying of ground and surface fuels. The retention of higher soil moisture in the late summer was associated with CWD in unthinned stands and wood chips in thinned stands. The removal of woody debris by burning releases carbon into the atmosphere, and both burning or the physical clearing of the debris removes organic matter (important for soil fertility and moisture retention) and enhances moisture loss by exposing tree roots [39–42]. The removal of post-thinning wood chips should be curtailed until their importance in retaining soil moisture is better understood.

The significant funds spent on fuel thinning in the coastal forests of B.C. ($10.1 million was allocated in 2022 for Whistler alone [43]) could be directed towards research in collaboration with the FireSmart program, to test the efficacy of planting green fuelbreaks on the urban side of the wildland-urban interface, to protect infrastructure, instead of removing trees which are essential for climate change mitigation and, based on this research, maintain a fire-resilient microclimate and the associated forest ecology. The current FireSmart prescription of harvesting conifer trees is opening up urban spaces that leads to increased warming and drying, which in turn exacerbates the heat and drought stress already occurring in concert with climate change.

Where fuel thinning is proven to be efficacious (i.e., reduces wildfire risk), monitoring for other unplanned effects should be included, specifically, the effect of fuel thinning on native wildlife populations (i.e., on the displacement of habitat-specialist species by disturbance-related species), and on soils with respect to fertility, erosion, and water retention. We need to manage for more than forest fuels. In communities like Whistler where the economy is dependent on recreation and tourism, the focus should be on the retention of the natural features of the forest ecosystem. Further research is required to understand the importance of CWD and old growth trees in retaining a fire-resilient microclimate while also maintaining ecosystem function.

Our results show that some of the indices of fire potential, support the conclusion that fuel thinning of south-facing slopes in coastal forests, has a higher predicted wildfire risk than unthinned stands in the same forest. We are increasing wildfire risk with fuel thinning practices. The additional ignition risk of opening the forest to unauthorized trails is a further reason to halt this practice. These results are consistent with Taylor and others [44] who found the probability of fire severity increased in older stands. Further research is required to determine how general the increased risk is across other slopes and other forest conditions.

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Appendix A

Fire management terms have morphed from the original definition (*given in italics*), leading to confusion and misuse (underlined text). For example, fuels management is defined as *the planned manipulation of forest vegetation to decrease the intensity and rate of spread of a wildfire* [45,46]. Today fuel reduction is conducted to create a defensible space in the forest surrounding infrastructure at a cost of $2000-8000 per ha [38].

Classically, thinning is defined as "cuttings made in immature stands in order to stimulate the growth of trees that remain and to increase the total yield of useful material from a stand" [46,47]. Fuel thinning (also called fire-thinning, mechanical thinning and overstory thinning) is based on management of crown-fire dominated boreal forests where fuel reduction is expected to reduce crowning potential without increasing surface fire intensity. The Resort Municipality of Whistler (RMOW)'s goal is to reduce fuel loads (removing ground brush and debris, pruning lower branches and removing tight second growth trees by reducing the number of trees in the stand, retaining species considered fire-resistant, reduce fine woody debris while leaving larger CWD, removing "danger" trees while maintaining high value wildlife trees where possible) in the wildland urban interface to reduce spread from wildlands into the community and vice versa, and to make wildfire easier to fight (Resort Municipality of Whistler 28 August 2021). Wood debris is burned.

The goal of a fuelbreak (also mistakenly called a firebreak [48}, defensible fuel zone or community protection zone), is to change fire behaviour to limit or slow fire spread, reduce flame length, reduce the probability of torching and of a fully-developed crown fire, by providing safe access for firefighting crews *A distinct area outside a community (or other value at risk) of any size and shape where anthropogenic modifications of forest fuels have been conducted to aid in the **protection** of that community **from future wildfires***. RMOW's focus is to reduce tree densities in tight second growth (but by sometime removing old growth trees), thinning stands 100-200 m of each side of service roads to reduce fuel available and create defensible areas for firefighting crews to safely work in.

Appendix B

The forest sites lie in the Coastal Western Hemlock Biogeoclimatic zone of British Columbia. The overstory is predominantly mature Subalpine fir, Western redcedar, Douglas fir and Western hemlock (Table A1).

Table A1. Overstory characteristics of the study sites.

