B.C. CANFIRE: EXAMINING CURRENT AND FUTURE EFFECTS OF CLIMATE AND FOREST CHANGES ON FUEL MANAGEMENT TREATMENTS FOR THE WILDLAND URBAN INTERFACE IN THE SOUTH CARIBOO, BRITISH COLUMBIA

by

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ABSTRACT

British Columbia is facing an increase in the number of large, intense high-severity wildfires in the Wildland Urban Interface. This increase is due to historical suppression efforts, climate change, forest structure alterations, exclusion of burning practices, and mismanagement of the landscape. Predictability of fire growth and behaviour is becoming challenging as these high severity wildfires create many uncertainties with respect to firefighter and public safety. Fire prediction modelers are stepping up to adapt to the growing needs of fire managers and with the pressure of climate change. In conjunction, proactive measures look to increase fuel treatments adjacent to communities to reduce wildfire threat, but implementation is slow due to funding limitations, priority setting, and feasibility uncertainties. In this research, I analyzed a fire effects model (BC CanFIRE) adapted to British Columbia and compared fuel treatment strategies with the goal to provide insight on building resilience in British Columbia's Wildland Urban Interface. Alongside B.C. CanFIRE, I gathered data from a harvesting prescription, TIPSY, ClimateBC, the B.C. Wildfire Legacy Weather Application, and the Carbon Budget Model to determine varying weather, climate change scenarios, and site-specific details for the South Green Lake research area. Fuel treatments focused on a reduction of coniferous species to <100 stems/ha while retaining the deciduous stems/ha in the Aspen Parklands. The Shaded Fuel Break focused on a 50% and 80% reduction of Douglas-fir, complete removal of other coniferous species, and tested a planting scenario of 196 stems/ha for each Douglas-fir scenario. Results from this research show that the Intensity Class with both planting and harvesting was reduced. There were also slight decreases in final head fire intensities post-harvest, and a reduction in rates of spread with planting but dependent on the percentage of Douglas-fir removed when examining future years and climate change.

Keywords: fuel treatment, fuel management, wildland urban interface, climate change

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Chapter 1 . Introduction

Living with wildfire is a new reality in British Columbia. In recent years, British Columbia (B.C.) has experienced multiple unanticipated, large, high-severity wildfires within the dry forested ecosystems (Brookes et al. 2021). The high-severity wildfire events have caused Provincial States of Emergencies in 2017, 2018, and 2021, coupled with tens of thousands of evacuees and the unfortunate loss of two small towns, Lytton, and Monte Creek. Historically, 92% of all wildfires were successfully suppressed before they reached four hectares in size (B.C. Wildfire Management Branch 2012). The remaining percentage exhibits the most extreme wildfire behaviour, which might escape initial attack capabilities (Westhaver and Taylor 2020) or remain as fires left to burn. This small percentage accounts for 90% of annual area burned (Westhaver and Taylor 2020). This management strategy to suppress unwanted wildfires quickly was to ensure the protection of people, communities, infrastructure, and resources that consider economic, social, and environmental values in both grasslands and forested regions (B.C. Wildfire Management Branch 2012). Unfortunately, with the absence of these frequent surface fires, researchers have suggested that some forests across B.C. have increased in surface and canopy fuel loads with an overall reduction in complex forest structures (Ziegler et al. 2017). These factors increase the potential for uncharacteristic wildfires, increase the historical range of fire behaviour and severity, and increase the severity of ecosystem impacts (Ziegler et al. 2017).

Prior to European contact, aboriginal use of fire was common across British Columbia. First Nations used fire for various land management purposes over long periods of time, so much so that ecosystems adapted to this anthropogenic disturbance (Wienscyzk et al. 2012). In one example of the Ne Sextsine (Williams Lake B.C. First Nations), fire stewardship used for medicinal purposes, food species, and for new forage growth for ungulates during hunting seasons (Copes-Gerbitz et al. 2022). These fires were traditionally low-severity surface fires that burned at intervals of < 50 years alongside high-severity, stand-initiating, lightning caused fires over 250 years (Brookes et al. 2021). These areas which have been generally fuel-limited from high fire frequencies, experience a ‘fuel-driven inverse correlation between frequency and intensity’ (Steel et al. 2015). This means, these fires operating continuously at low intensities, decreased or limited tree mortality and woody biomass loss was relatively low (Steel et al. 2015). These periodic surface fires consumed fuels, rejuvenated most herb and shrubs, thinned younger stands, and raised live crown base heights (BCFS 1995). Additionally, these fires maintained vegetative species and forest stand structures (BCFS 1995).

Further research gives 250 years as the mean fire interval for stand-replacing disturbances for Interior Douglas-fir subzones, also known as the Natural Disturbance Type 4 ecosystems (NDT4) (Wong et al. 2023). The mosaic in this NDT class ranges from droughty, low elevation sites to less arid sites dominated with old, thick barked, fire-resistant trees (BCFS 1995). This incorporates the drier elements of the Interior Douglas-fir (IDF) Biogeoclimatic (BEC) zone like grasslands and shrublands (BCFS 1995). Since European settlement, this NDT class has been affected by the colonial actions of eliminating indigenous traditional uses of fire, land use changes towards cattle grazing and timber production, and increasing fire suppression (Daniels et al. 2020). The repercussions of this have decreased forest diversity and increased widespread forest health issues (i.e., outbreaks of mountain pine beetle and Douglas-fir bark beetle) (Daniels et al. 2020). Despite historical evidence of beneficial natural and non-natural surface fires in the IDF BEC zone, B.C. today is experiencing the cumulative effects of European settlement and forest management changes. In the 20th century, fire management ideologies stemmed from ‘protecting people, properties, forests, and grasslands’ to the new mandate of ‘delivering effective fire management and emergency response to protect human life and values at risk while encouraging sustainable, healthy and resiliency in forest ecosystems’ (Daniels et al. 2020). This new mandate was to address the overwhelming need for diverse suppression capabilities due to increasing global trends, and the associated social, ecological, and economic costs of managing wildfires as higher temperatures, droughts, and excessive fuels on the forest floor are contributing to a new era of wildfires with extreme consequences toward vulnerable communities (Daniels et al. 2020).

In the first two weeks of July 2021, B.C. saw on average forty starts a day due to the volatility of fuels and repeat severe thunderstorms and lightning (Government of British Columbia 2022). B.C. also had to deal with an ongoing COVID-19 pandemic and the high number of wildfires across Canada and the United States of America (U.S.A.) limited the province's ability to acquire additional resources for support (Government of British Columbia 2022). Abbott and Chapman (2018). reported that these sudden intense wildfire seasons are creating concerns that 'megafires' like those in 2017 and 2018 will be common for seasons to come. Although there is no true scientific definition of a 'mega-fire', the common concept of 'megafires' is based on their 'socioeconomic and environmental impacts' (Linley et al. 2021). This generally refers to the combined effects of (but not limited too) the 'fire size, behaviour, resistance to suppression, novelty, severity, socio-economic costs, and environmental effects" (Linley et al. 2021).

Since 2017, B.C.'s public have raised concerns around the potential impacts that the changing forest structure will have in and around their communities with respect to wildfires. The government and public are looking to put more emphasis on using fuel treatments to modify the forest structure to mimic historical patterns and reduce wildfire threats (Ziegler et al. 2017). However, ownership of fuel treatments, funding, and personnel for implementation has not occurred in a timely manner. There are a minimal number of first-hand observations for both natural and experimental wildfires on ember exposure, pathways for wildfire growth across individual properties and adjacent structures, and vulnerability of structural components, landscaping, and combustibles surrounding structures (Westhaver and Taylor 2020). The lack of information creates a bottleneck between allocating funding, decisions on location of treatments, and which community requires attention first given B.C.'s large rural area exposed to the Wildland Urban Interface (WUI). With the pressure for increased community support, the government of B.C. announced in March of 2022 that the $145 million dollars of new funding will go toward strengthening both Emergency Management B.C. and the B.C. Wildfire Service (Government of British Columbia 2022). An additional $98 million will fund wildfire prevention work and maintenance of forest service roads to aid in response time (Government of British Columbia 2022). To support communities, $210 million will be allocated to community climate change preparedness through FireSmart, Community Emergency Preparedness Funds, Indigenous-led emergency management groups, and to First Nations communities (Government of British Columbia 2022). This increase in budget will include year-round workforces to support prevention and mitigation programs from wildfires (Government of British Columbia 2022).

Fuel treatments are meant to change and reduce the intensity and severity of a wildfire while restoring forest structures that can safely support natural wildfire systems, specifically in dry forests that naturally experience frequent, low-intensity regimes (Syphard et al. 2011). Fire intensity is the "physical combustion process of energy release from organic matter" during the various stages of fire growth (Keeley 2009). Fire intensity is most frequently used in the context of flame length, scorching height of trees, and other biological impacts from the wildfire (Keeley 2009). Fire severity on the other hand, was a term invented to describe how fire intensity affects ecosystems post fire (Keeley 2009). Often used to describe the environmental changes post wildfire, it essentially refers to the loss of organic matter above and below ground post fire (Keeley 2009).

Common practices of fuel reduction treatments include thinning, clearing, removal of surface and ladder fuels (also known as shaded fuel breaks), prescribed burns, planting wildfire-resistant species, and cattle grazing (Seto et al. 2022). There are difficulties to determining the appropriate level and number of fuel treatments, use of wildland wildfire, and suppression given B.C.'s vast and differing landscapes (Keane et al. 2019). Few strategies are being tested that include size of treatment areas, location, and fuel treatment type (Keane et al. 2019). With respect to treatment size, fuel treatments reduced fuel loads and wildfire intensities but to see any significant impact, there needs to be large scale treatment areas to offset historical wildfire suppression (0.08% of the land or 10,000 hectares per year) (Keane et al. 2019). On the landscape, 10,000 hectares (100 km^2) is a large amount of fuel to manage each year especially when considering maintenance planning and costs. If size is unattainable, location may be the next alternative. Location of treatments is chosen by ignition risks, wildfire spread and intensity probabilities, and values at risk (Massada et al. 2011). It accounts for vegetation type, structure, terrain, and accessibility for suppression crews (Massada et al. 2011). The largest concern with fuel treatment implementation is feasibility. Fires often rarely or never meet fuel treatments, and those that do are undocumented or have not had an opportunity to play a significant role (Syphard et al. 2011). Essentially, for fuel treatments to be functional, they must intercept the path of wildfire and must perform according to the management objectives (Syphard et al. 2011). In the U.S.A. (where fuel treatments are commonly used), in fifty-three events examined, twenty-three of those (46%) effectively confined the wildfire within the fuel break (Syphard et al. 2011). As for the remaining thirty incidents (54%), the wildfire spread across the entirety of the treatment area (Syphard et al. 2011). Only one wildfire event stopped completely in the treatment (Syphard et al. 2011). These statistics area important to consider for B.C. as there is minimal research on fuel treatment effectiveness within the province. However, continuing to develop and conduct fuel management around residential areas is a growing demand from most at-risk rural communities stemming from the outcomes of wildfires in 2017, 2018, and 2021.

The objective of this research is to look at a Wildfire Risk Reduction fuel management strategy within the Interior Douglas-fir Biogeoclimatic zone and utilize site-specific details to determine if the current fuel treatment prescription will reduce wildfire intensity, rates of spread, and increase wildfire suppression success. The novelty of this research is based on few literature reviews, case studies, field experiments, and/or documented interface wildfires within BC and across Canada. The subject matter of fuel treatment efficacy makes this thesis an important part of future research streams.

To determine fuel treatment efficacy for this research, a fire effects model coined BC CanFIRE will be used to compare the pre-harvest and post-harvest stand characteristics and associated fire behaviour. The preharvest state is the ‘natural’ forest prior to harvest. Post-harvest treatment will look at a 50% and 80% reduction in the Interior Douglas-fir (*Pseudotsuga menziesii var. glauca*) dominated areas with deciduous planting. The trembling aspen (*Populus tremuloides*) dominated areas will have a reduction of coniferous stems to <100 stems/ha with no change to aspen composition. In addition, prediction of future site characteristics and fire behaviour for both pre- and post-harvest will be analyzed. The research hypothesis is that the current fuel treatment practice on the site will reduce the intensity, rate of spread, and crown fire involvement.

Chapter 2 . Methods

Site and Stand Characteristics

Location of the research area is at South Green Lake, British Columbia (51º 24’ 59.99” N, -121º 12’ 60.00” W). It is located within the IDF BEC Zone in the South Cariboo (1080-1130 metres elevation). It is within the 100 Mile House Regional District and operates under the Thompson Nicola Regional District and Ministry of Forests. In terms of the B.C. Wildfire Service boundaries, the site is in southern area of Cariboo Fire Centre (Figure 2.1).

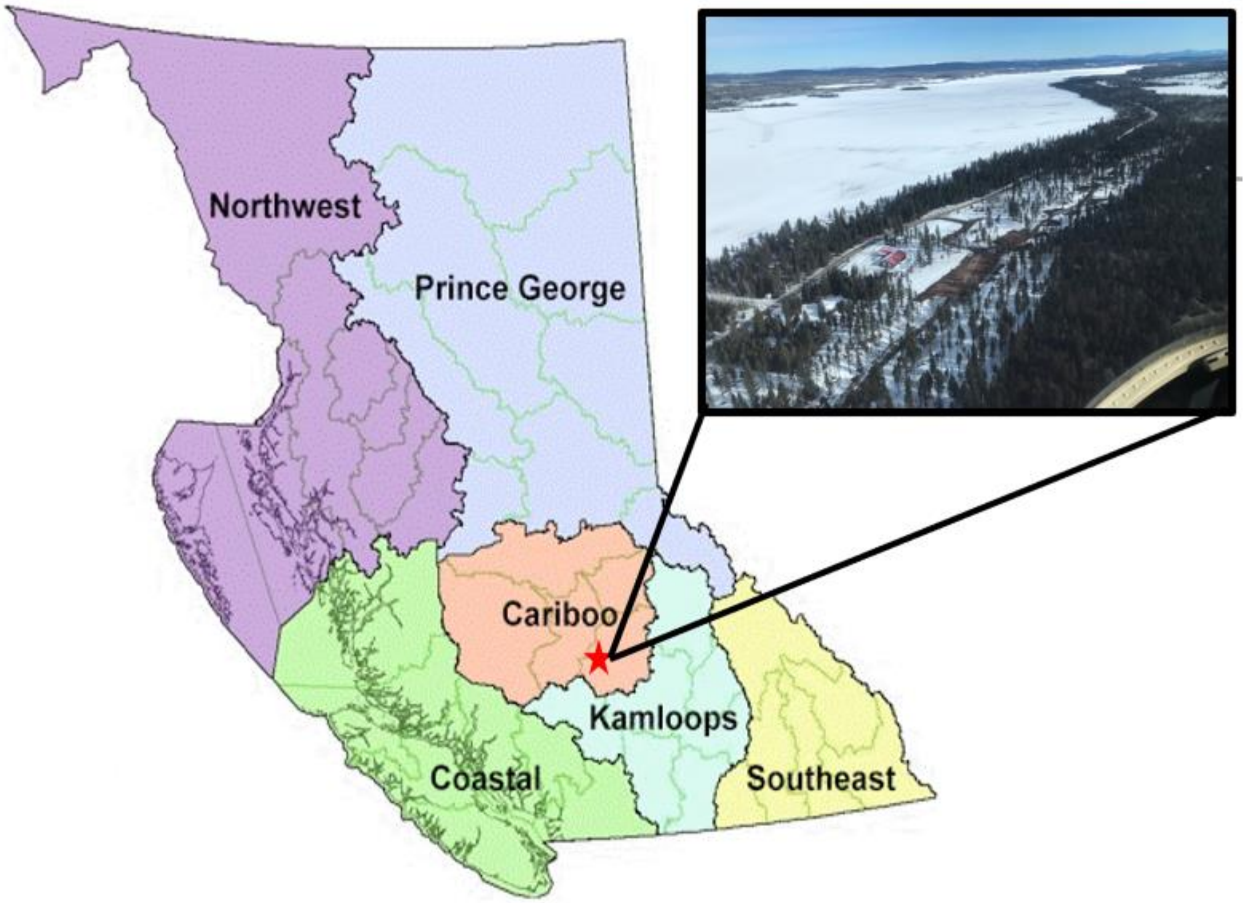

Figure 2.1. Map of British Columbias’ Fire Centres with an insert of the South Green Lake research site (map from: https://wildfiretoday.com., Image by: Johnna Wandler)

The site is approximately 80 hectares in size and divided into four blocks. Three blocks will be treated as an Aspen Parkland and the largest block treated as a Shaded Fuel Break (Figure 2.2). The Aspen Parkland Blocks (1, 2, and 3) are 11.2, 21.0, and 11.2 hectares respectively, while the Shaded Fuel Break is 36.8 hectares. Data was provided by the 100 Mile House District in the form of a forest harvesting prescription.

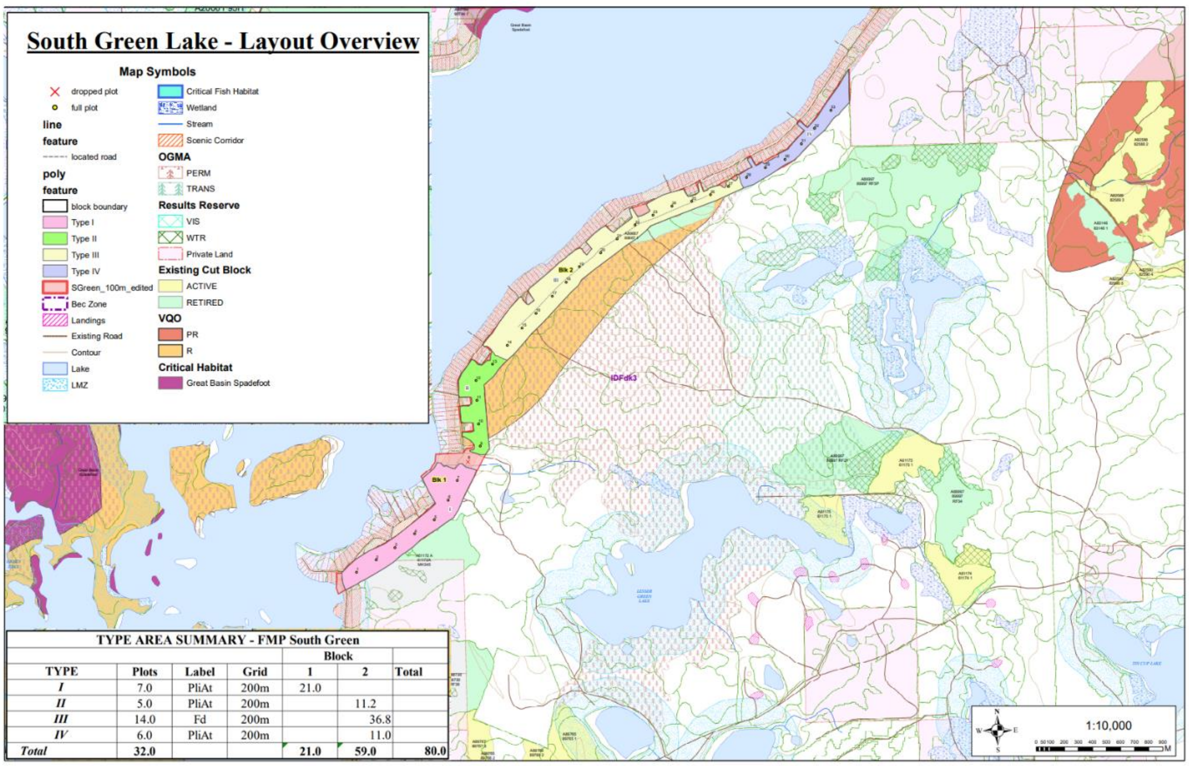

Figure 2.2. Map of the South Green Lake research area with the four identified blocks: Aspen Parklands (pink, green, purple) and Shaded Fuel Break (yellow) (Map from: Johnna Wandler, 100 Mile District).

Prescription data was conducted by field surveys from a second party contractor, Go Wood Forestry Ltd. This research took the forest harvesting prescription and the initial cruise composition and simplified the site into pre and post harvest stems/ha, species composition percentages, forest floor depth (cm), forest floor fuel load (kg/m^2), dead woody debris (DWD) (kg/m^2), and course woody debris (CWD) (kg/m^2) fuel loads. DWD is a 'balance between tree mortality and breakage versus decomposition' (Hanes et al. 2021). DWD increases due to mortality during natural tree life cycle processes (Hanes et al. 2021). Additionally, DWD increases due to natural thinning in immature stands and stand break up in mature stands, therefore making the size of DWD variable vary both spatially and temporally (Hanes et al. 2021). CWD is defined as sound or rotting logs and stumps that 'provide habitat for plants, animals and insects and a source of nutrients for soil development (material typically range from 8-10 cm in diameter)' (Stevens 1997). These debris types are both important because they affect the critical transition phase from surface fires to crown fires (Hanes et al. 2021). The crowning threshold is generally impacted by the amount of surface fuel loading from DWD and CWD. Other variables for crown initiation include surface rate of spread, foliar moisture contents, and the live crown base heights (Hanes et al. 2021).