Site	Treatment	Overstory Tree Species[1]	Avg. DBH	Avg. Height (m) (min-max)	Avg. Density (SPH)	Avg. Age (Min-Max)
Alpine	Unthinned	Bl, Cw, Fd, Hw	33.4	20.1 (12-26)	440	87.4 (54 - 195)
	Thinned	Bl, Cw, Fd	44.6	21.5 (16-26)	220	71.6 (34-102)
Lost Lake	Unthinned	Bl, Cw, Fd, Hw, Pw, Pl	29.8	18.0 (8-30)	548	97.7 (25-163)
	Thinned	Bl, Cw, Fd, Hw, Pw, Pl, Py	26.9	18.9 (11-26)	733	78.0 (47-118)
Callaghan	Unthinned	Bl, Cw, Fd, Hw	22.4	18.9 (12-35)	900	33.7 (22-41)
	Thinned	Bl, Cw, Fd, Hw	35.5	19.9 (12-26)	567	36.3 (28-41)
Cheakamus	Unthinned	Bl, Cw, Fd, Hw	29.0	20.1(11-27)	717	40.7 (36-47)
	Thinned	Bl, Cw, Fd, Hw, Pw	33.6	21.7 (13-28)	317	40.5 (30-48)

[1] where Bl = Subalpine fir, *Abies lasiocarpa*; Cw = Western redcedar, *Thuja plicata*; Fd = Douglas fir, *Pseudotsuga menziesii*; Hw = Western hemlock, *Tsuga heterophylla*; Pw = Western white pine, *Pinus monticola*; Pl = Ponderosa pine, *Pinus ponderosa*; Py = Lodgepole pine, *Pinus contorta.*

References

1. Coogan, S.C.P.; Daniels, L.D.; Boychuk, D.; Burton, P,J.; Flannigan, M.D.; Gauthier, S.; Kafka, V.; Park, J.S.; Wotton, B.M. Fifty years of wildland fire science in Canada. *Can. J. For. Res.* **2020**, 51, 283–302.
2. Beverly, J.L.; Leverkus, S.E.R.; Cameron, H.; Schroeder, D. Stand-level fuel reduction treatments and fire behaviour in Canadian boreal conifer forests. *Fire* **2020**, 3, 35.
3. Beresford, H. (Environmental Manager, Resort Municipality of Whistler). Personal communication, 4 January 2022.
4. Van Wagner, C.E. Conditions for the start and spread of crown fire. *Can. J. For. Res.* **1977**, 7, 23–34.
5. Agee, J.K.; Skinner, C.N. Basic principles of forest fuel reduction treatments. *For. Ecol. Manage*. **2005**, 211, 83–96.
6. Flannigan, M.D.; Wotton, B.M.; Marshall, G.A.; de Groot, W.J.; Johnston, J.; Jurko, N.; Cantin, A.S. Fuel moisture sensitivity to temperature and precipitation: Climate change implications. *Clim. Change* **2016**, 134, 59–71.
7. Reilly, M.J.; Zuspan, A.; Halofsky, J.S.; Raymond, C.; McEvoy, A.; Dye, A.W.; Donato, D.C.; Kim, J.B.; Potter, B.E.; Walker, N.; Davis, R.J.; Dunn, C.J.; Bell, D.M.; Gregory, M.J.; Johnston, J.D.; Harvey, B.J.; Halofsky, J.E.; Kerns, B.K. Cascadia Burning: The historic, but not historically unprecedented, 2020 wildfires in the Pacific Northwest, USA. *Ecosphere*, **2022**, 13, e4070 https://doi.org/10.1002/ecs2.4070.
8. Alexander, M.E.; Cruz, M.G. Evaluating the 3-m tree crown spacing guideline for the prevention of crowning wildfires in lodgepole pine forests, Alberta. For. Chron. **2020**, 96, 165-173.
9. Byram, G.M.; Jemison, G.M. Solar radiation and forest fuel moisture. *J. Agric. Res*. **1943**, 67, 149-176.
10. Gibos, K.E. Effect of Slope and Aspect on Litter Layer Moisture Content of Lodgepole Pine Stands in the East Slopes of the Rocky Mountains of Alberta. Master's Thesis, University of Toronto, Toronto, ON, Canada, **2010**; pp. 1-155.
11. Marshall, G.; Thompson, D.K.; Anderson, K.; Simpson, B.; Linn, R.; Schroeder, D. The impact of fuel treatments on wildfire behaviour in North America boreal fuels: A simulation study using FIRETEC. *Fire* **2020**, 3, 18.
12. Flannigan, M.D.; Logan, K.A.; Amiro, B.D.; Skinner, W.R.; Stocks, B.J. Future area burned in Canada. *Clim. Change* **2005**, 72: 1–16.
13. Whitehead, R.J.; Russo, G.; Hawkes, B.C.; Taylor, S.W.; Brown, B.N.; Armitage, O.B.; Barclay, H.J.; Benton, R.A. *Effect of Commercial Thinning on Within-stand Microclimate and Fine Fuel Moisture Conditions in a Mature Lodgepole Pine Stand in Southeastern British Columbia*. In Information Report; FI-X-004; Natural Resources Canada, Canadian Forest Service, Canadian Wood Fibre Centre: Victoria, BC, Canada, 2008; pp. 1-16.
14. Simpson, M. Case Study 2015 Elaho fire. **2015**, Unpublished; pp. 1-10.