Species on site were Interior Douglas-fir (*Pseudotsuga menziesii var. glauca*), Engelmann spruce (*Picea engelmannii*), lodgepole pine (*Pinus contorta*), and trembling aspen (*Populus tremuloides*). Forest floor depth measured at each site totaled 4.0 centimeters (cm): 2.0 cm for litter/moss/lichen (top layer), 1.0 cm for duff – ferm layer (middle layer), and 1.0 cm for the humus (bottom layer). Forest floor fuel loads pre-harvest were measured at 0.33-0.60 kg/m^2 while post harvest will focus on reducing fuel loads to 0.10 kg/m^2 with pile burning and future prescribed fires.

The Aspen Parkland blocks, and the Shaded Fuel Break block pre-harvest or 'natural' state and site characteristics were unchanged during analysis (Table 2.1). Images of the pre-harvested state is shown in (Figure 2.3).

Table 2.1. Pre-Harvest site conditions of Douglas-fir, Engelmann spruce, lodgepole pine, and trembling aspens' stems/ha and diameter at breast height (cm) [dash line represents no value].

	DOUGLAS-FIR	ENGELMANN SPRUCE	LODGEPOLE PINE	TREMBLING ASPEN
BLOCK 1 (STEMS/HA)	28	36	330	108
MEAN DBH (CM)	18.1	27.6	16.6	22.5
BLOCK 2 (STEMS/HA)	-	-	60	192
MEAN DBH (CM)	-	-	25.2	19.9
BLOCK 3 (STEMS/HA)	129	-	175	21
MEAN DBH (CM)	20.3	-	22.0	21.2
SHADED (STEMS/HA)	269	19	31	66
MEAN DBH (CM)	28.8	21.9	24.2	22.0

Figure 2.3. Images of South Green Lake site pre-harvest or ‘natural’ state (Left image: Aspen Parkland area. Right image: Shaded Fuel Break area).

The Shaded Fuel Break block post harvest had 100% removal of spruce and lodgepole pine, with varying levels of Douglas-fir removal. This research tested both a 50% and 80% reduction of Douglas-Fir stems/ha in addition to planting a total of four thousand trembling aspen saplings. The Aspen Parkland blocks post harvest had a reduction of coniferous species to <100 stems/ha and no change the deciduous stems/ha composition (Table 2.2). Images of the post harvested state are shown in Figure 2.4. Images of South

Green Lake site post-harvest. (Left image: Aspen Parkland area. Right image: Shaded Fuel Break area).

Table 2.2. Post Harvest site conditions of Douglas-fir, Engelmann spruce, lodgepole pine, and trembling aspens' stems/ha and diameter at breast height (cm) [dash line represents no value].

	DOUGLAS-FIR	ENGELMANN SPRUCE	LODGEPOLE PINE	TREMBLING ASPEN
BLOCK 1 (STEMS/HA)	20	30	50	108
MEAN DBH (CM)	18.1	27.6	16.6	22.5
BLOCK 2 (STEMS/HA)	-	-	40	192
MEAN DBH (CM)	-	-	25.2	19.9
BLOCK 3 (STEMS/HA)	60	-	40	119
MEAN DBH (CM)	20.3	-	22.0	21.2
SHADED / PLANTED (STEMS/HA) 50%	135	-	-	194
80%	54	-	-	194
SHADED/NO PLANTING (STEMS/HA) 50%	135	-	-	-
80%	54	-	-	-
MEAN DBH (CM)	28.8	-	-	22.0

Figure 2.4. Images of South Green Lake site post-harvest. (Left image: Aspen Parkland area. Right image: Shaded Fuel Break area).

Biomass Calculations

For the biomass calculations, a B.C. program called TIPSY (Table Interpolated Stand for Growth Yields) was utilized. This model retrieves and interpolates yield tables, customizes information, displays graphics, and develops summaries for the research area, species on site, and management regime if chosen (Government of British Columbia. 2022a).

The TIPSY biomass program was run for each block in the sites preharvest state. The site-specific parameters were entered into TIPSY which include the forest region, forest district, Biogeoclimatic Zone, and slope. The highest percentage of slope was used for each block to account for increased fire behaviour and forest dynamics associated with slopes. Aspen Parkland Block 1, 2, and 3 used slopes 10%, 8% and 5% respectively, while the Shaded Fuel Break used a slope of 27%. Each tree species was then calculated separately because of TIPSY's inability to provide mixed-species yield tables with consideration to species dynamics, but rather it uses a simple area-weighted averaging (Government of British Columbia. 2022a). The species run through the program were trembling aspen, Interior Douglas-fir, Engelmann spruce, and lodgepole pine.

The site index used was provided by pre—programmed calculations. For the stand specifics, the stand regeneration chosen looked at a natural 2-year delay with the stand density (stems/ha) calculated from the harvesting prescription. The operational adjustment factors remained in their suggested format, and no treatment options chosen. The table specifications selected a range from 0-150 years in steps of 5 years. The stand description display species information tab uses the default information, and then the output is generated.

To access information, an option to select variables to plot on a graph appear, but for the purpose of this research, the view data source tab will extract out all biomass information in tabular form. Extraction of the data source provides information on all biomass, harvesting, and additional site specifics given the species and site information provided by the user. This process was repeated for all remaining pre harvested blocks. Information taken from TIPSY was live foliage biomass (kg/ m^2), dead branchwood biomass (kg/m^2), live crown base height (LCBH) (m), diameter at breast height (DBH) (cm), and height (m).

For post harvest conditions, the research took the calculated biomass from TIPSY, and used the following equations to analyse post harvest biomass:

$$Post\ Harvest\ Live\ Foliage\ Biomass (kg/\mathrm{m}^2) =$$
$$\left(\frac{Live\ Foliage\ Biomass\ Pre\ Harvest\ (kg/\mathrm{m}^2)}{total\ stems}\right) x\ \#\ stems\ post\ harvest$$

$$Post\ Harvest\ Dead\ Brandwood\ Biomass\ (kg/\mathrm{m}^2)\ =$$
$$\left(\frac{Dead\ Branchwood\ Biomass\ Pre\ Harvest\ (kg/\mathrm{m}^2)}{total\ stems}\right) x\ \#\ stems\ post\ harvest$$

To estimate what age the tree species in each block were, and where to begin the 50-year projection, DBH was used from the TIPSY calculations. The closest TIPSY DBH to the average DBH determined from the initial cruise composition was used as the current age of stand. After determining the estimated age of the stand, the following 50 years of biomass calculations were used.

An error was identified in the TIPSY calculations. For spruce and lodgepole pine, there was an error in the LCBH calculations. The TIPSY calculations suggested that both species had a LCBH that exceeded the total height of the species. For this research, the LCBH will use the predetermined LCBH assessed by the initial cruise composition information. The LCBH used for Douglas-fir, spruce, lodgepole, and aspen were 8, 3, 4, and 12 metres respectively.

Forest Floor Biomass Accumulation Analysis

To assess post harvest forest floor biomass accumulations, this research looked at the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) version 1.2. The CBM-CFS3 is a stand and landscape-level model that is used to simulate forest carbon dynamics required under the United Nations Framework Convention on Climate Change (Kull et al., 2019). The CBM-CFS3 model tested a simulation on all four blocks from the South Green Lake site. The simulation tested, for each block, an initial partial cut followed by one hundred years of natural succession focusing on litter accumulation (Appendix A. Carbon Budget Model – Litter Accumulation Projections Post Harvest). When testing each block in the CBM-CFS3 programme, after the first 15 years the curve is relatively flat as decomposition and litter fall balance out. Therefore, this research will leave DWD and CWD variables pre and post harvest unchanged over the fifty-year timeline. In addition, the research did not address the shrub and understory changes and growth over time.

Weather Calculations

Weather was obtained from the British Columbia Wildfire Service Legacy Weather Application. The Legacy Weather Application is an internal government weather recording resource used by the B.C. Wildfire Service and can only be accessed by government employees. This method was chosen because of the ability to access daily weather readings that spanned the required research timeline of 30 years and accessibility during time of the research.

This application was run to collect baseline weather information from 1991-2021 from the Lone Butte (representative weather station) and Meadow Lake (drier weather station) for the month of July. Lone Butte (51° 30’ 25.20 N, 121° 9’43.20 W) is approximately 15 km from the site and Meadow Lake (51° 22’30.00 N, 121° 43’0.00 W) 33 km (Figure 2.5).

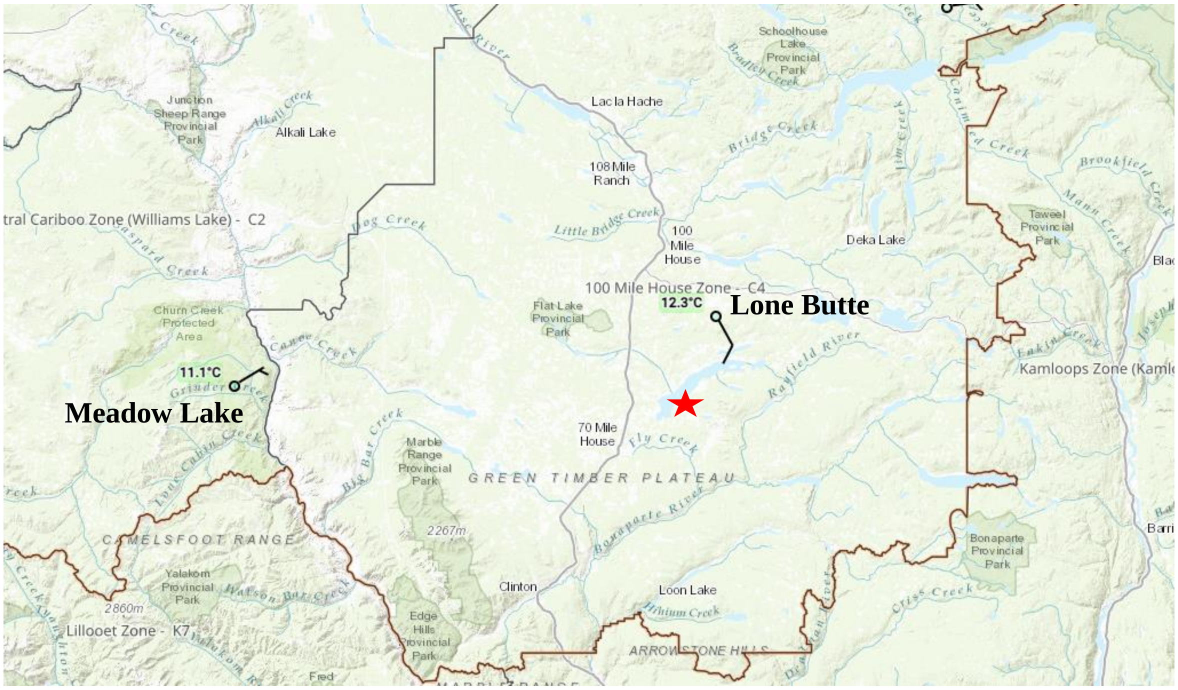

Figure 2.5. Image of the Lone Butte (representative) and Meadow Lake (drier station) weather stations in reference to the research area (indicated by the red star). Image from: BC Wildfire Fire Weather System hub [April 28, 2023].

For these two weather stations, seasonal weather station start-up conditions are important as the stations start recording as soon as fire danger can be measured. Start up instructions are as follows (as per Lawson and Armitage 2008):

1. Fire Weather Index (FWI) calculations will begin on the third day after complete snow removal around the station when fire danger ratings apply.
2. If the region experiences no snow, calculations commence on the third day of noon temperatures at 12 ^{o}C or higher.
3. In either case, following starting values are FFMC 85, DMC 6, DC 15.

FFMC is the fine fuel moisture code. It is the moisture content of litter and other cured fine fuels given in a numerical rating of 0-101 (Lawson and Armitage 2008). DMC is the duff moisture code. This is defined as the moisture content of the loosely compacted 'duff' layers usually at moderate depths of the soil profile (Lawson and Armitage 2008). DC is the drought code. Its importance is its role as an indicate for seasonal drought conditions and the effects on deep, compact organic material (Lawson and Armitage 2008).

This is important to note as these instructions consider the fact that supplementary data may be required for weather stations that cannot operate at the beginning of fire season (Lawson and Armitage 2008). Luckily, these two stations start up in the early spring, when snow has been absent from site for 3 days, making the overwintering of the drought code negligible. Overwintering the drought code is a process that the regional fire weather authority handles but essentially adjusts the DC starting value when station start up in the later spring, early summer timeframes (Lawson and Armitage 2008). Start up values are important as a DC of 15 versus 500 explains two very different types of burning conditions (DC of 500 means extreme hazard, deep burning, hard to extinguish wildfires).

For this research, the Meadow Lake weather station was assessed to determine if there were any significant differences between the two weather stations nearest the research area. July daily weather information was extracted from each station and the 50^{th}, 95^{th}, and 99^{th} percentiles were calculated focusing on DC, ISI, and BUI, as these are the variables required for the fire effects model. For the remainder of the research, baseline weather used the Lone Butte weather stations FWI system variables.

For future climate change projections, the ClimateBC application (https://ClimateBC.ca/) was used to calculate weather variables for the years 2050 and 2080 from baseline weather data. For this research, an ensemble of 13 General Circulation Models (GCMs) was chosen. The GCMs climate projections use scenarios for future greenhouse gas emissions coined Shared Socioeconomic Pathways (SSPs). SSP2-4.5 and SSP3-7.0 were utilized for this research. SSP2-4.5 “assumes moderate mitigation roughly consistent with current emission policies and economic trends” while SSP3-7.0 represents a “broader range of ‘baseline’ scenarios that assume the absence of mitigation policies and its associated linear increase in the rate of greenhouse gas emissions” (Mahony et al. 2022). Figure 2.6 below shows a visual of the 13 GCM simulations under three different SSPs focusing on temperature for the month of July in the Central Interior of B.C.

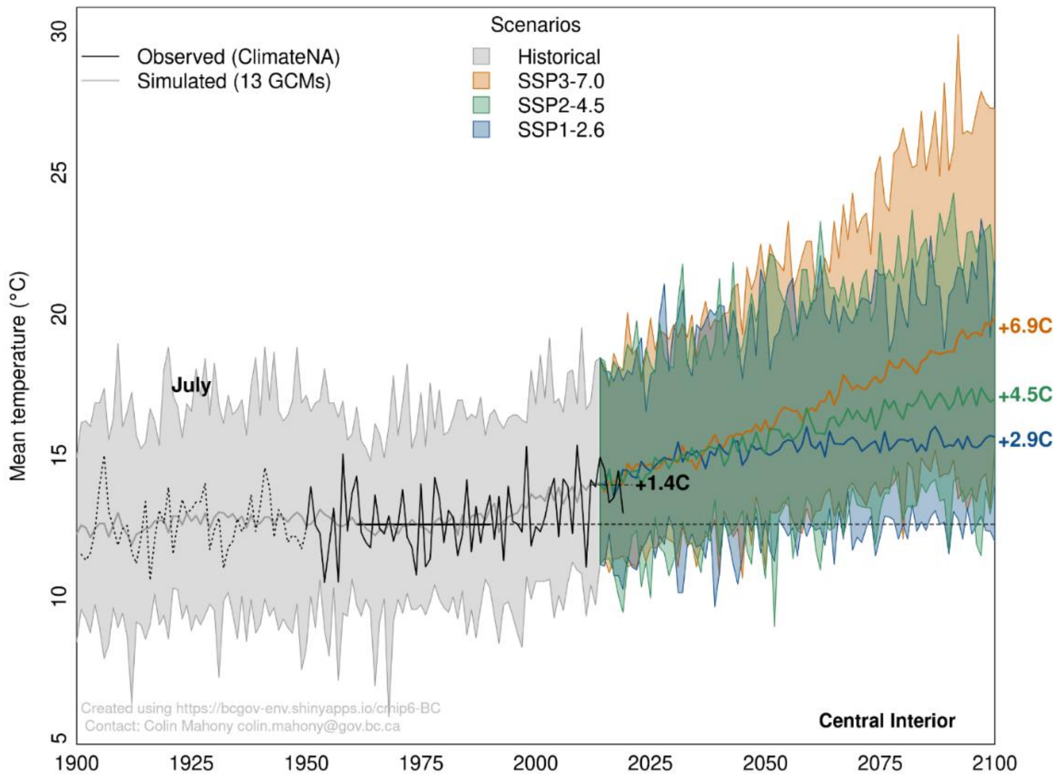

Figure 2.6. Image of 13 General Circulation Model simulations under three different Shared Socioeconomic Pathways focusing on temperature for the month of July in the Central Interior of British Columbia taken from ClimateBC. (Image from: https://www.climatewna.com/ClimateBC_Map.aspx).

Once the changes in precipitation, temperature, and relative humidity's from baseline to 2050 and 2080 in ClimateBC were determined, these changes were then adjusted off the baseline weather outputs for the months of May, June, and July (Table 2.3 and Table 2.4). Baseline weather refers to the FWI variables calculated from the Lone Butte weather station from the 1991-2021 data.

Table 2.3. Changes in temperature (^oC), relative humidity (RH), and precipitation from baseline to 2050 and 2080 focusing on Shared Socioeconomic Pathway 2-4.5 from ClimateBC.

	MAY BASELINE	**MAY 2050**	**MAY 2080**
TEMPERATURE (^OC)	9.4	11.2	11.5
RH	56	56	56
PRECIPITATION	44	43	45
	JUNE BASELINE	**JUNE 2050**	**JUNE 2080**
TEMPERATURE (^OC)	12.8	15.7	16.1
RH	59	57	58
PRECIPITATION	65	50	48
	JULY BASELINE	**JULY 2050**	**JULY 2080**
TEMPERATURE (^OC)	15.6	17.6	18.7
RH	56	57	57
PRECIPITATION	47	43	43

Table 2.4. Changes in temperature (^oC), relative humidity (RH), and precipitation from baseline to 2050 and 2080 focusing on Shared Socioeconomic Pathway 3-7.0 from ClimateBC.

	MAY BASELINE	**MAY 2050**	**MAY 2080**
TEMPERATURE (^OC)	9.4	10.7	12.7
RH	56	57	57
PRECIPITATION	44	37	43
	JUNE BASELINE	**JUNE 2050**	**JUNE 2080**
TEMPERATURE (^OC)	12.8	15.8	17.2
RH	59	58	59
PRECIPITATION	65	52	50
	JULY BASELINE	**JULY 2050**	**JULY 2080**
TEMPERATURE (^OC)	15.6	18.7	21.1
RH	56	59	61
PRECIPITATION	47	39	34

After adjustment, the data was entered into the multi-day Fire Weather Index spreadsheet (Government of British Columbia. 2012) to gather FWI variables from 1991 to 2021 starting with May. The months of May, June, and July were calculated in the FWI spreadsheet to ensure there was quantitative data for Julys' final FWI variables. An example of the changes in the three weather variables for July 2021 with SSP2-4.5 is shown in Table 2.5. The 50^{th}, 95^{th}, and 99^{th} percentiles from July 1991-2021 under each SSP and research year were calculated and used for analysis in the fire effects model. Wind speed (km/hr) and wind direction (360^o) outputs from baseline calculations were used for 2050 and 2080 (no adjustments made).

Table 2.5. Weather calculation adjustments for July 2021 focusing on temperature (temp), relative humidity (RH), and precipitation (precip) with baseline (base) weather values from Lone Butte and future weather predictions from ClimateBC in 2050 and 2080 with Shared Socioeconomic Pathway (SSP) 2-4.5.

Weather Date	*Temp BASE*	*Temp 2050*	*Temp 2080*	*RH BASE*	*RH 2050*	*RH 2080*	*Precip BASE*	*Precip 2050*	*Precip 2080*
20210701	27	29	30	40	41	42	0	0	0
20210702	24	26	27	24	25	26	0	0	0
20210703	25	27	28	31	32	33	0	0	0
20210704	23	25	26	34	35	36	0	0	0
20210705	22	24	25	43	44	45	0	0	0
20210706	24	26	28	34	35	36	1.2	1.1	1.0
20210707	27	29	30	26	27	28	0	0	0
20210708	25	27	28	37	38	39	0	0	0
20210709	25	27	28	40	41	42	0.2	0.2	0.2
20210710	25	27	28	28	29	30	0	0	0
20210711	22	24	25	36	37	38	0.4	0.4	0.3
20210712	25	27	28	25	26	27	0	0	0
20210713	28	30	31	19	20	21	0	0	0
20210714	25	27	28	30	31	32	0	0	0
20210715	23	25	26	33	34	35	0	0	0
20210716	23	25	26	34	35	36	0	0	0
20210717	21	23	24	34	35	36	0	0	0
20210718	22	24	25	28	29	30	0	0	0
20210719	25	27	28	22	23	24	0	0	0
20210720	22	24	25	25	26	27	0	0	0
20210721	20	22	23	26	27	28	0	0	0
20210722	15	17	18	40	41	42	3.0	2.7	2.5
20210723	19	21	22	32	33	34	0	0	0
20210724	22	24	25	35	36	37	0	0	0
20210725	22	24	25	34	35	36	0	0	0
20210726	24	26	27	31	32	33	0	0	0
20210727	21	23	25	35	36	37	0	0	0
20210728	27	29	30	24	25	26	0	0	0
20210729	24	26	27	36	37	38	0	0	0
20210730	28	30	31	27	28	29	0	0	0
20210731	27	29	30	27	28	29	0	0	0

For each FWI adjusted value from baseline to 2050 and 2080, a frequency graph was created to show the distribution of values for each year and SSP. As identified in Figure 2.7 below, the lines show that the distribution for the build-up index have a high number of values on the left-hand side of the graph, however, the trend is shifting toward the right. Trends to the right mean that the site will experience higher fire behaviour (extreme) in future years despite the lack of frequency at the higher bins. For the other FWI graphs, check Appendix B. Frequency distributions for Fire Weather Index variables.

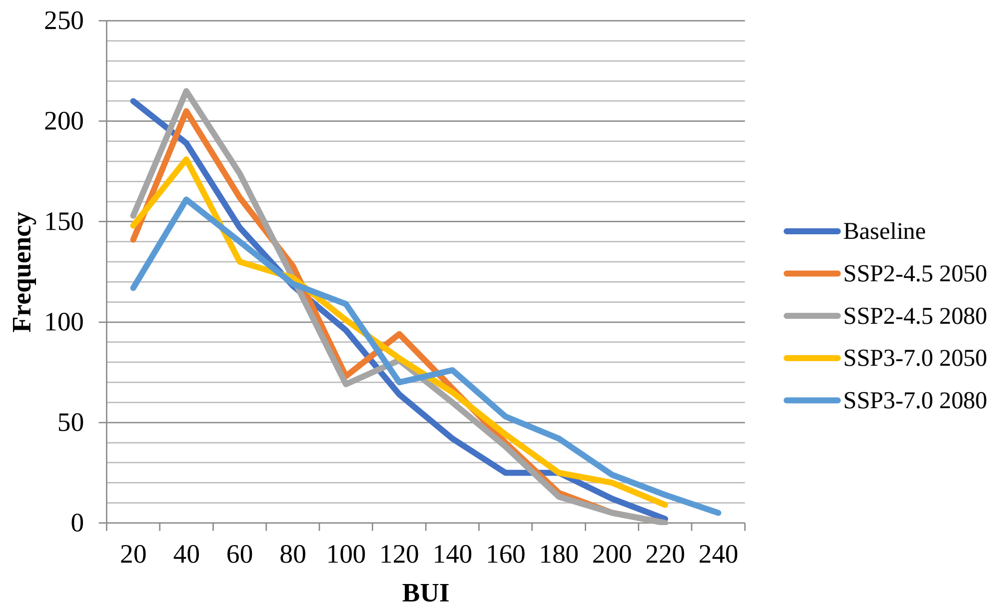

Figure 2.7. Frequency graph of the Build-up Index (BUI) for July 1991-2021 from baseline, 2050, and 2080 adjustments with Shared Socioeconomic Pathways (2-4.5 and 3-7.0).

Season of Burn Data

Growing Degree Days (GDD) were analysed using ClimateBC. GDD is the "average heat energy available for plant growth and development" (B.C. Ministry of Environment 2016). GDD is a necessary component of the fire effects model. This component of the model requires phenological information for the species on site. Essentially, the model focuses on hardwood tree condition (leafless or green), the date of burn (Julian dates), and the Growing Degree Day (used for conifer bud flush). Bud flush or green, leafed out deciduous species offer low flammability's to hinder the spread of a wildfire due to their characteristics of longer ignitions times and slower heat releases (Cui et al. 2019). Optional data requires the current Growing Degree Day, and the White Spruce Seed Ripening date (which does not apply to this research). The GDD >5 ^{o}C was used for baseline, 2050, and 2080 years with the corresponding GDD shown below (Table 2.6). The July baseline (1991-2020) GDD of 333 was used for the current conditions of both the pre and post harvest.

Table 2.6. Growing Degree Days (GDD) for Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for the month of July in the years 2050 and 2080 taken from ClimateBC.

	2050 GROWING DEGREE DAYS (GDD)	**2080 GROWING DEGREE DAYS (GDD)**
SSP 2-4.5	391	424
SSP 3-7.0	426	498

Fire Effects Model

The model being tested is called B.C. CanFIRE (demonstration version). This model uses the original CanFIRE system as its operating baseline but has been adapted to suit the tree species found on the research site. The species include Interior Douglas-fir, trembling aspen, lodgepole pine, and Engelmann spruce. The B.C. CanFIRE model is PC based and calculates fire behaviour at stand and landscape levels (de Groot 2012). The model was designed to calculate fire behaviour and effects on individual stands (de Groot 2022). It can be used to determined multiple 'what if' scenarios for both estimating wildfire behaviour and prescribed burn planning (de Groot 2022). CanFIRE "is driven by the Canadian Forest Fire Weather Index System parameters, and fuel load values obtained from direct measurements (i.e., prescribed fire) or estimated from forest inventories" (de Groot 2022). Forest floor and DWD information is estimated from fuel surveys (de Groot 2022). Fire ROS is calculated by using the Canadian Forest Fire Behaviour Prediction System equations and related procedures (i.e., foliar moisture content and BUI effect) (de Groot 2022). Fuel composition is calculated from the Canadian fuel composition models while fire intensity if calculated using Byram's 1959 equation [$l=hwr$] (de Groot 2022). For the species algorithms, for the purpose of the B.C. CanFIRE fire effects, lodgepole used Jack pine algorithms from previous versions, spruce and trembling aspen algorithms remained the same, while Bill de Groot adapted new algorithms for Interior Douglas-fir.

A sensitivity analysis was conducted testing the DWD and CWD variables in the B.C. CanFIRE model. For the remainder of the Methods and Results sections, the acronym D/CWD will be used. This analysis was completed to ensure any variation to D/CWD would not significantly impact the outputs of the model. The analysis looked at different D/CWD weights totalling the 0.6 kg/m^2 for both the Aspen Parkland and Shaded Fuel Break blocks, focusing on final HFI and ROS variations. Any variation was taken into consideration during the B.C. CanFIRE simulations and any final HFI values that were close between two intensities, the highest intensity was chosen.

Fire Effects Model Simulations

For the B.C. CanFIRE runs, the following process occurred for each block.

Note: This model simulated a prescribed burn every five years over the total fifty years.

Step 1
- Input hectares, latitude, longitude, and elevation into **Location Data** for block/site of interest

Step 2
- Input **FWI System Data** information for 50th, 95th, or 99th percentile from baseline or future data

Step 3
- Input **Ground and Surface Fuel Data**

Step 4
- Input **Season of Burn** data

Step 5
- Input **Standing Timber Fuel Types**. Input all variables for the current age of the stand.

Step 6
- Repeat Step 5 every five years (fifty years of data total).

Step 7
- Repeat Step 2, Step 5, and Step 6

The process listed above was repeated for each weather percentile (50th, 95th and 99th), climate change variation (SSP2-4.5 and 3-7.0), year (current, 2050, and 2080), and block (Aspen Block 1-3 and the Shaded Fuel Break).

Below is a chart showing how the different models and applications used throughout this research fits into the inputs of BC CanFIRE (Figure 2.8). The blue boxes are the inputs required by BC CanFIRE; the other colors are the external resources used.

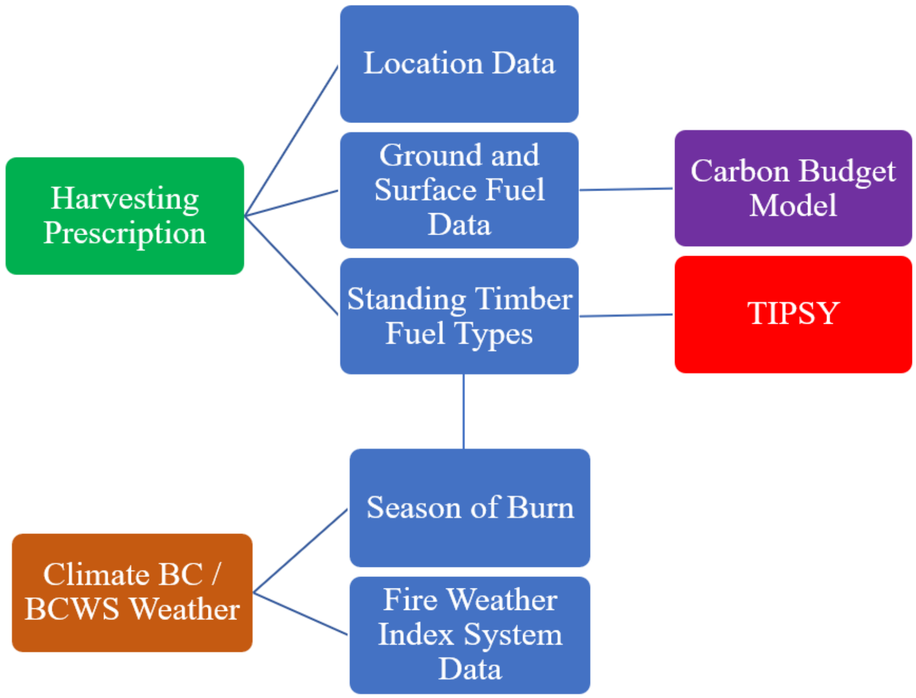

Figure 2.8. Flow chart of BC CanFIRE inputs (blue) and associated programs or applications used.

For the focus of this research, the outputs of interest from the simulations were final head fire intensity, critical head fire intensity per tree species, rates of spread, intermittent crowning or crowning, and Intensity Classes. For the post harvest final HFIs, increasing D/CWD at the 95th and 99th percentiles for 2050 and 2080 (with SSP2-4.5 and SSP3-7.0) were assessed to determine how much fuel accumulation is required to cause individual species crowning (a.k.a. intermittent crowning) or to sustain a crown fire. Any percentile that had Intermittent crowning or crowning was not explored with increases in D/CWD since the outcome is already expressing a type of crown fire. As per de Groot (2022), a crown fire in the fire effects model is classified as “at least 50% of the stand can support a crown fire.” Rates of spread for each block were rounded to the nearest whole number and Intensity

Classes rounded to the highest intensity class if within 700 kw/m. Critical HFI's pre-harvest for each species were 4,823 kw/m (Interior Douglas-fir), 1,107 kw/m (Engelmann spruce), 1,705 kw/m (lodgepole pine), and not applicable for trembling aspen. Post harvest critical HFI for all species, except trembling aspen, reached 6,740 kw/m. Intensity Classes are as follows (written in the more common terms used in B.C. = 'Rank'):

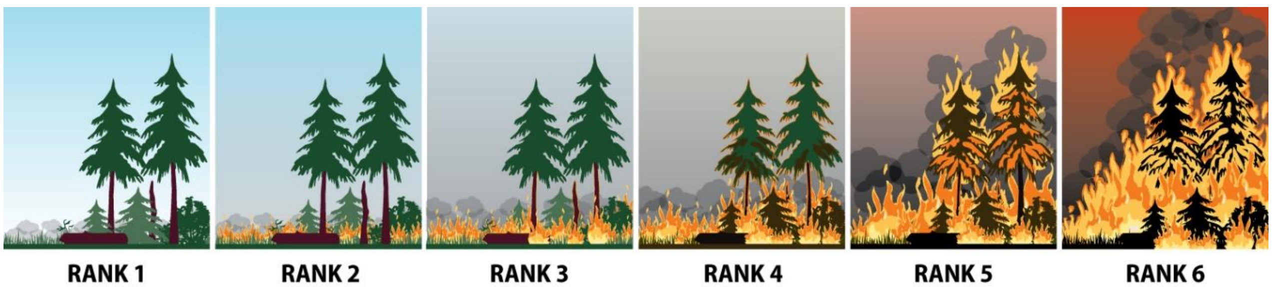

Figure 2.9. Fire Behaviour 'Ranks' based in visual indicators used commonly in British Columbia (Image from: https://www2.gov.bc.ca/gov/content/safety/wildfire-status/wildfire-response/about-wildfire/wildfire-rank*)*.

In summary, Rank 1 – 3 (roughly consistent with Intensity Class 1-3), involves more direct attack suppression tactics with fire behaviour ranging from a creeping ground fire to a high vigorous surface fire with easier containment success rates (Government of British Columbia 2023b). Rank 4 – 6 experience more erratic fire behaviour. Rank 4 and 5 require more indirect or parallel suppression tactics with intermittent crowning and short to mid range spotting (Government of British Columbia. 2023b). For Rank 6, suppression tactics are limited. Air and ground suppression tactics may not be viable and fire behaviour is expected to cause mid to long range spotting (Government of British Columbia. 2023b). Rank 4 to 6 are fires difficult or almost unlikely to be contained (Government of British Columbia. 2023b). The method of using Intensity Class or Rank is to simplify and provide a visual context for what type of fire behaviour suppression crews and aircraft personnel are experiencing when communicating to one another.

Chapter 3 . Results

Data Analysis

The sensitivity analysis for D/CWD was conducted to test the fire effects model sensitivity and changes in fire behaviour as D/CWD changes and increases over time. If there were significant variability in fire behaviour outputs, the research would have had considered the distribution of fuel class sizes in further detail, choosing a strategy that best represented the site. For example, examining the likelihood of 0.0 kg/m^2 of DWD in size class 0-1 cm (shown in Table 10). In Table 3.1, are two variations tested within the model (using Aspen Block 1 inputs) among the handful examined.

Table 3.1. Example of Dead Woody Debris (DWD) (kg/m^2) and Coarse Wood Debris (CWD) (kg/m^2) variations focusing on different size classes tested in the BC CanFIRE fire effects model [total biomass = 0.60 kg/m^2 for each column - i.e., variation].

DWD Size Classes (cm)	**SET 1 (kg/m^2 of biomass per size class)**					**SET 2 (kg/m^2 of biomass per size class)**		
0-1	0.1	0.1	0.1	0.1	0.2	0	0.2	0
1-3	0.1	0.1	0.1	0.2	0.1	0	0.2	0.2
3-5	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.2
5-7	0.1	0.2	0.1	0.1	0.1	0.2	0	0.2
CWD (7+)	0.2	0.1	0.1	0.1	0.1	0.2	0	0

The sensitivity analysis concluded that when testing multiple variations of D/CWD fuel sizes, final HFIs had a variation 11-12% for both the Aspen Parklands and the Shaded Fuel Break. Rates of spread for the Aspen Parkland remained constant at 8.0 m/min, and 8.2 m/min for the Shaded Fuel Break.

Weather Station Data

For weather station data, Table 3.2 shows the July percentiles for the Lone Butte weather station and the Meadow Lake weather station, two weather stations closest the South Green Lake Site.

Table 3.2. The July percentiles [50th, 95th, 99th] and associated Fire Weather Index values for the Lone Butte (representative) and Meadow Lake (drier) weather stations from 1991-2021.

Weather Station	**Percentile (%)**	**Fine Fuel Moisture Code (FFMC)**	**Duff Moisture Code (DMC)**	**Drought Code (DC)**	**Initial Spread Index (ISI)**	**Build Up Index (BUI)**	**Fire Weather Index (FWI)**
Lone Butte	50	87	31	297	4.1	48	11
	95	94	119	547	12.8	151	38
	99	95	626	18	17.8	188	47
Meadow Lake	50	89	43	422	5.3	68	16
	95	95	135	657	15.3	169	47
	99	96	243	730	20.9	265	54

For future years (with no SSP), the ClimateBC application stated that for the year 2050 from baseline, there was an increase of approximately 1.0 ^{o}C, an 8% increase to the precipitation, and no change in the relative humidity (RH) for the month of May. June saw an increase of approximately 3.0 ^{o}C, a decrease in RH by 1, and a 17% decrease in precipitation. For the month of July, the ensembles from ClimateBC suggests there will be an increase of temperature by 2.0 ^{o}C, no change to the RH, and a 6% decrease in precipitation. For the year 2080, May saw a temperature increase by 2.0. ^{o}C, no change to RH, and a decrease in precipitation by 8%. Junes' temperature increased by 1.4 ^{o}C, precipitation decreased by 4%, and RH saw an increase by 1. July sees a temperature increase of 2.4 ^{o}C, an increase in RH by 2, and a decrease in precipitation of 13%.

Climate Change Data

For future calculations using the FWI variables collected and calculated from ClimateBC, Table 3.3 shows the changes in FWI variables over time and with the different SSPs.

Table 3.3. The July Fire Weather Index percentiles from ClimateBC with Shared Socioeconomic Pathways 2-4.5 and 3-7.0 for the year 2050 and 2080 using 13 General Circulations Models [numbers in brackets are the Lone Butte baseline values from 1991-2021].

ClimateBC	Percentile (%)	Fine Fuel Moisture Code (FFMC)	Duff Moisture Code (DMC)	Drought Code (DC)	Initial Spread Index (ISI)	Build Up Index (BUI)	Fire Weather Index (FWI)
SSP2-4.5 2050	50	88 (87)	36 (31)	309 (297)	5 (4)	54 (49)	12 (11)
	95	94 (94)	120 (119)	519 (548)	13 (13)	145 (151)	40 (38)
	99	95 (97)	146 (164)	587 (614)	18 (17)	173 (186)	49 (47)
SSP3-7.0 2050	50	88 (87)	39 (31)	348 (297)	5 (4)	60 (49)	13 (11)
	95	94 (94)	135 (119)	581 (548)	13 (13)	166 (151)	41 (38)
	99	95 (97)	183 (164)	660 (614)	17 (17)	202 (186)	48 (47)
SSP2-4.5 2080	50	87 (87)	31 (31)	367 (297)	4 (4)	51 (49)	12 (11)
	95	94 (94)	108 (119)	600 (548)	14 (13)	145 (151)	40 (38)
	99	96 (97)	132 (164)	676 (614)	18 (17)	174 (186)	50 (47)
SSP3-7.0 2080	50	88 (87)	43 (31)	425 (297)	5 (4)	68 (49)	15 (11)
	95	94 (94)	141 (119)	665 (548)	13 (13)	178 (151)	42 (38)
	99	95 (97)	187 (164)	756 (614)	18 (17)	217 (186)	54 (47)

The FFMCs for all variables ranged from 88-96, which is the indicator of how dry the smallest forest fuels are (Government of Alberta 2023). DMC ranged from 31-187 which determines the fire hazard for medium sized surface fuels and the upper duff layers (Government of Alberta 2023). DC ranged from 309-756 which indicates the dryness of the largest surface fuels and the deeper duff layers (Government of Alberta 2023). ISI ranged from 5-18 indicating a slow-extreme initial fire spread across the site. BUI ranged from 51-217 which measures the amount of fuel on site available for combustion (Government of Alberta 2023). FWI ranged from 12-54 which measures the potential fire intensity Government of Alberta 2023). Essentially, for each FWI variable, the higher the number, the higher chance of ignition, the higher intensity to burn, and the higher hazard. Overall, the site is expected to experience High-Extreme hazard across the site (see Appendix C**.** Fire Weather Indices and Hazard Ratings with Head Fire Intensities represented by Rank).

B.C. CanFIRE Results

There are some considerations with the following fire effects model results. Trembling aspen did not have a critical HFI pre or post harvest, therefore it is not represented in the graphs and tables but remains a factor in the results. Although this research focuses on manipulation of forest stand dynamics and climate change scenarios, the results listed below are heavily driven by weather.

In the pre harvest graphs, the left-hand side of the graph (final HFI) is represented by the solid-coloured lines of the differing years and weather percentiles, whereas the right-hand side (critical HFI) is represented by the dashed lines coinciding with the differing species on site. The pre harvest graphs assess scenarios of changing fire behaviour with changing fuel and weather conditions over time. For example, this research is testing 2050 weather on the current stand with changing fuel conditions 5-50 years from now. This is to analyze what will happen with respect to fire behaviour on the research site if no harvesting is conducted.

For post harvest graphs, the left-hand side (final HFI) is represented by the dotted lines of the different SSPs and weather percentiles. The right-hand side (critical HFI) is represented by the solid line for 'All Species' that remain on site or an identified species. The post harvest graphs show the affect of weather on the different treatment blocks. Forest floor accumulations are negligible for all post harvest treatments since the forest floor accumulation analysis concluded there is minimal impact on fire behaviour with increasing biomass.

Aspen Parkland Block 1

Pre-Harvest Final Head Fire Intensity

Figure 3.1 identifies the variation of final HFIs over 50 years without harvesting and the changing weather variables with Shared Socioeconomic Pathway 2-4.5. In the figure, there is slight overlap in values between different years and percentiles. The baseline 50th percentile (medium blue) is hidden behind the other 50th percentile values. The baseline 99th percentile (light grey) is hidden behind the other 99th percentile values.