15. Cohen, J.D.; Westhaver, A. An examination of the Lytton, British Columbia wildland-urban fire destruction. Summary report to the British Columbia FireSmart ™ Committee. Institute for Catastrophic Loss research paper #73, **2022**, pp. 1-43.
16. Van Wagner, C.E. *Development and Structure of the Canadian Forest Fire Weather Index System*. In Forestry Technical Report 35; Government of Canada, Canadian Forestry Service: Ottawa, ON, Canada, 1987; pp. 1-37.
17. Stocks, B.J.; Lawson, B.D.; Alexander, M.E.; Van Wagner, C.E.; McAlpine, R.S.; Lynham, T.J.; Dubé, D.E. The Canadian Forest Fire Danger Rating System: An overview, *For. Chron.* **1989**, 65, 450-457.
18. Kane, J.M. Stand conditions alter seasonal microclimate and dead fuel moisture in a Northwestern California oak woodland. *Agric. For. Meteorol.* **2021**, 308-309, 108602.
19. Bates D.; Mächler M.; Bolker B.; Walker S. Fitting linear mixed-effects models using lme4. J. Stat. Softw. **2015**, 67, 1-48.
20. Forestry Canada Fire Danger Group. Development and Structure of the Canadian Forest Fire Behavior Prediction System. In
21. Information Report; ST-X-3; Forestry Canada, Science and Sustainable Development Directorate: Ottawa, ON, Canada, 1992; pp. 1–63.
22. Pickering, B.J.; Duff, T.J.; Baillie, C.; Cawson, J.G. Darker, cooler, wetter: Forest understories influence surface fuel moisture. *Agric. For. Meteorol*. **2021**, 300, 108311.
23. Faiella, S.M.; Bailey, J.D. Fluctuations in fuel moisture across restoration treatments in semi-arid ponderosa pine forests of northern Arizona, USA. *International Journal of Wildland Fire* **2007**, 16:119-127. doi:10.1071/WF06018.
24. Stickel, P.W. The measurement and interpretation of forest fire-weather in the western Adirondacks. In Technical Publication No. 34; Syracuse University, New York State College of Forestry: Syracuse, NY, USA, 1931; pp. 1-115.
25. Bigelow. S.W.; North, M.P. Microclimate effects of fuels-reduction and group-selection silviculture: Implications for fire behaviour in Sierran mixed-conifer forests. *For. Ecol. Manage*. **2011** 264, 51-59.
26. Weatherspoon, C. P. *Fire-silviculture relationships in Sierra forests.* In: Sierra Nevada Ecosystem Project, Final Report to Congress, II: Assessments, scientific basis for management options, ed., vol. II: Assessments and scientific basis for management options. Centers for Water and Wildland Resources, University of California, Davis, Water Resources Center Report No. 37, pp. 1167– 1176. Available at https://pubs.usgs.gov/dds/dds-43/VOL_II/VII_C44.PDF [Verified 12 May 2023], **1996**, 1167-1176.
27. Wotton, B.M. A grass moisture model for the Canadian Forest Fire Danger Rating System. In *Proceedings of the 8th Fire and Forest Meteorology Symposium, Kalispell, MT, USA, 13-15 October 2009*; American Meteorological Society, MA, USA, 2009; Paper 3A.2.
28. Hallett, D.J.; Lepofsky, D.S.; Mathewes, R.W.; Lertzman, K.P. 11 000 years of fire history and climate in the mountain hemlock rain forests of southwestern British Columbia based on sedimentary charcoal. *Can. J. For. Res*. **2003**, 33, 292–312.
29. Hoffman, K.M.; Gavin, D.G.; Lertzman, K.P.; Smith, D.J.; Starzomski, B. M. 13,000 years of fire history derived from soil charcoal *in* a British Columbia coastal temperate rain forest. *Ecosphere*, **2016**, 7, e01415.
30. Brown, K.J.; Hebda, N.J.; Conder, N.; Golinski, K.G.; Hawkes, B.; Schoups, G. Changing climate, vegetation, and fire disturbance in a sub-boreal pine-dominated forest, British Columbia, Canada. *Can. J. For. Res*. **2017**, 47, 615–627.
31. Brown, K.J.; Hebda, N.J.R.; Schoups, G.; Conder, N.; Smith, K.A.P.; Trofymow, J.A. Long-term climate, vegetation and fire regime change in a managed municipal water supply area, British Columbia, Canada. *Holocene* **2019**, 29, 1411–1424.
32. Graham, R.T.; Harvey, A.E.; Jain, T.B.; Tonn, J.R. The effects of thinning and similar stand treatments on fire behavior in Western forests. In General Technical Report; PNW-GTR-463;: USDA Forest Service, Pacific Northwest Research Station: Portland, OR, USA, 1999; pp. 1-27.
33. Lezberg, A.L.; Battaglia, M.A.; Shepperd, W.D.; Schoettle, A.W. Decades-old silvicultural treatments influence surface wildfire severity and post-fire nitrogen availability in a ponderosa pine forest. *For. Ecol. Manage*. **2008**, 255, 49–61.
34. Cumming, S.G. Forest type and wildfire in the Alberta boreal mixedwood: What do fires burn? *Ecol. Appl*. **2001**, 11, 97–110.
35. Parisien, M.-A.; Barber, Q.E.; Hirsch, K.G.; Stockdale, C.A.; Erni, S.; Wang, X.; Arsenault, D.; Parks, S.A. Fire deficit increases wildfire risk for many communities in the Canadian boreal forest. *Nat. Commun*. **2020**, 11, 2121.
36. PIP. FireSmart: Protecting your community from wildfire. 2nd ed. Partners in Protection, Edmonton, AB, Canada, 2003; pp. 1-165.
37. Alexander, M.E. Surface fire spread potential in trembling aspen during the summer in the boreal forest region of Canada. *For. Chron*. **2010**, 86, 200-212.