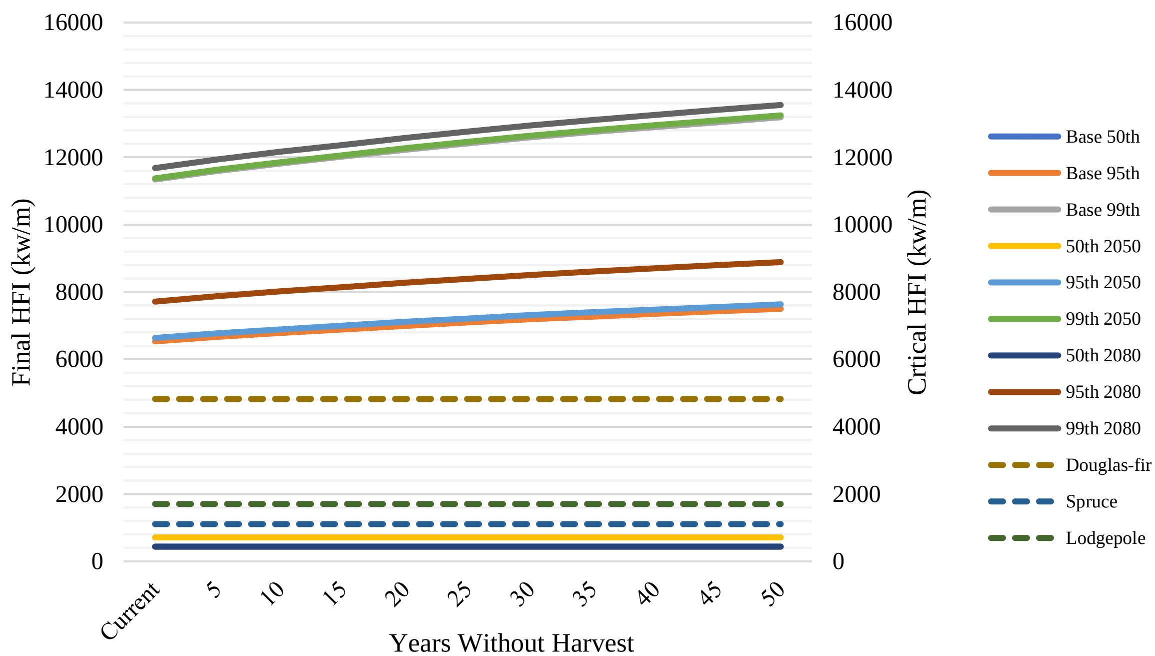

Figure 3.1. Aspen Parkland Block 1: Pre-Harvest Final Head Fire Intensity (k/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathway 2-4.5.

For the above graph, at the 95th and 99th percentiles for all years and SSPs have exceeded the critical HFIs, concluding that the site will experience a crown fire at these percentiles. The 50th percentiles will not experience any type of crowning.

Figure 3.2, identifies the variation of final HFIs over 50 years without harvesting and the changing weather variables with Shared Socioeconomic Pathway 3-7.0. In the figure, there is slight overlap between some of the values. For 2050s' 50th percentile (yellow), it is hidden behind the other 50th percentile values.

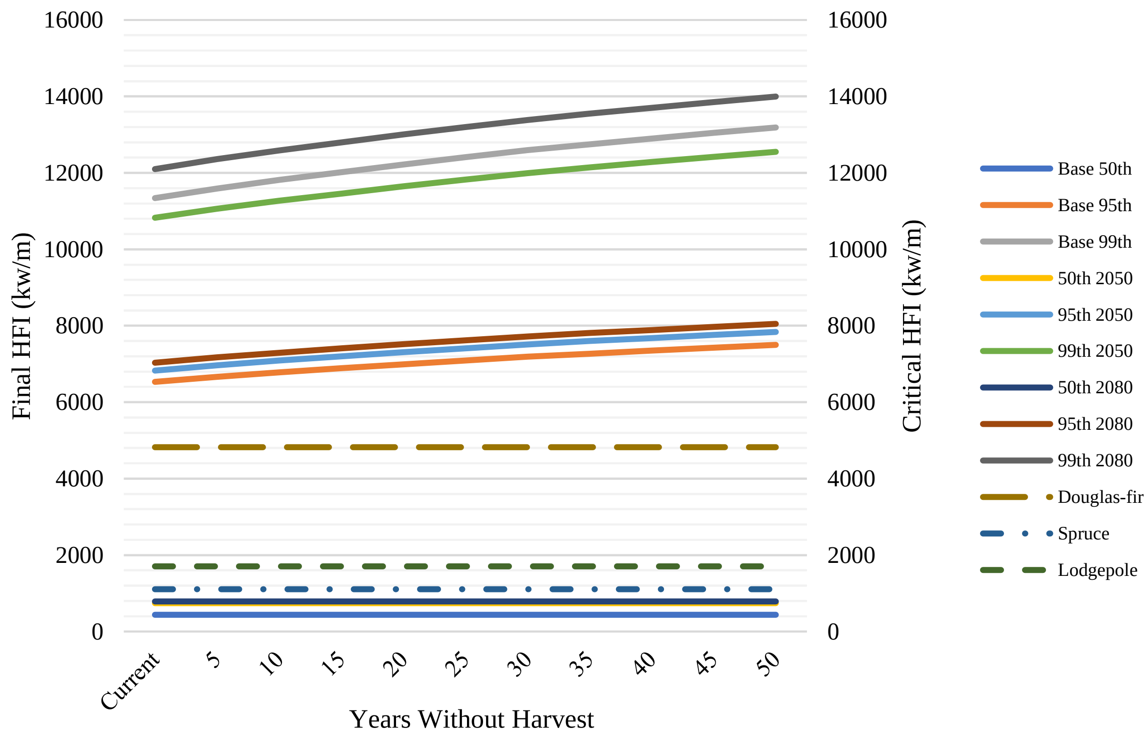

Figure 3.2. Aspen Parkland Block 1: Pre-Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathway 3-7.0.

For the above graph, the 95th and 99th percentiles for all years and SSPs have exceeded the critical HFIs, concluding that the site will experience a crown fire at these percentiles. The 50th percentiles will not experience any type of crowning.

Post Harvest Final Head Fire Intensity

Figure 3.3 is Aspen Parkland Block 1 post harvest final and critical HFI (kw/m) with Shared Socioeconomic Pathways (2-4.5 and 3-7.0) from current (baseline) through to 2080. In the figure, for visual purposes, there was a change in both axis parameters from the pre harvest figures.

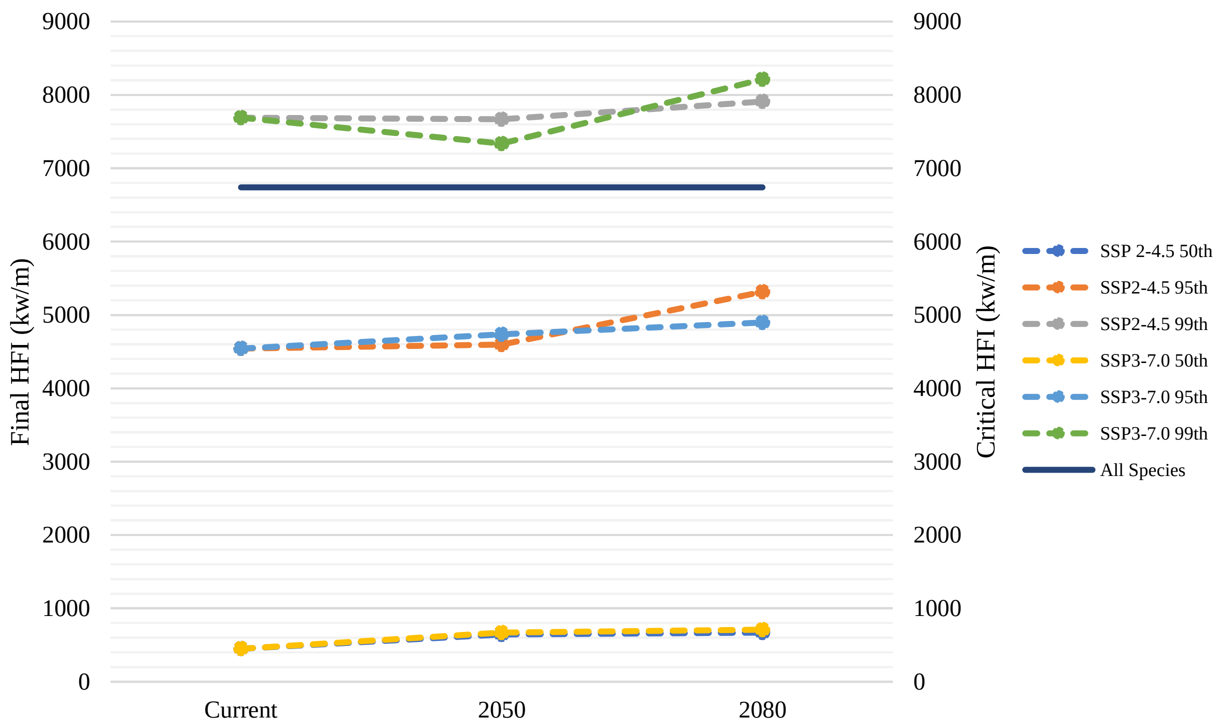

Figure 3.3. Aspen Parkland Block 1: Post Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathways (2-4.5 and 3-7.0).

For Aspen Parkland Block 1 post harvest, 'All Species' in the graph refers to all the species found on this site (Douglas-fir, spruce, lodgepole, trembling aspen). The graph shows that the 99th percentile for SSP2-4.5 and SSP3-7.0 is above the critical HFI line indicating that the site will experience intermittent crowning at the current state (baseline) through to 2080. In 2050, there is minimal change to final HFI for the 50th and 95th percentiles. In 2080, SSP2-4.5 exceeds SSP3-7.0 slightly at the 50th percentile and exceeds at the 95th percentile by over 500 kw/m.

In terms of forest floor fuel load accumulations for Aspen Parkland Block 1, the 95th percentile was analyzed to assess how much fuel is needed to cause intermittent crowning or crowning on site. Table 3.4 shows the increases in forest floor fuel load (kg/m^2) for each SSP and year, along with the associated final HFI's and type of crown fire the site will experience.

Table 3.4. Aspen Parkland Block 1: Post harvest forest floor fuel load increases for baseline, 2050, and 2080 with differing SSPs, associated Final HFIs, and crown fire type [the value in brackets is the standard for forest floor fuel loads post harvest].

		95th Percentile (kg/m^2)	**Final HFI (kw/m)**	**Crown?**
	Baseline	2.8 (0.6)	7433	Intermittent
SSP2-4.5	*2050*	3.5 (0.6)	6855	Intermittent
	2080	2.0 (0.6)	6359	Intermittent
SSP3-7.0	*2050*	3.5 (0.6)	6679	Intermittent
	2080	3.0 (0.6)	6845	Intermittent

The 99th percentile was not analyzed since the site experienced intermittent crowning without increasing D/CWD. For the 95th percentile, increasing biomass to reach 2.0-3.5 kg/m^2 from 0.6 kg/m^2 will cause the site to experience intermittent crowning.

Rates of Spread

For Aspen Block 1, pre and post harvest ROS varied between the SSPs and years (Figure 3.4). For baseline, ROS increased post harvest at the 95th and 99th percentiles. In 2050, post harvest ROS increased, from 1-3 m/min with each percentile and SSP. In 2080, post harvest ROS decreased, from 1-3 m/min, with each percentile and SSP. The 50th percentile, however, saw no change in ROS between pre and post harvest.

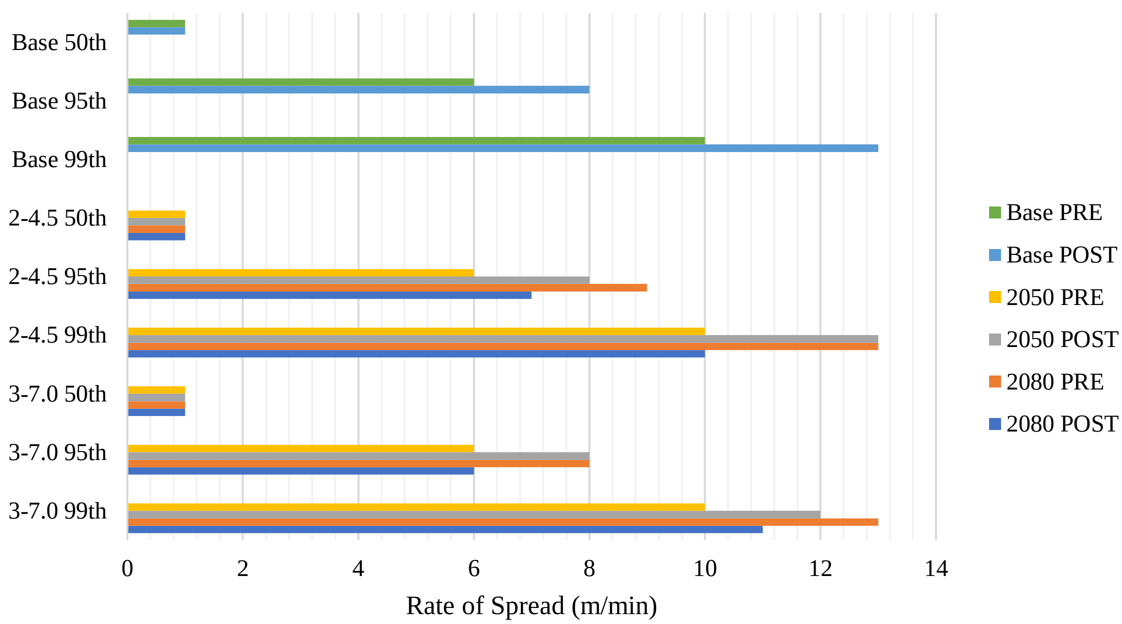

Figure 3.4. Aspen Parkland Block 1: Pre- and Post-Harvest Rate of Spread (m/min) with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080.

Intensity Classes

The Intensity Class at the 50th and 95th percentiles had no change across all years and SSPs at Intensity Class 3 and 5 respectively, while all 99th percentiles decreased from Intensity Class 6 to 5 (Figure 3.5).

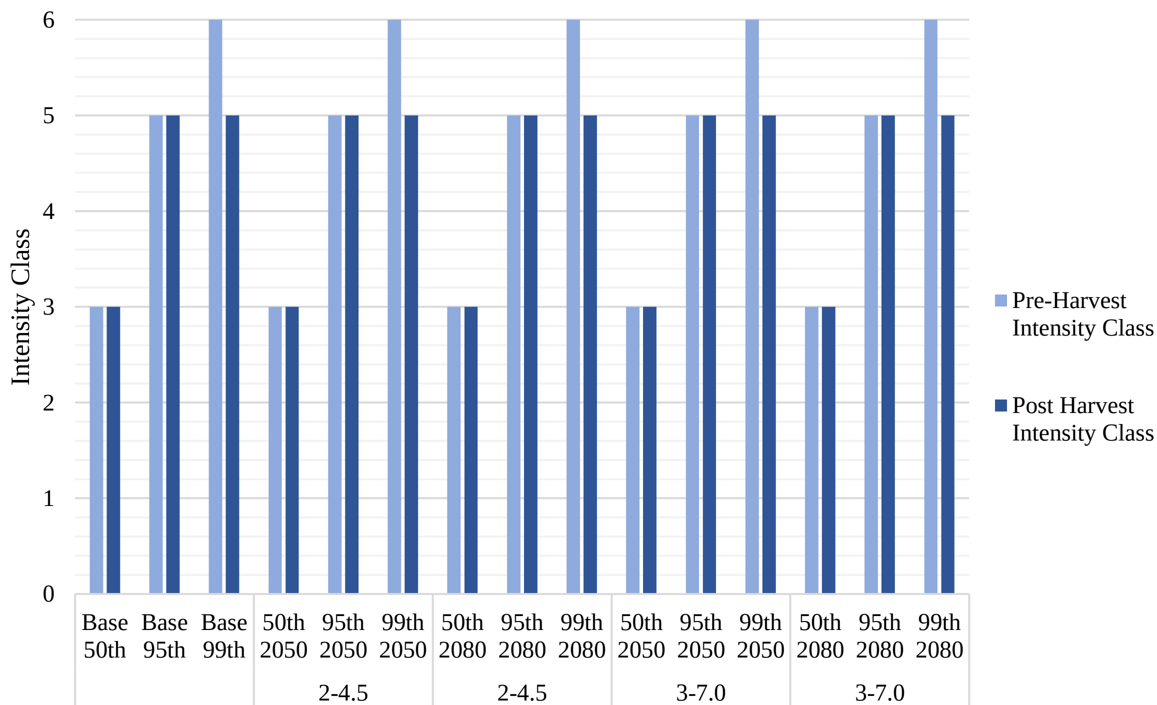

Figure 3.5. Aspen Parkland Block 1: Pre and Post Harvest Intensity Classes with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080.

Aspen Parkland Block 2

Pre-Harvest Final Head Fire Intensity

Figure 3.6, shows the variation of final HFIs over 50 years without harvesting and the changing weather variables with Shared Socioeconomic Pathway 2-4.5. In the figure, there is slight overlap between some of the values. The baseline 99th percentile (light grey) is hidden behind the other 99th percentile values. The baseline 50th percentile (medium blue) is hidden behind the other 50th percentile values.

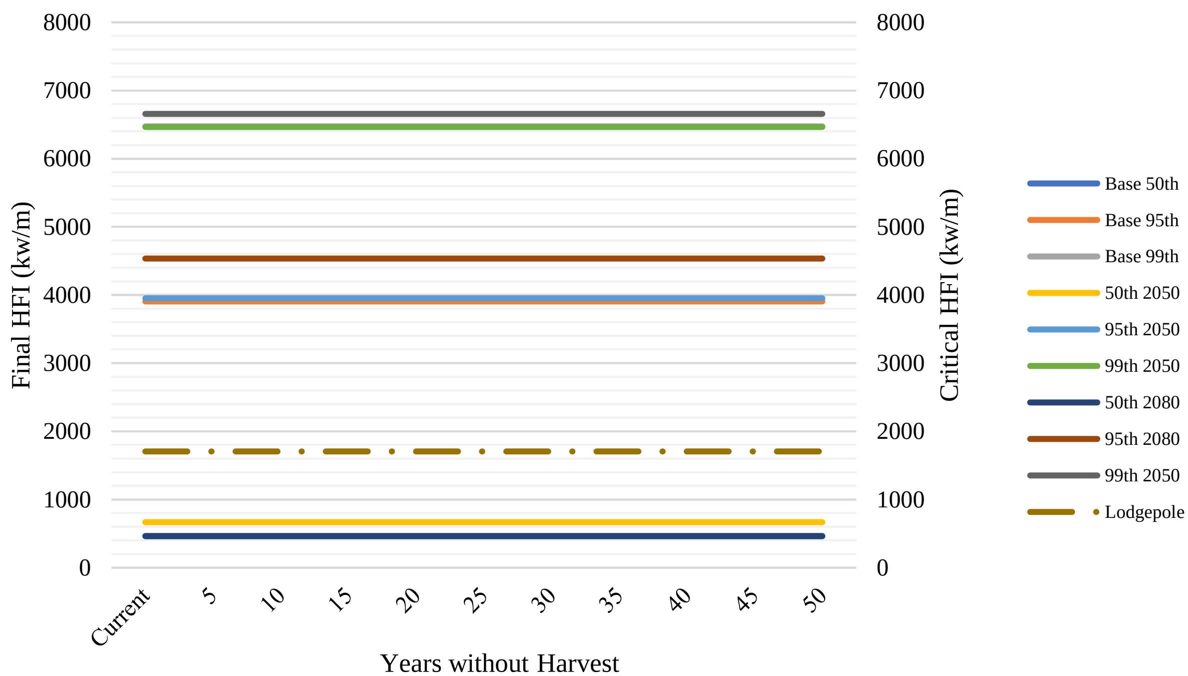

Figure 3.6. Aspen Parkland Block 2: Pre-Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by the dashed line] for baseline, 2050, and 2080 with Shared Socioeconomic Pathway 2-4.5.

For the graph above, lodgepole pine and trembling aspen were the only two species on site, therefore only lodgepoles' critical HFI is shown. For the 95th and 99th percentiles for each year analyzed, the site will experience intermittent crowning at these percentiles. The 50th percentiles will not experience any type of crowning.

Figure 3.7, shows the variation of final HFIs over 50 years without harvesting and the changing weather variables with Shared Socioeconomic Pathway 3-7.0. In the figure, there is slight overlap between some of the values. The 2050s' 50th percentile (yellow) is hidden behind the other 50th percentile values.

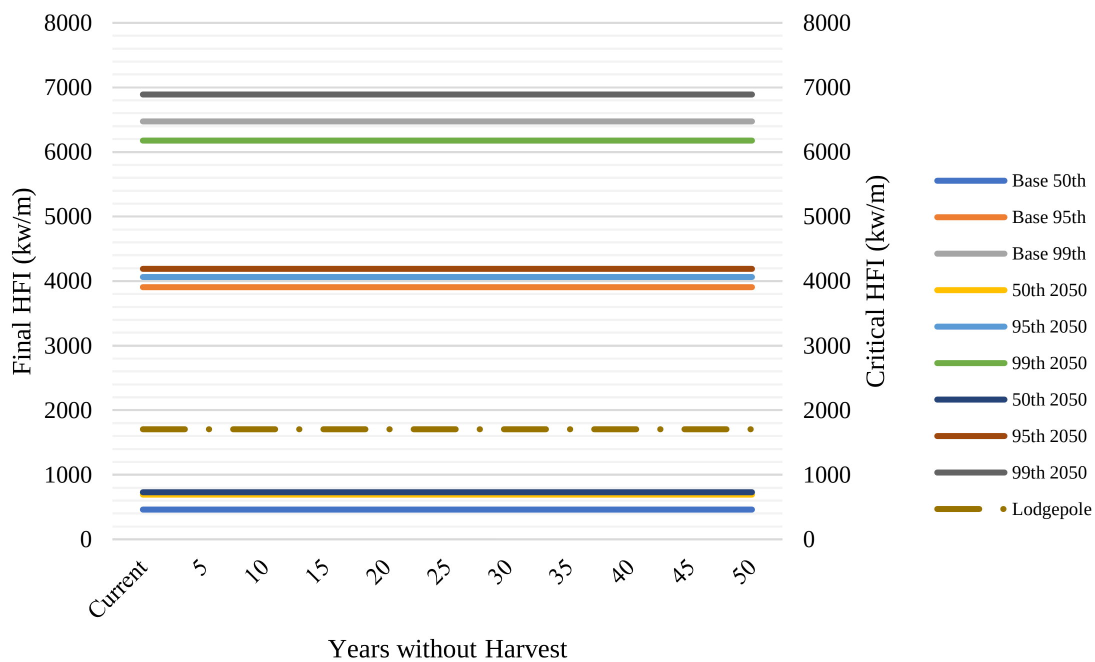

Figure 3.7. Aspen Parkland Block 2: Pre-Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by the dashed line] for baseline, 2050, and 2080 with Shared Socioeconomic Pathway 3-7.0.

Lodgepole pine and trembling aspen were the only species on site, therefore lodgepoles' critical HFI is only shown. For the 95th and 99th percentiles for each year analyzed, the site will experience intermittent crowning at these percentiles. The 50th percentiles will not experience any type of crowning.

Post Harvest Final Head Fire Intensity

Figure 3.8 is Aspen Parkland Block 2 post harvest final and critical HFI (kw/m) with Shared Socioeconomic Pathways (2-4.5 and 3-7.0) from current (baseline) through to 2080.

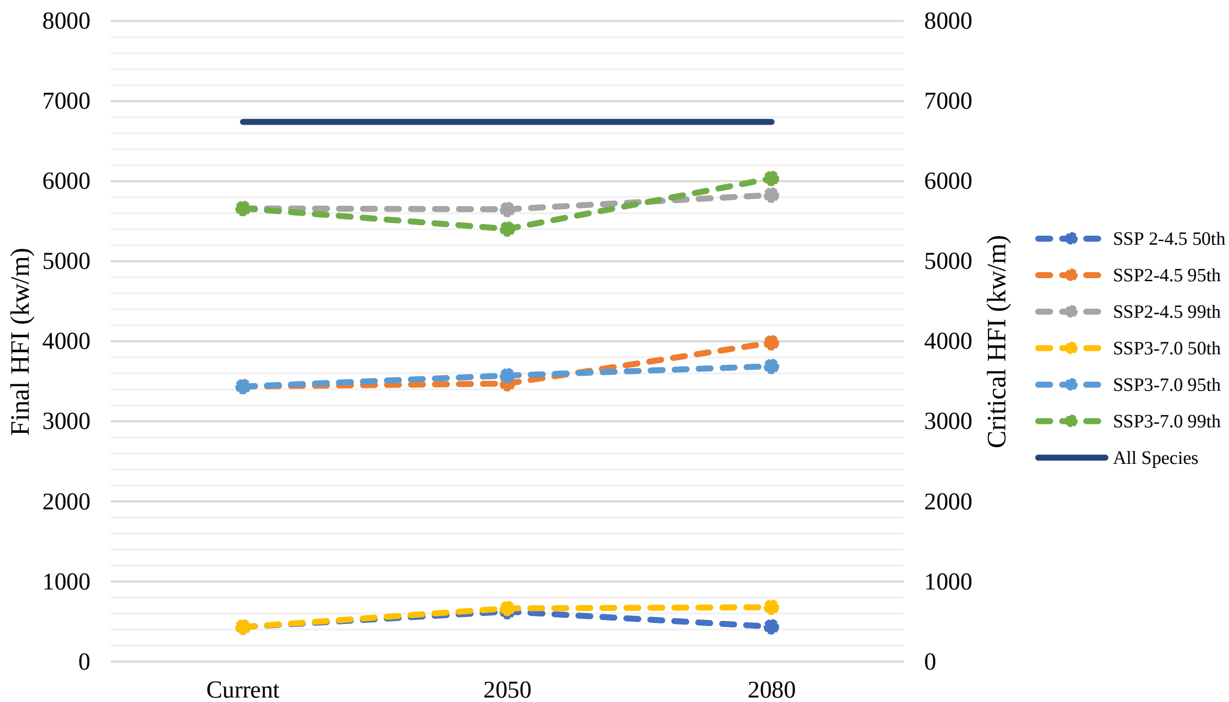

Figure ***3.8*****.** Aspen Parkland Block 2: Post harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by the dashed line] for baseline, 2050, and 2080 with Shared Socioeconomic Pathways (2-4.5 and 3-7.0).

For Aspen Parkland Block 2 post harvest, no variables overlapped or exceeded the critical HFI line, indicating no intermittent crowning or crowning will be expected. Each percentile indicates slight variation from current (baseline) through to 2080. For 2050, SSP3-7.0 values were above SSP2-4.5 for the 50th and 95th percentiles, however, SSP2-4.5 exceeds SSP3-7.0 at the 99th percentile. For 2080, SSP3-7.0 values were above SSP2-4.5 for the 50th and 99th percentiles, however, SSP2-4.5 exceeds SSP3-7.0 at the 95th percentile.

In terms of forest floor fuel load accumulations for Aspen Parkland Block 2, the 95th and 99th percentiles were analyzed to assess how much fuel is needed to cause intermittent crowning or crowning on site. Table 3.5 shows the increases in forest floor fuel (kg/m^2) for each SSP and year, along with the associated final HFI's and type of crown fire the site will experience.

Table 3.5. Aspen Parkland Block 2: Post harvest forest floor fuel load increases for baseline, 2050, and 2080 with differing SSPs, associated Final HFIs, and Crown fire type [the value in brackets is the standard for forest floor fuel loads post harvest].

		95th Percentile (kg/m^2)	**99th Percentile (kg/m^2)**	**Final HFI (kw/m)**	**Crown?**
	Baseline	6.5 (0.6)	1.5 (0.6)	6804 / 6764	Intermittent
SSP2-4.5	*2050*	7.5 (0.6)	1.5 (0.6)	7186 / 6764	Intermittent
	2080	5.5 (0.6)	1.5 (0.6)	7001 / 6942	Intermittent
SSP3-7.0	*2050*	6.5 (0.6)	2.0 (0.6)	6804 / 6814	Intermittent
	2080	6.5 (0.6)	1.0 (0.6)	6815 / 6939	Intermittent

For Aspen Parkland Block 2, the site requires a significant amount of biomass (6.5-7.5 kg/m^2) at the 95th percentile on the forest floor to experience intermittent crowning. On the other hand, the 99th percentile requires only 1.0-2.0 kg/m^2 for the site to experience intermittent crowning.

Rates of Spread

For Aspen Parkland Block 2, pre and post harvest ROS varied between SSPs and years. For baseline, ROS remained the same for all percentiles. In 2050, ROS remained the same for all percentiles except for SSP3-7.0 at the 99th percentile where there as an increase in ROS by 2 m/min post harvest. In 2080, ROS remained the same for all percentiles except for SSP2-4.5 at the 95th percentile where there was a decrease by 1 m/min post harvest (Figure 3.9).

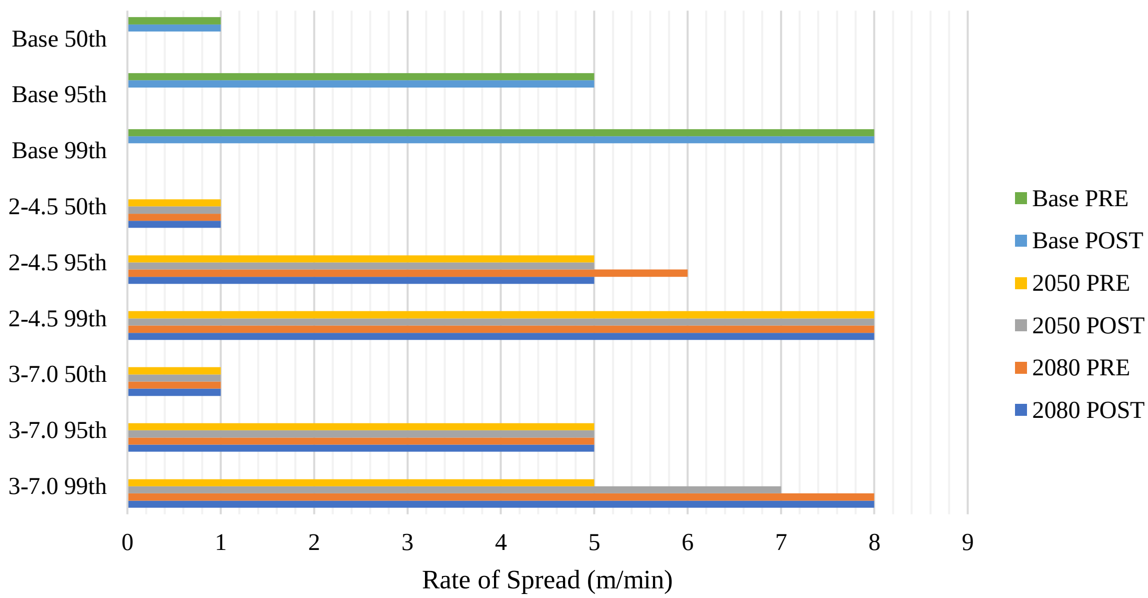

Figure 3.9. Aspen Parkland Block 2: Pre- and Post-Harvest Rate of Spread (m/min) with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080.

Intensity Classes

The Intensity Class at the 50th percentile remained constant at Intensity Class 3 for pre and post harvest except for Baseline and SSP2-4.5 in 2080 where there was a slight decrease from Intensity Class 3 to 2. At the 95th percentile, the Intensity decreased from Intensity Class 5 to 4 except for SSP2-4.5 in 2080 where the Intensity remained constant at Intensity Class 5. At the 99th percentile, the Intensity remained the same for pre and post harvest at Intensity Class 5 (Figure 3.10).

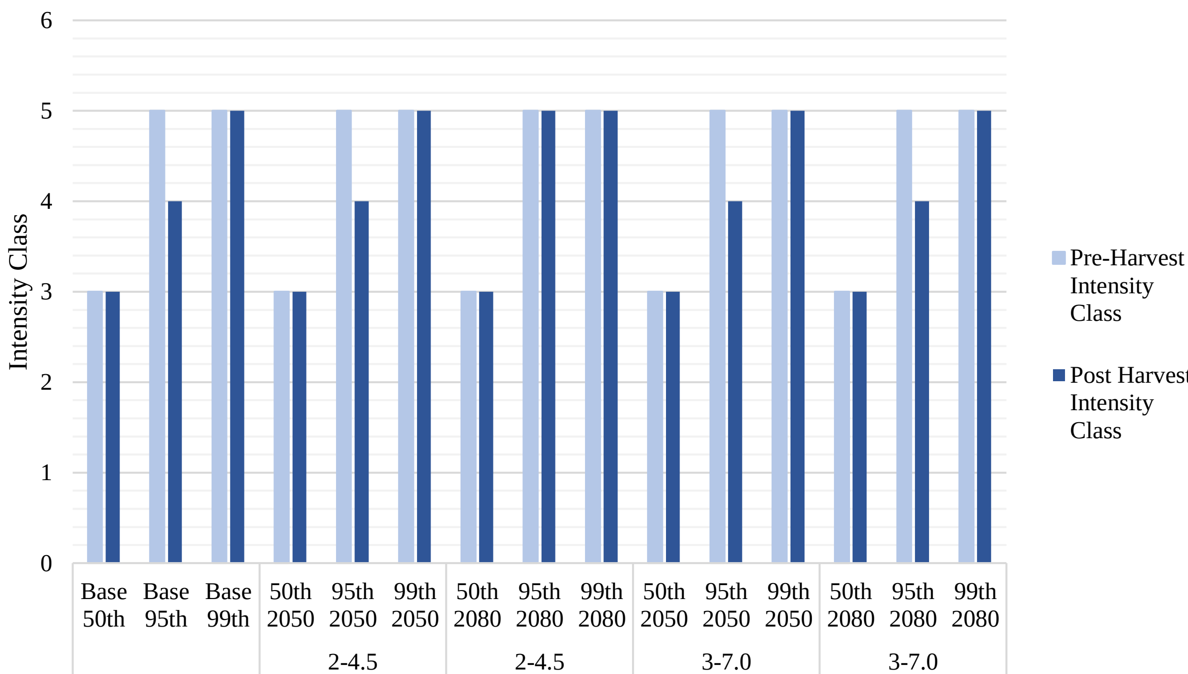

Figure 3.10. Aspen Parkland Block 2: Pre and Post Harvest Intensity Classes with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080.

Aspen Parkland Block 3

Pre-Harvest Final Head Fire Intensity

Figure 3.11, shows the variation of final HFIs over 50 years without harvesting and the changing weather variables with Shared Socioeconomic Pathway 2-4.5. In the figure, there is slight overlap between some of the values. The baseline 99th percentile (light grey) is hidden behind the other 99th percentile values. The baseline 50th percentile (medium blue) is hidden behind the other 50th percentile values.

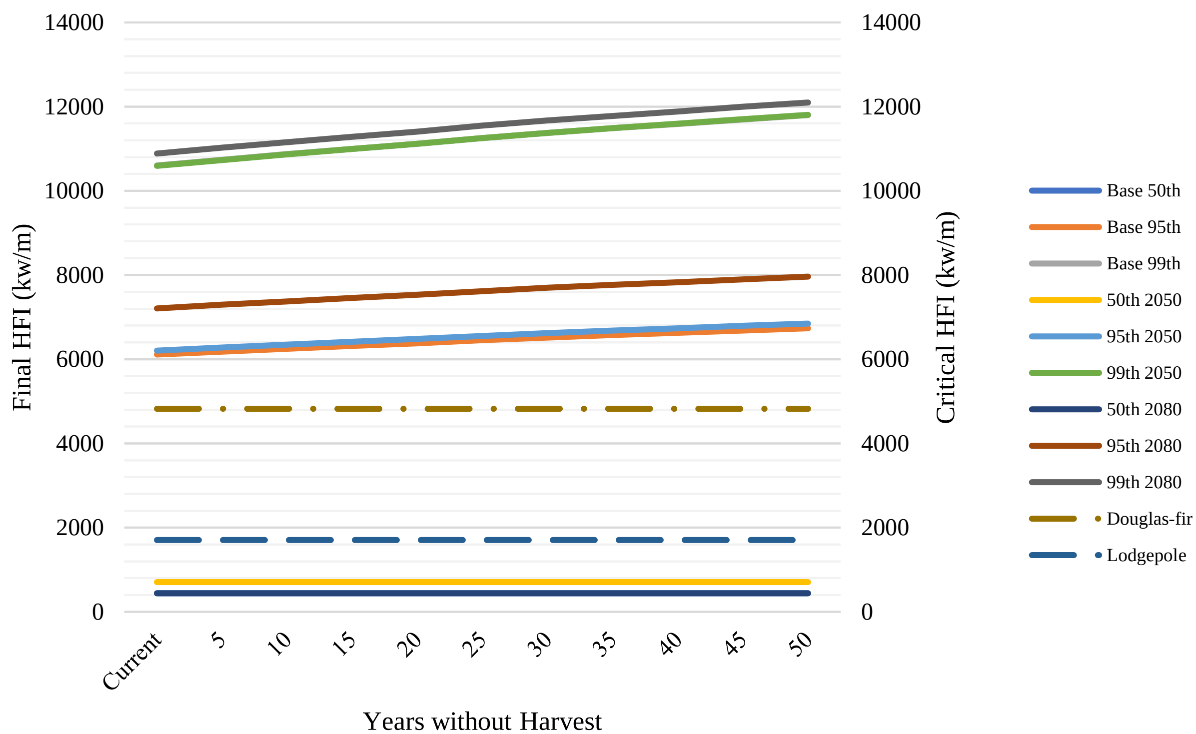

Figure 3.11. Aspen Parkland Block 3: Pre-Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathway 2-4.5.

In the graph above, lodgepole pine, Douglas-fir, and trembling aspen were the only species found on site, therefore the coniferous species critical HFIs are shown. Both the 95th and 99th percentiles for each year exceeded the critical HFIs, concluding that the site can expect crowning. The 50th percentile, however, did not experience any type of crowning.

Figure 3.12 shows the variation of final HFIs over 50 years without harvesting and the changing weather variables with Shared Socioeconomic Pathway 3-7.0. In the figure, there is slight overlap between some of the values. The 50th percentile for 2050 (yellow) is hidden behind the other 50th percentile values.

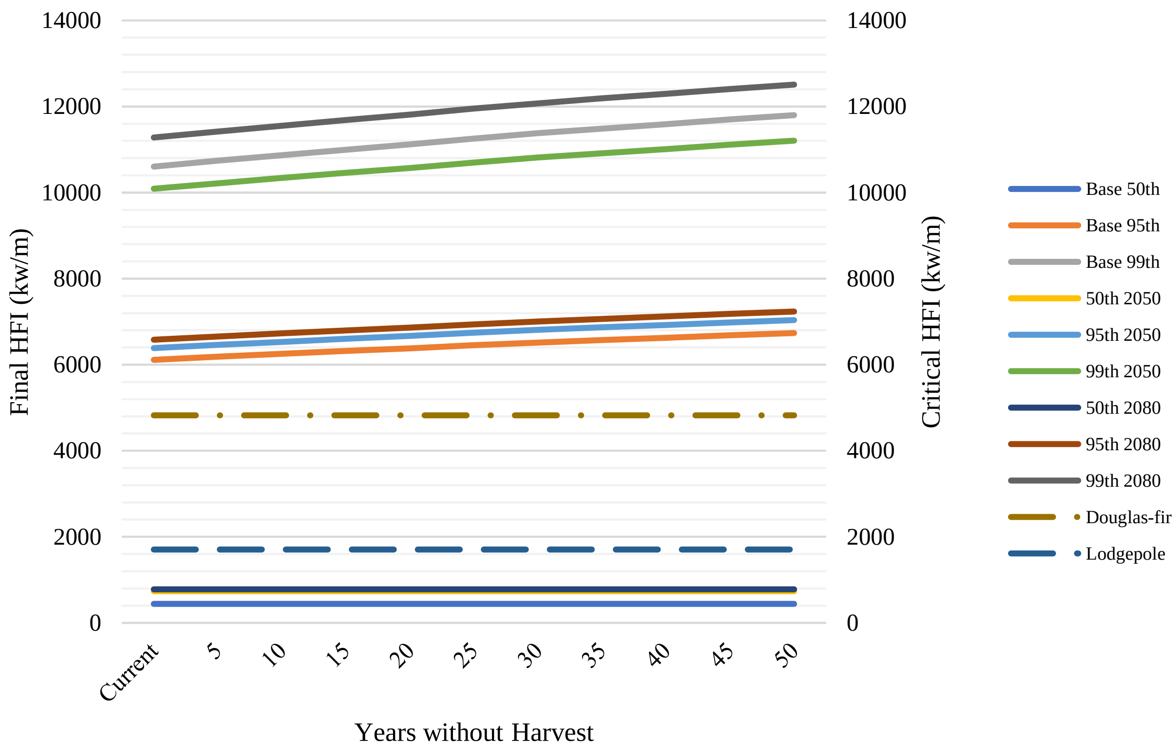

Figure 3.12. Aspen Parkland Block 3: Pre-Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathway 3-7.0.

In the graph above, like the previous graph, the critical HFIs for lodgepole pine and Douglas-fir are shown. Both the 95th and 99th percentiles for each year analysed can expect crowning (Figure 3.12). The 50th percentile, however, did not experience any type of crowning.