 doi:10.20944/preprints202310.1426.v1

38. Ricotta, C.; Bajocco, S.; IGuglietta, D.; Conedera, M. Assessing the influence of roads on fire ignition: Does land cover matter? *Fire* **2018**, 1, 24.
39. https://www2.gov.bc.ca/gov/content/safety/wildfire-status/prevention/vegetation-and-fuel-management
40. Stevens, V. 1997. The ecological role of coarse woody debris: An overview of the ecological importance of CWD in B.C. forests. Res. Br., B.C. Min. For., Victoria, B.C. Work. Pap. 30/1997.
41. Scheungrab, D.B.; Trettin, C.C.; Lea, R.; Jurgensen, M.F. 2000. Woody debris. In: *Gen. Tech. Rep. SRS-38. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station*. p. 47-48.
42. van Galen, L.G.; Jordan, G.J.; Baker, S.C. Relationships between coarse woody debris habitat quality and forest maturity attributes. *Conserv. Sci. Pract*. **2019**, 1, e55.
43. Hart, S.C.; Porter, T.M.; Basiliko, N.; Venier, L.; Hajibabaei, M.; Morris, D. 2022. Fungal community dynamics and carbon mineralization in coarse woody debris across decay stage, tree species, and stand development stage in northern boreal forests. https://doi.org/10.1101/2022.01.31.478531
44. Whistler.ca Available online: URL (accessed on 10 November 2022). https://www.whistler.ca/media/news/media-advisory-infrastructure-announcement-whistler?utm_medium=email&utm_campaign=Whistler%20Today%20November%2010%202022&utm_content=Whistler%20Today%20November%2010%202022+CID_36a9958ef0633a2e4eba703717db32dc&utm_source=Email%20marketing%20software&utm_term=Read%20More
45. Taylor, C.; Blanchard, W; Lindenmayer, D.B. Does forest thinning reduce fire severity in Australian eucalypt forests? *Conserv. Lett*. **2020**, 14, e12766.
46. Merrill, D.L.; Alexander, M.E., Eds. 1987. Glossary of Forest Fire Management Terms, 4th ed. In *Publication*; NRCC No. 26516; National Research Council of Canada, Canadian Committee on Forest Fire Management: Ottawa, ON, Canada, 1987; pp. 1-91.
47. Hirsch, K.G.; Pengelly, I. Forest fuels management in theory and practice. In C.R. Bamsey, editor. Stand Density Management: Planning and Implementation. Proceedings of a Conference, November 6-7, 1997, Edmonton, Alberta. Clear Lake Ltd., Edmonton, Alberta. **1998**. 112-116.
48. Smith, D.M. *The Practice of Silviculture*, 7th ed.; John Wiley & Sons, New York, NY, USA, 1962; pp. 1-578.
49. Alexander, M.E. Are shaded fuelbreaks the answer to Canada's community wildfire protection problem? *For. Chron.* **2019**, 95, 2-3.