Post Harvest Final Head Fire Intensity

Figure 3.13, shows Aspen Parkland Block 3 post harvest final and critical HFI (kw/m) with Shared Socioeconomic Pathways (2-4.5 and 3-7.0) from current (baseline) through to 2080. The figure shows the affect of weather because fuel accumulations are negligible for this research sites post harvest treatment. Additionally, for visual purposes, both axis in the figure were changed from pre harvest figures.

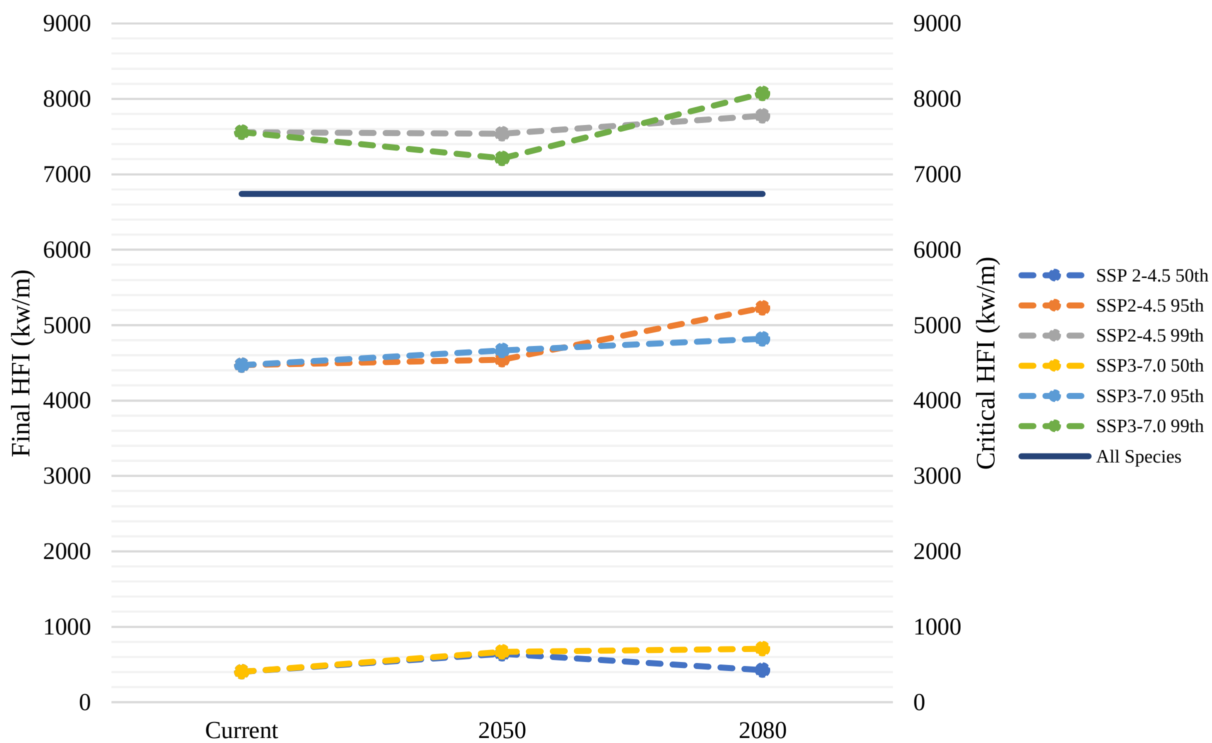

Figure 3.13. Aspen Parkland Block 3: Post Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathways (2-4.5 and 3-7.0).

For Aspen Parkland Block 3, the 99th percentile for both SSPs (3-7.0 and 2-4.5) exceeded the critical HFI line indicating that there will be intermittent crowning. In 2050, SSP3-7.0 saw a slight increase in final HFI over SSP2-4.5 at the 50th and 95th percentile. In 2080, SSP2-4.5 saw an increase in final HFI over SSP3-7.0 by 400 kw/m despite SSP3-7.0 exceeding SSP2-4.5 at the 50th and 99th percentile.

In terms of forest floor fuel load accumulations for Aspen Parkland Block 3, the 95th percentile was analyzed to assess how much fuel is needed to cause intermittent crowning or crowning on site. Table 3.6 shows the increases in forest floor fuel (kg/m^2) for each SSP and year, along with the associated final HFI's and type of crown fire the site may experience.

Table 3.6. Aspen Parkland Block 3: Post harvest forest floor fuel load increases for baseline, 2050, and 2080 with differing SSPs, associated Final HFIs, and Crown fire type [the value in brackets is the standard for forest floor fuel loads post harvest].

		95th Percentile (kg/m^2)	**Final HFI (kw/m)**	**Crown?**
	Baseline	4.0 (0.6)	6063	Intermittent
SSP2-4.5	*2050*	3.5 (0.6)	6672	Intermittent
	2080	2.5 (0.6)	6690	Intermittent
SSP3-7.0	*2050*	3.5 (0.6)	6903	Intermittent
	2080	3.5 (0.6)	7067	Intermittent

For Aspen Parkland Block 3, for the 95th percentile to experience intermittent crowning, the site will need fuel accumulations to increase from 2.5-4.0 kg/m^2. The 99th percentile was not analyzed since the site already experiences intermittent crowning.

Rates of Spread

For Aspen Parkland Block 3, pre and post harvest ROS varied between SSPs and years. For baseline, ROS decreased by 2 m/min at the 99th as well as a reduction of 1 m/min at the 95th. In 2050, the ROS saw decreased from 2-4 m/min depending on the SSP post harvest. In 2080, ROS decreased from 1-3 m/min post harvest dependent on the SSP. All 50th percentiles remained constant for between pre and post harvest for each year and SSP (Figure 3.14).

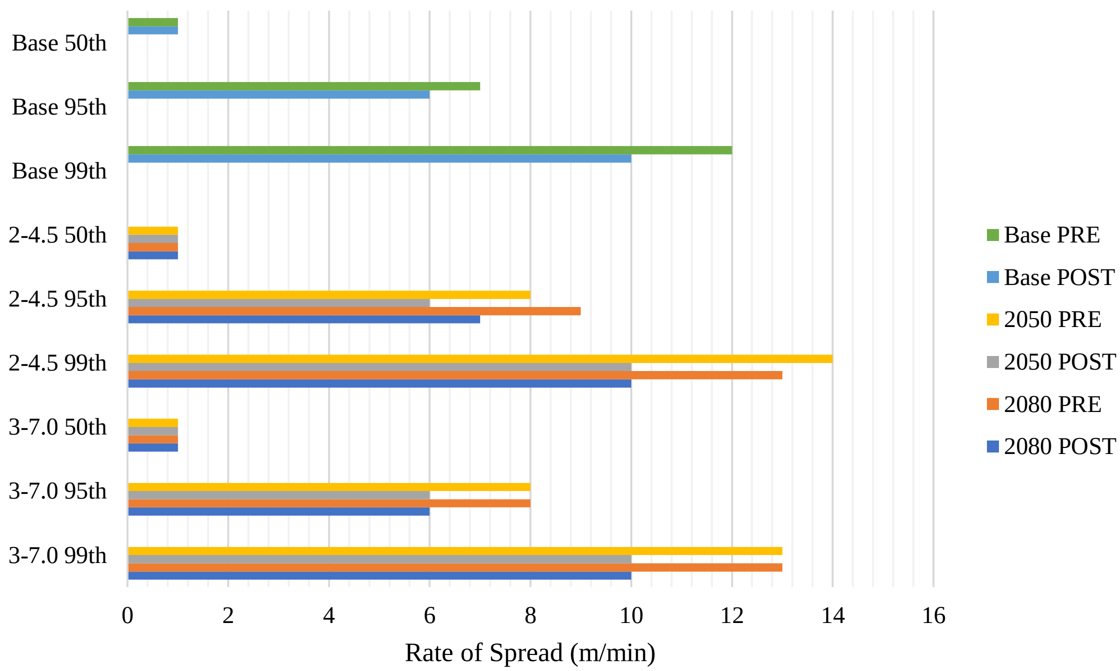

Figure 3.14. Aspen Parkland Block 3: Pre- and Post-Harvest Rate of Spread (m/min) with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080.

<u>Intensity Classes</u>

The Intensity Class at the 50th percentiles remained the same at Intensity Class 3 except for baseline where the Intensity changed from Intensity Class 3 to 2. At the 95th percentile, for each year and SSP, the Intensity remained unchanged at Intensity Class 5. At the 99th percentile, for each year and SSP, the Intensity changed from Intensity Class 6 to 5 post harvest (Figure 3.15).

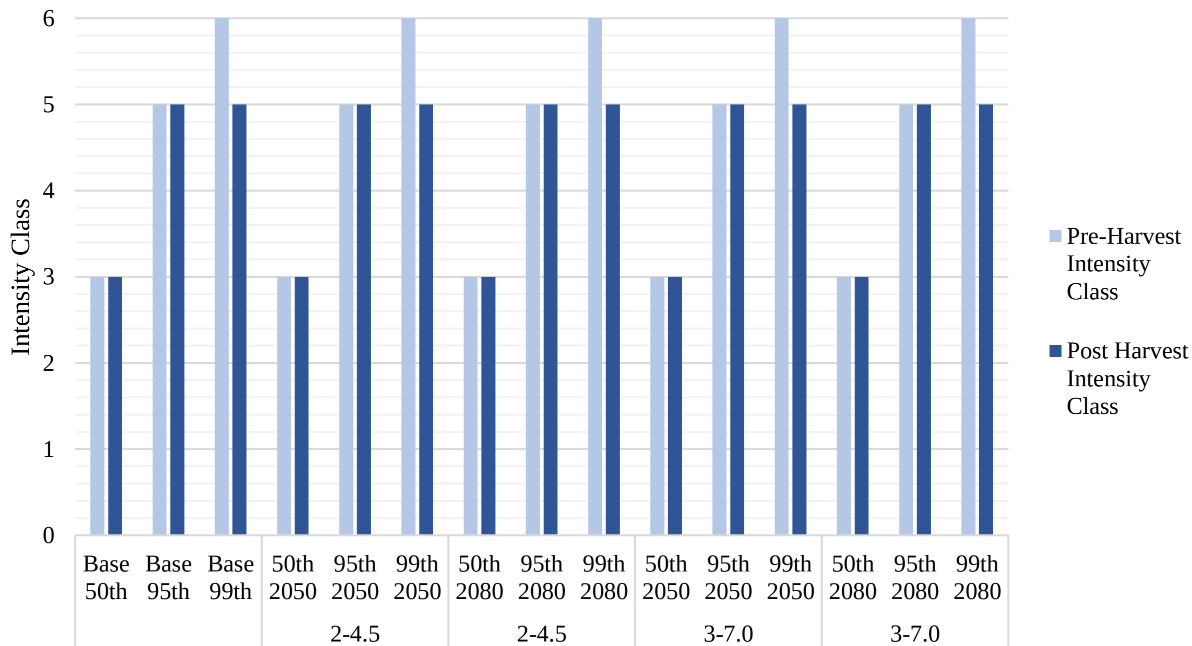

Figure 3.15. Aspen Parkland Block 3: Pre and Post Harvest Intensity Classes with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080.

Shaded Fuel Break

Pre-Harvest Final Head Fire Intensity

Figure 3.16, shows the variation of final HFIs over 50 years without harvesting and the changing weather variables with Shared Socioeconomic Pathway 2-4.5. In the figure below, there is slight overlap between some of the values. The baseline 99th percentile (light grey) is hidden behind the other 99th percentile values. Baseline 50th percentile (medium blue) is hidden behind the other 50th percentile values.

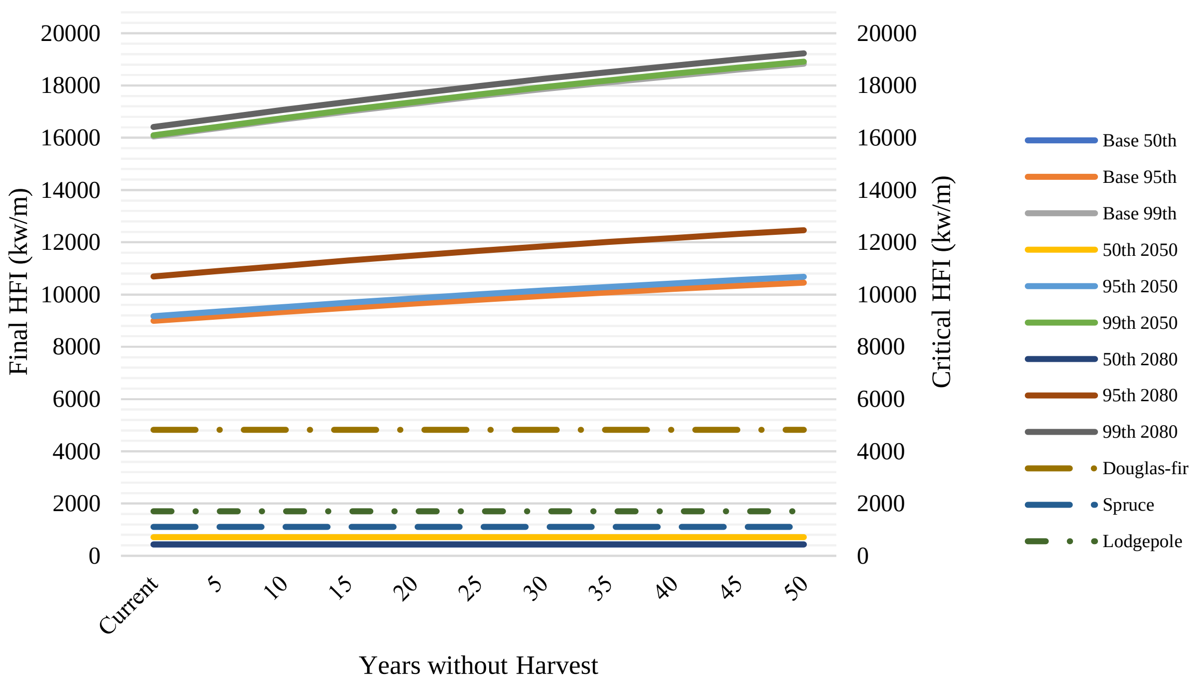

Figure 3.16. Shaded Fuel Break: Pre-Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathway 2-4.5.

In the graph above, all four species were found onsite, but the coniferous species critical HFIs are shown. The 95th and 99th percentiles for each year analysed exceeded the critical HFIs, concluding that the site can expect a crown fire at these percentiles. The 50th percentiles will not experience any type of crown fire.

Figure 3.17 shows the variation of final HFIs over 50 years without harvesting and the changing weather variables with Shared Socioeconomic Pathway 3-7.0. In the figure below, there is slight overlap between some of the values. The 50th percentile in 2050 (yellow) is hidden behind the other 50th percentile values.

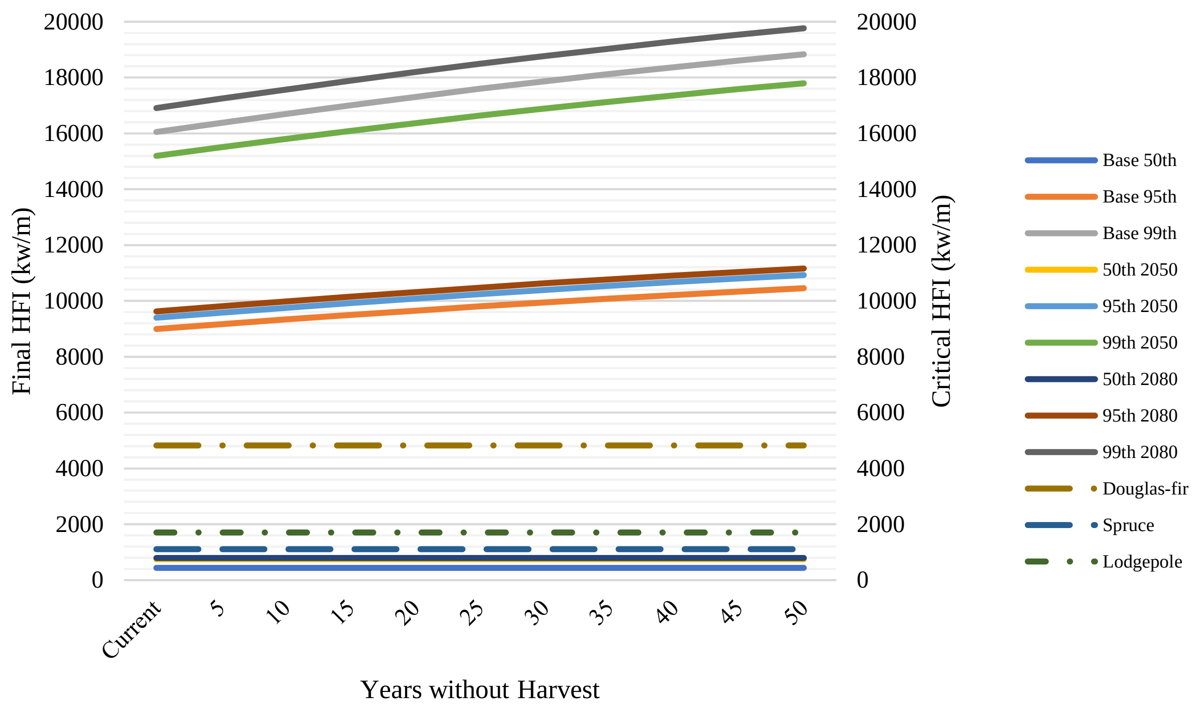

Figure 3.17. Shaded Fuel Break: Pre-Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathway 3-7.0.

In the graph above, like the previous graph, all coniferous species critical HFIs are shown. The 95th and 99th percentiles for each year analysed exceeded the critical HFIs, concluding that the site can expect a crown fire at these percentiles. The 50th percentiles will not experience any type of crown fire.

<u>Post Harvest Final Head Fire Intensity</u>

50% removal without planting

Figure 3.18 shows Shaded Fuel Break post harvest final and critical HFI (kw/m) with Shared Socioeconomic Pathways (2-4.5 and 3-7.0) from current (baseline) through to 2080 at 50% removal and without planting.

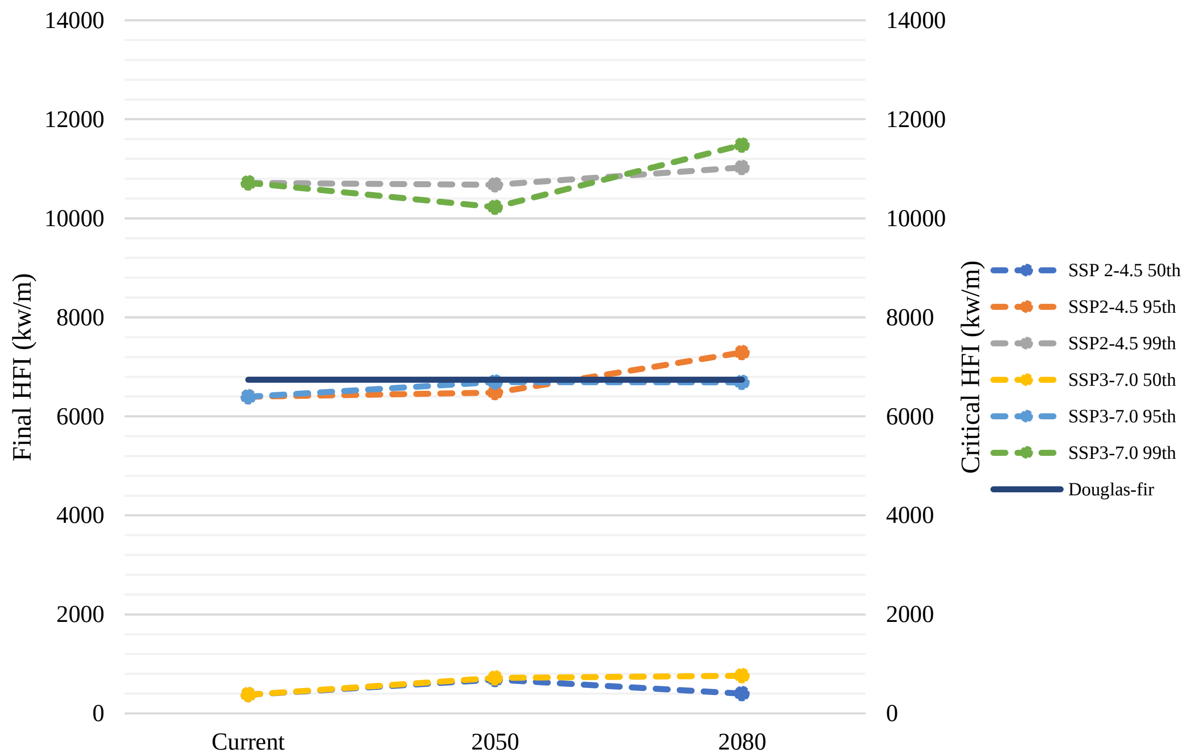

Figure 3.18. Shaded Fuel Break: Post Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathways (2-4.5 and 3-7.0) at 50% removal and no planting.

In the graph above, Douglas-fir is the only species found on site, therefore it is the only species critical HFI. For this Shaded Fuel break treatment, the 99th percentile surpasses the critical HFI line indicating that the site will experience a crown fire. Additionally, in 2080, the SSP2-4.5 at the 95th percentile will experience a crown fire while SSP3-7.0 at the

95th will only experience an Intermittent crown fire. For 2050, SSP3-7.0 values surpass SSP2-4.5 other than the 99th percentile. In 2080, SSP2-4.5 exceeds the SSP3-7.0 value by over 500 kw/m at the 95th percentile whereas the inverse happens as SSP3-7.0 exceeds SSP2-4.5 at the 50th and 99th percentile.

In terms of forest floor fuel load accumulations for Shaded Fuel Break at 50% removal and without planting, the 95th percentile was analyzed to assess how much fuel is needed to cause intermittent crowning or crowning on site. Table 3.7 shows the increases in forest floor fuel (kg/m^2) for each SSP and year, along with the associated final HFI's and type of crown fire the site may experience.

Table 3.7. Shaded Fuel Break at 50% removal without planting: Post harvest forest floor fuel load increases for baseline, 2050, and 2080 with differing SSPs, associated Final HFIs, and Crown fire type [the value in brackets is the standard for forest floor fuel loads post harvest].

		95th Percentile (kg/m^2)	**Final HFI (kw/m)**	**Crown?**
	Baseline	1.1 (0.6)	6549	Crown
SSP2-4.5	*2050*	1.1 (0.6)	6640	Crown
	2080	-	-	Intermittent
SSP3-7.0	*2050*	1.1 (0.6)	6838	Crown
	2080	1.1 (0.6)	6838	Crown

For this Shaded Fuel Break treatment, the 95th percentile for SSP2-4.5 in 2080 did not require manipulation of biomass accumulation on the forest floor because the site already experiences an intermittent crowning without. Across all years and SSP variables, increasing the forest floor biomass by 0.5 kg/m^2 will cause crowning.

50% removal with planting

Figure 3.19, is Shaded Fuel Break post harvest final and critical HFI (kw/m) with Shared Socioeconomic Pathways (2-4.5 and 3-7.0) from current (baseline) through to 2080 at 50% removal and planting. In the figure, for visual purposes, the vertical axis has changed.

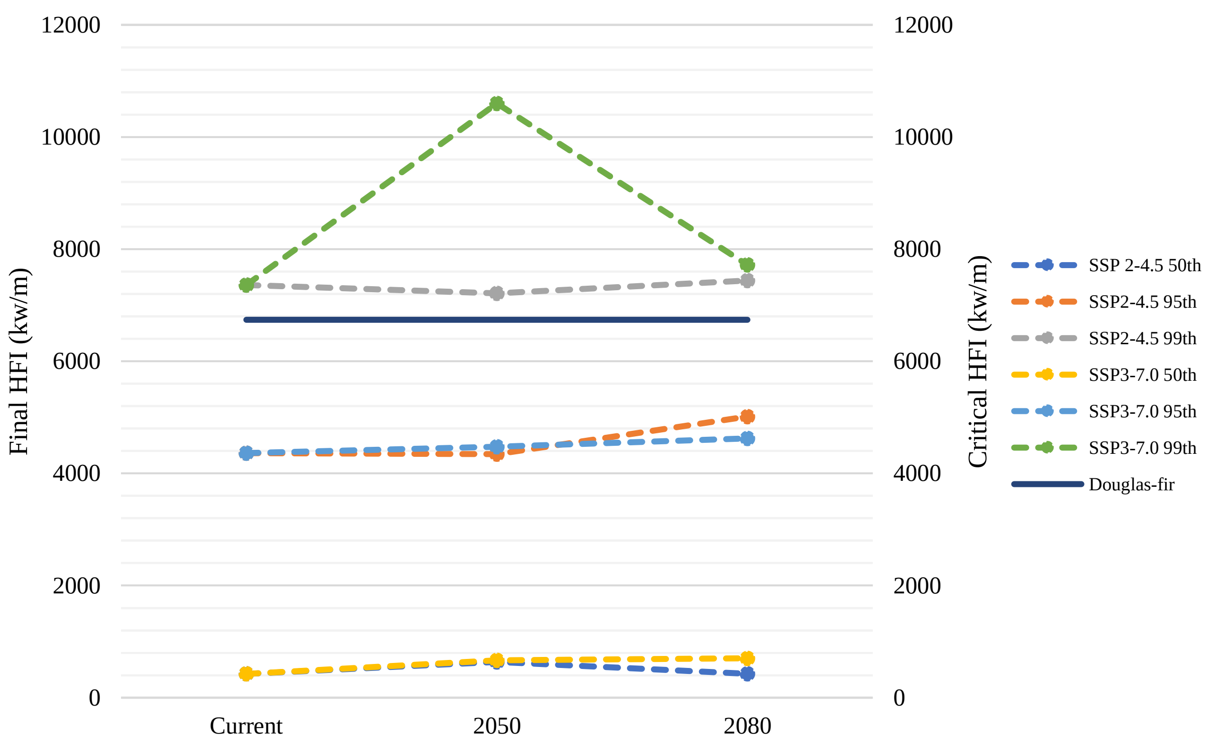

Figure 3.19. Shaded Fuel Break: Post Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathways (2-4.5 and 3-7.0) at 50% removal and planting.

In the graph above, Douglas-fir and trembling aspen are on the site, however, the Douglas-fir critical HFI is shown. For this Shaded Fuel Break treatment, the 99th percentile has a unique variation in final HFI as it surpasses the critical HFI. In 2050, the final HFI for SSP3-7.0 significantly surpasses SSP2-4.5 by over 3,000 kw/m with near similar final HFIs for current (baseline) and 2080. At the 99th percentiles, from current (baseline) through to

2080, the site will experience a crown fire. At the 95th percentile, SSP3-7.0 slightly surpasses SSP2-4.5, but finds an inverse in 2080 as SSP2-4.5 exceeds SSP3-7.0 by over 400 kw/m.

In terms of forest floor fuel load accumulations for Shaded Fuel Break at 50% removal and planting, the 95th percentile was analyzed to assess how much fuel is needed to cause intermittent crowning or crowning on site. Table 3.8 shows the increases in forest floor fuel (kg/m^2) for each SSP and year, along with the associated final HFI's and type of crown fire the site may experience.

Table 3.8. Shaded Fuel Break at 50% removal with planting: Post harvest forest floor fuel load increases for baseline, 2050, and 2080 with differing SSPs, associated Final HFIs, and Crown fire type [the value in brackets is the standard for forest floor fuel loads post harvest].

		95th Percentile (kg/m^2)	**Final HFI (kw/m)**	**Crown?**
	Baseline	4.0 (0.6)	6796	Intermittent
SSP2-4.5	*2050*	4.0 (0.6)	6790	Intermittent
	2080	3.0 (0.6)	7055	Intermittent
SSP3-7.0	*2050*	1.1 (0.6)	6941	Intermittent
	2080	3.5 (0.6)	6781	Intermittent

This harvesting treatment in the shaded fuel break will require 0.5-4.0 kg/m^2 to cause intermittent crowning. The 99th percentile was not analyzed because the site experienced crowning without needing to manipulate forest floor biomass.

80% removal without planting

Figure 3.20 is Shaded Fuel Break post harvest final and critical HFI (kw/m) with Shared Socioeconomic Pathways (2-4.5 and 3-7.0) from current (baseline) through to 2080 at 80% removal and without planting.

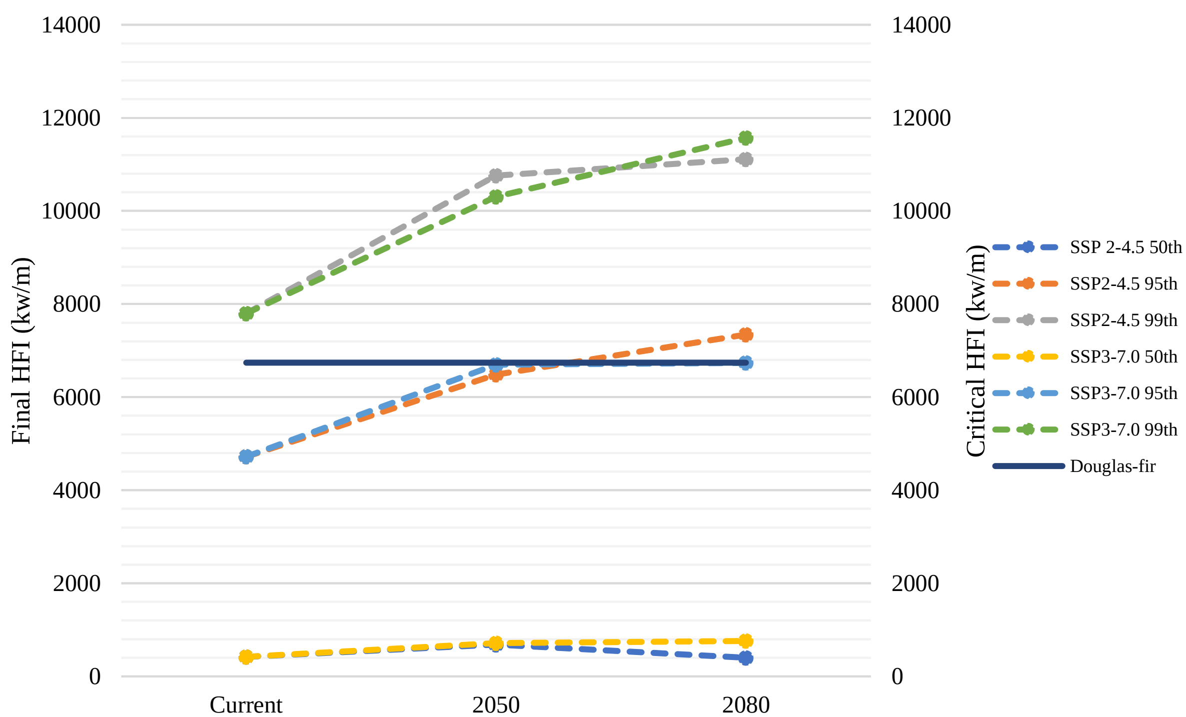

Figure 3.20. Shaded Fuel Break: Post Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathways (2-4.5 and 3-7.0) at 80% removal and no planting.

In the graph above, Douglas-fir was the only species on site for this treatment, therefore it is the only critical HFI representation shown. For this Shaded Fuel Break treatment, the 99th percentile exceeds the critical HFI line indicating the site will experience a crown fire from current (baseline) through to 2080. Additionally, the 95th percentiles in 2080 will experience a crown fire. In 2050, at the 95th percentile, the site is near intermittent crowning but didn't reach the critical HFI threshold. SSP3-7.0 values exceeded SSP2-4.5 in 2050 other than the 99th where SSP2-4.5 surpassed by over 400 kw/m. SSP3-7.0 also exceeded SSP2-4.5 in 2080 other than the 95th where SSP2-4.5 surpassed by over 500 kw/m.

In terms of forest floor fuel load accumulations for Shaded Fuel Break at 80% removal and without planting, the 95th percentile was analyzed to assess how much fuel is needed to cause intermittent crowning or crowning on site. Table 3.9 shows the increases in forest floor fuel (kg/m^2) for each SSP and year, along with the associated final HFI's and type of crown fire the site may experience.

Table 3.9. Shaded Fuel Break at 80% removal without planting: Post harvest forest floor fuel load increases for baseline, 2050, and 2080 with differing SSPs, associated Final HFIs, and Crown fire type [the value in brackets is the standard for forest floor fuel loads post harvest].

		95th Percentile (kg/m^2)	**Final HFI (kw/m)**	**Crown?**
	Baseline	3.5 (0.6)	6869	Crown
SSP2-4.5	*2050*	1.0 (0.6)	6580	Crown
	2080	0.9 (0.6)	6585	Crown
SSP3-7.0	*2050*	1.0 (0.6)	6580	Crown
	2080	0.9 (0.6)	6585	Crown

For this Shaded Fuel Break treatment, for all years and SSPs other than baseline, increasing D/CWD by 0.3-0.4 kg/m^2 will cause a crown fire. Baseline requires an increase in D/CWD to 3.5 kg/m^2 to cause crowning.

80% removal with planting

Figure 3.21 is Shaded Fuel Break post harvest final and critical HFI (kw/m) with Shared Socioeconomic Pathways (2-4.5 and 3-7.0) from current (baseline) through to 2080 at 80% removal and with planting. In the figure below, for visual purposes, the vertical axis as changed.

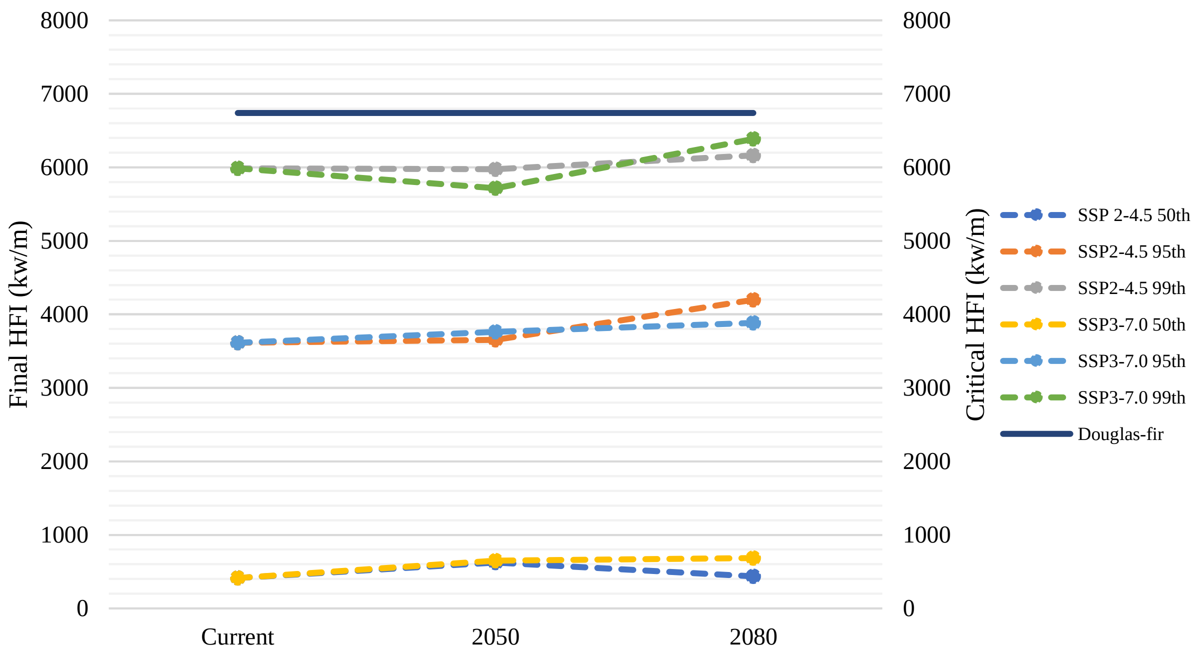

Figure *3.21*. Shaded Fuel Break: Post Harvest Final Head Fire Intensity (kw/m) and Critical Head Fire Intensity (kw/m) per species [represented by dashed lines] for baseline, 2050, and 2080 with Shared Socioeconomic Pathways (2-4.5 and 3-7.0) at 80% removal and planting.

In the graph above, critical HFI is represented by Douglas-fir despite both Douglas-fir and trembling aspen are found on site. For this Shaded Fuel break treatment, no values exceeded the critical HFI to cause a crown fire, however, both SSPs at the 99th percentile will experience intermittent crowning. In 2050 at the 99th, SSP3-7.0 sees a slight dip in final HFI below SSP2-4.5, however, SSP3-7.0 values remain slightly above for the 50th and 95th percentiles. In 2080, SSP2-4.5 at the 95th percentile exceeds SSP3-7.0 by over 300 kw/m. Alternatively, SSP3-7.0 slightly exceeds SSP2-4.5 at the 50th and 99th percentiles.

In terms of forest floor fuel load accumulations for Shaded Fuel Break at 80% removal and with planting, the 95th percentile was analyzed to assess how much fuel is needed to cause Intermittent crowning or crowning on site. Table 3.10 shows the increases in forest floor fuel (kg/m^2) for each SSP and year, along with the associated final HFI's and type of crown fire the site may experience.

Table 3.10. Shaded Fuel Break at 80% removal with planting: Post harvest forest floor fuel load increases for baseline, 2050, and 2080 with differing SSPs, associated Final HFIs, and Crown fire type [the value in brackets is the standard for forest floor fuel loads post harvest].

		95th Percentile (kg/m^2)	**99th Percentile (kg/m^2)**	**Final HFI (kw/m)**	**Crown?**
	Baseline	6.5 (0.6)	1.5 (0.6)	6921 / 7152	Intermittent
SSP2-4.5	*2050*	6.0 (0.6)	1.5 (0.6)	6769 / 6733	Intermittent
	2080	4.5 (0.6)	1.0 (0.6)	6790 / 6921	Intermittent
SSP3-7.0	*2050*	6.0 (0.6)	1.5 (0.6)	6896 / 6816	Intermittent
	2080	5.5 (0.6)	1.0 (0.6)	6762 / 7151	Intermittent

For this Shaded Fuel Break treatment, at the 95th percentile, increasing D/CWD to 4.5-6.5 kg/m^2 will cause intermittent crowning. At the 99th, increasing forest floor biomass to 1.0-1.5 kg/m^2 will also cause intermittent crowning.

Rates of Spread

50th removal without/with planting

For the Shaded Fuel Break at 50% stand removal, with no planting, pre and post harvest ROS varied between SSPs and years. For the 50th percentiles, there was no change in ROS between pre and post harvest at 1/min. For baseline, post harvest saw an increase in ROS by 1-2 m/min at the 95th and 99th percentiles. In 2050, post harvest saw an increase in ROS by 1 m/min for each SSP at the 95th and 99th percentiles. In 2080, the 95th and 99th percentiles saw an increase in ROS by 1 m/min for each SSP (Figure 3.22).

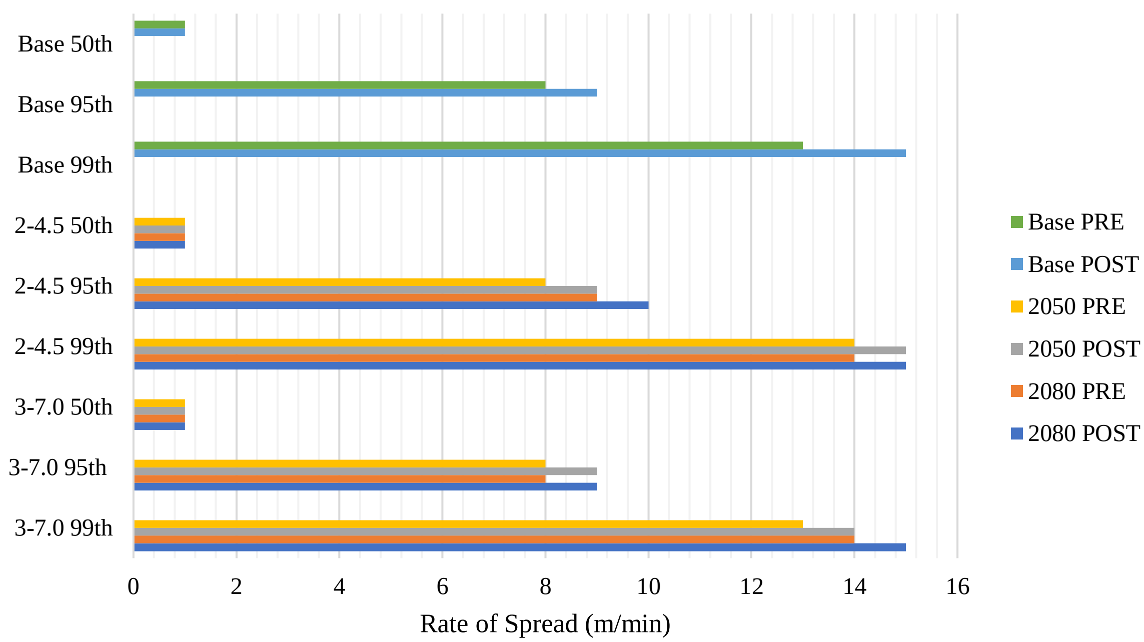

Figure 3.22. Shaded Fuel Break: Pre and Post Harvest Rate of Spread (m/min) with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080 at 50% stand removal without planting.

For the Shaded Fuel Break at 50% removal, with planting, the baseline and 50th percentiles remained the same at 1 m/min. However, for both 2050 and 2080, the ROS decreased post harvest from 2-4 m/min depending on the SSP and year analyzed (Figure 3.23).

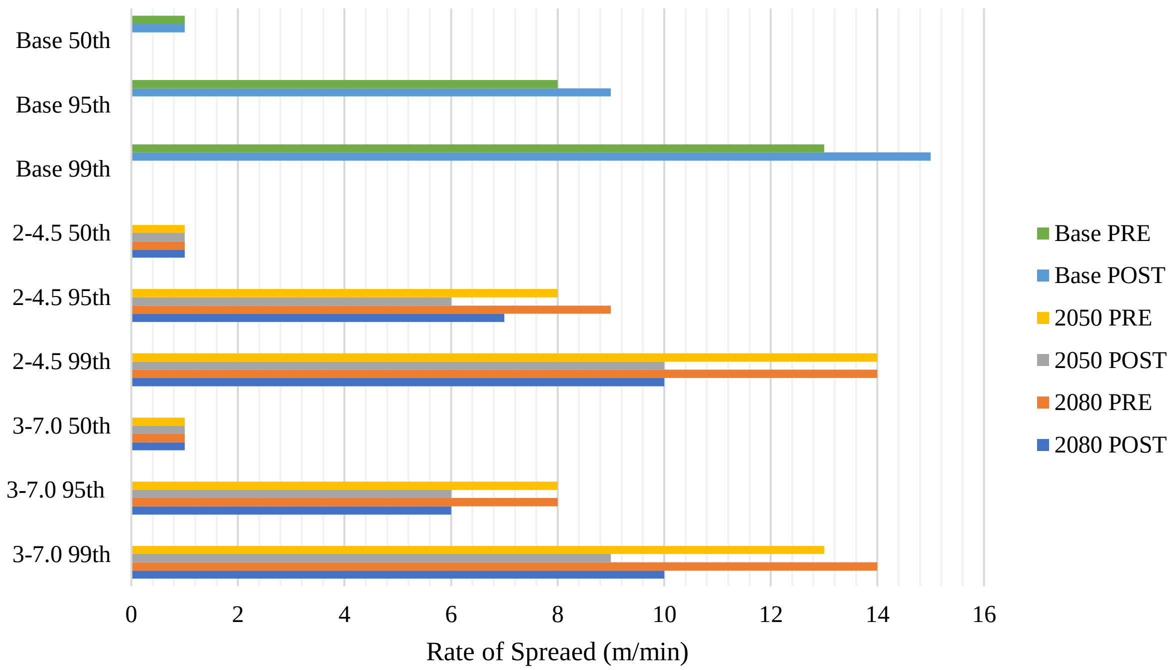

Figure 3.23. Shaded Fuel Break: Pre and Post Harvest Rate of Spread (m/min) with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080 at 50% stand removal with planting.

80% removal without/with planting

For the Shaded Fuel Break at 80% removal, with no planting, pre and post harvest ROS varied between years and SSPs. At the 50th percentiles for each SSP and year, there was no change between pre and post harvest at 1 m/min. For baseline, the ROS decreased by 3-5 m/min at the 95th and 99th percentiles. In 2050 and 2080, there was a minor increase in ROS of 1 m/min for each year and SSP (Figure 3.24).

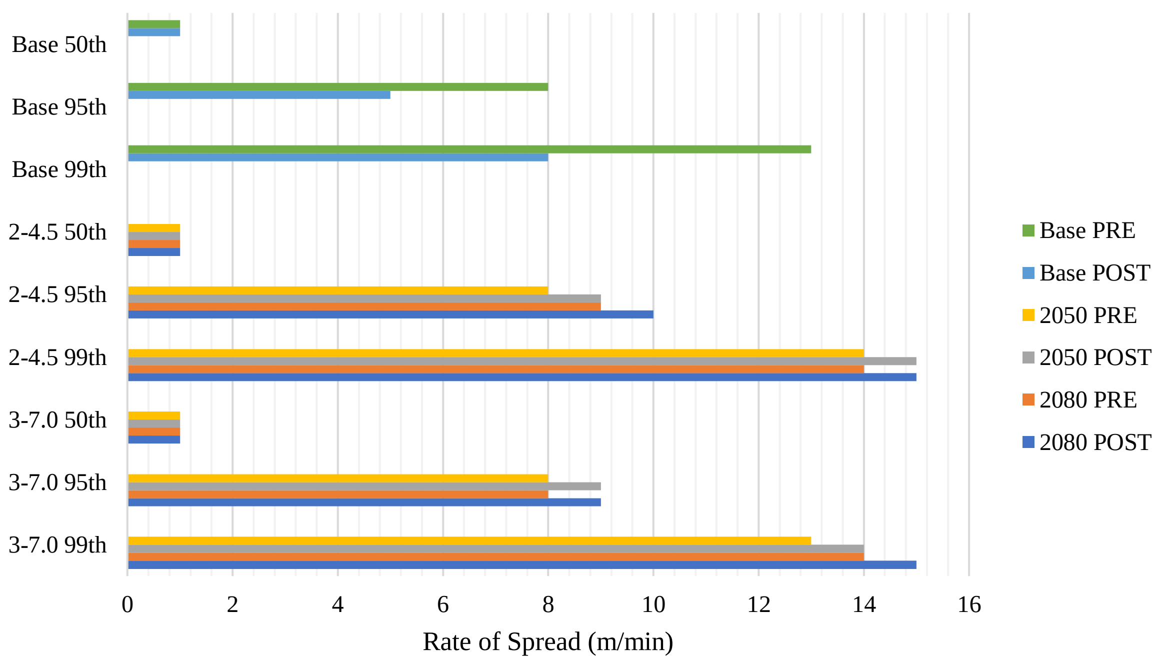

Figure 3.24. Shaded Fuel Break: Pre and Post Harvest Rate of Spread (m/min) with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080 at 80% stand removal without planting.

For the Shaded Fuel Break at 80% removal, with planting, the baseline and 50th percentiles remained the same at 1 m/min. However, in 2050, the ROS decreased from 3-6 m/min dependent on the SSP. In 2080, the ROS also decreased from 3-6 m/min dependent on the SSP (Figure 3.25).

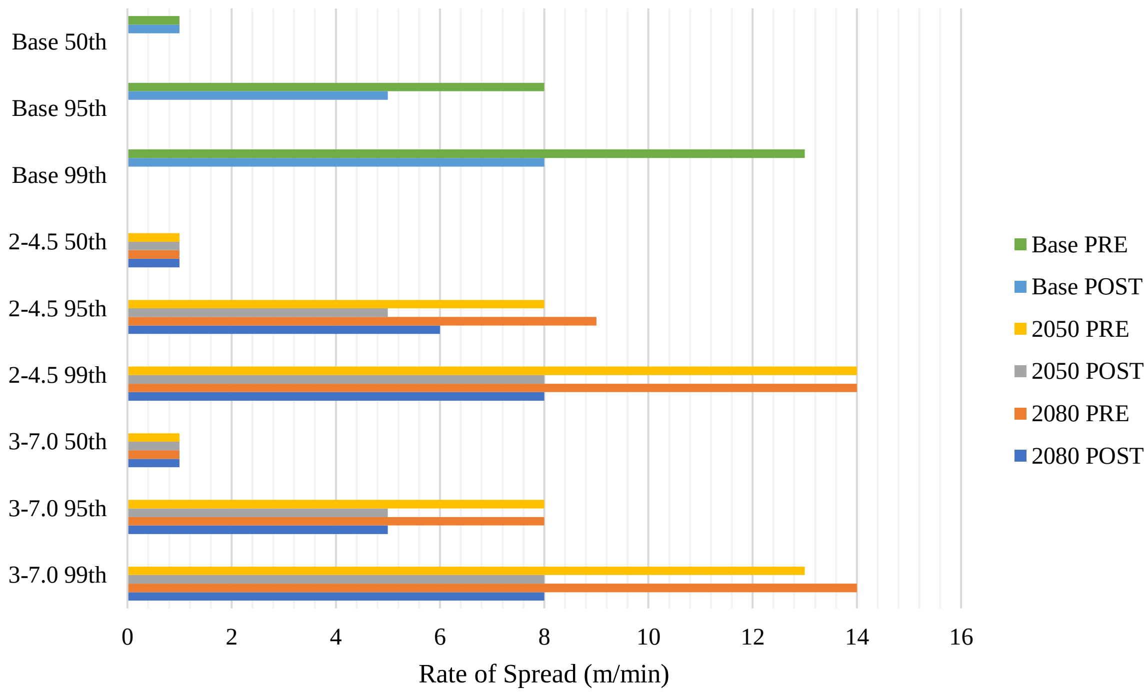

Figure 3.25. Shaded Fuel Break: Pre and Post Harvest Rate of Spread (m/min) with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080 at 80% stand removal with planting.

Intensity Classes

The Intensity Classes for 50% removal at the 50th percentile, generally, remained the same as pre harvest at Intensity Class 3 for all years and SSPs. However, baseline saw an increase from Intensity Class 2 to 3. At the 95th and 99th percentiles, the site saw a decrease in Intensity Class from 6 to 5 except for SSP3-7.0 at the 99th saw no change from Intensity Class 6 (Figure 3.26).

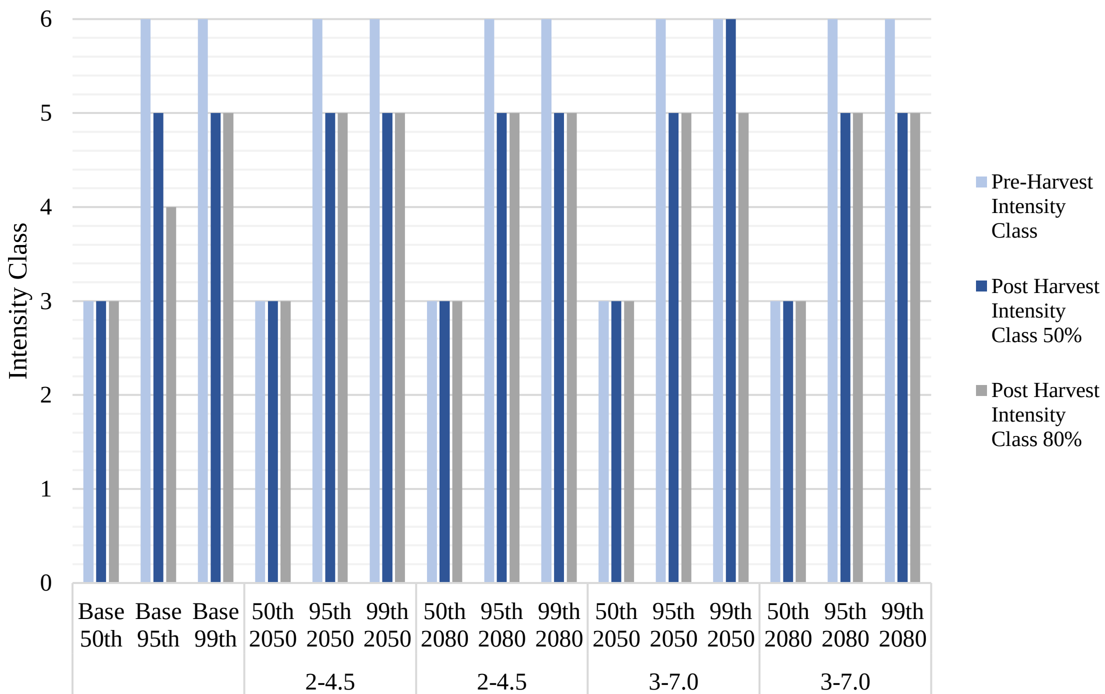

Figure 3.26. Shaded Fuel Break with Planting: Pre and Post Harvest Intensity Classes with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080.

For 80% removal, the Intensity Class at the 50th percentile, when comparing to pre harvest, remained unchanged from pre harvest for each year and SPP at Intensity Class 3 except for baseline where the Intensity remained the same as pre harvest at Intensity Class 2. The 95th percentile also decreased for each year and SSP from Intensity Class 6 to 5 apart from baseline where there was a decrease from Intensity Class 6 to 4. The 99th percentiles saw a similar decrease in Intensity from Intensity Class 6 to 5 except for SSP3-7.0 in 2050 where the Intensity remained at Intensity Class 6.

For the Shaded Fuel Break without planting at the 50th percentile, the Intensity Classes remained constant with pre-harvest at Intensity Class 2 for baseline and Intensity Class 3 for the remaining years and SSPs. For the 95th percentiles, each year and SSP saw a decrease in Intensity Class from 6 to 5. At the 99th percentiles, pre and post harvest Intensity Classes remained the same at Intensity Class 6 (Figure 3.27).

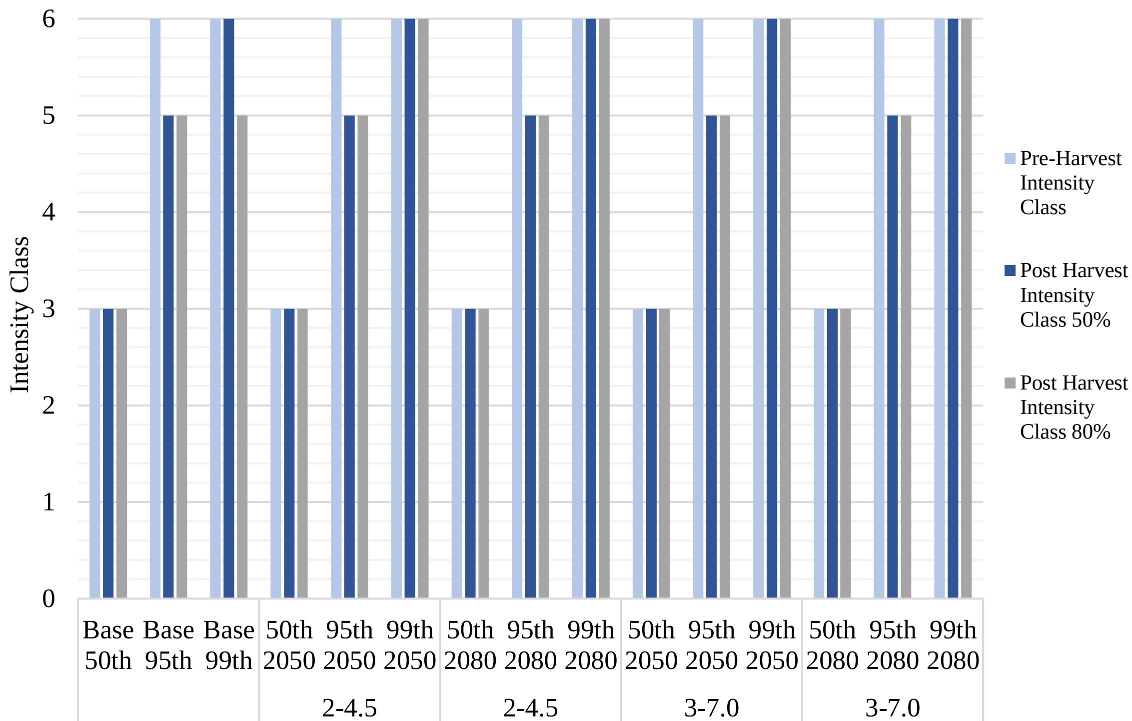

Figure 3.27. Shaded Fuel Break without Planting: Pre and Post Harvest Intensity Classes with Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) for baseline, 2050 and 2080.

At 80% removal, the 50th percentiles remained the same at Intensity Class 3 except for baseline which saw an increase in Intensity Class from 2 to 3. The 95th percentile saw a decrease in Intensity for each year and SSP from Intensity 6 to 5. At the 99th percentile, the Intensity Class post harvest remained unchanged from pre harvest with an Intensity Classes of 6. However, the 99th percentile for baseline saw a decrease in Intensity Class from 6 to 5.

Chapter 4 . Discussion

Pre-Harvest

For pre harvest conditions, this research looked at the final and critical HFIs, rates of spread, and Intensity Classes with varying weather and stand biomass accumulations over time. The pre harvest conditions are classified as the 'natural' state of the stand without any manipulation to overstory or understory vegetation. Natural, in quotations, means that the research took the current state of the stand to have grown naturally prior to assessment. Meaning there was no harvesting, treatments, and cultural or prescribed burning within 20 years prior to this research.

The results show that with increasing forest biomass, the entire research area (all four blocks) will experience some sort of crowning with intensities >6,000 kw/m at the lowest and >18,000 kw/m near the highest. Two of the three Aspen Parkland Blocks will experience crowning at the 95th and 99th percentile (over 50 years) while the other will experience intermittent crowning. With the same parameters, the Shaded Fuel Break will experience crowning. For each Aspen block, the rates of spread range from 6-13 m/min with rates of spread ranging from 9-15 m/min in the Shaded Fuel Break. Intensity Classes for pre harvest were between Intensity Class 5 and 6 for Aspen Parkland blocks with an Intensity Class of 6 for the Shaded block.

These results show that without treatment, we can expect extreme fire behaviour across the entire research area. This research would also suggest that with the extreme outcomes, long distance spotting is a strong possibility. With the high rates of spread and intensity classes, we can expect major challenges for fire suppression personnel. Direct suppression methods will be unfavorable and ineffective. Aircraft, and advanced planning will be required to contain and suppress, extending the timeline to have the wildfire under control. These outcomes will challenge the adjacent community; therefore, future alerts or evacuations are a strong possibility and unfortunately, the probability of structure loss.

Post Harvest

Aspen Parkland

After harvest, sparser canopies can produce faster windspeeds at the understory level, increasing rates of spread and elongating spread patterns (Finney 2001). This is hypothesized because treatments remove overstory and understory trees to eliminate horizontal and vertical continuity (Finney 2001). When comparing treatments, the most successfully tested treatments use more than one treatment type and were maintained more frequently. This multi-tiered approach looks to increase canopy base height, reduce canopy bulk density, and reduce surface fuel loads creating discontinuity between surface, ladder, and crown fuels (Vaillant et al. 2009). An assumption made is that all treatments with these characteristics should slow the spread of wildfire (Finney 2001). However, treatments in certain fuel types can encourage increases in wildfire spread over time if harvesting or burning do not mitigate growth of fine fuels in the understory (Finney 2001). The research conducted in this thesis, looks at a similar multi-tiered approach of increasing live crown base heights, reducing canopy bulk density, and reducing surface fuel loads with prescribed burning.

For Aspen Parkland Block 1, despite fuel treatment in this area, the research concluded that the site will still experience Intermittent crowning at the 99^{th} percentiles post harvest for each year analyzed (current, 2050, and 2080). This outcome may be because all four species (Douglas-fir, lodgepole pine, spruce, and trembling aspen) are present on site after harvesting. Spruce characteristics (regardless of the 10 m LCBH) have sloping downward branches, and thin, gray-brown bark that can break into larger loose scales (Government of British Columbia 2023a). The downward sloping branches and lose bark could influence a fire to move up the stem of the tree causing some Intermittent crowning if the fire reaches the crown. Lodgepole pine (regardless of stems removed) may experience stagnation at the early stages of development from previous overstocking (Government of British Columbia 2023a). The BC CanFIRE model was not able to differentiate the specific size classes on site (focused on average size) therefore, any stems that experience fire may support Intermittent crowning due to small stem diameters adjacent to other species. For both Douglas-fir and trembling aspen, these species generally do not support increases in fire behaviour and intensity, however, dead standing stems from disease or overuse from insects and animals could impact fire behaviour if not removed from the site. BC CanFIRE considers spacing of stems but does not consider dead standing stems.

Although the 95th percentile values were below the critical HFI, an increase in forest floor fuel accumulations to upwards of 2.0-3.5 kg/m^2 will cause intermittent crowning. The results found that the post harvest current (baseline) values at the 95th and 99th percentiles will see an increase in rate of spread of up to 2-3 m/min. For future years, 2050 weather values at the 95th and 99th percentiles will see an increase in rate of spread of up to 2-3 m/min while 2080 weather values at the same percentile will see a decrease in rate of spread of up to 2-3 m/min. Bearing in mind that with these increases and decreases, the rates of spread still ranged between 6-13 m/min post harvest. With respect to Intensity Classes, the site will see minimal change in the future with the different climate variables and years. The 99th percentiles will experience a decrease from Intensity Class 6 to 5, but from this research point of view, the difference between the two Intensity Classes are minimal. The 95th and 50th percentiles will exhibit Intensity Class 5 and 3 respectively.

For Aspen Parkland Block 2, this block was the only Aspen treatment that did not experience any type of crowning post harvest for all percentiles and years analyzed. This block had lodgepole pine and trembling aspen as the only two species remaining on site after harvest. A possible rationale for the difference in outcomes from the other Aspen blocks may be because the coniferous to deciduous ratio was much lower. Post harvest, lodgepole pine had 40 stems/ha while trembling aspen had 192 stems/ha. In the pre-harvest conditions, Lodgepole pine had 60 stems/ha and therefore under the 100 stems/ha criteria from the harvesting prescription, but for the argument of testing new stem densities for each block, reducing the stems further could account for dead standing, immature, or beetle killed trees.

For this block to experience any type of crowning at the 99th and 95th percentiles, the forest floor fuel loads will need to be increased by a range of 5.5-7.5 kg/m^2. In addition to the lack of crowning, the site generally experienced no change in rates of spread. However, there were two outliers in the results. In future years, at SSP3-7.0 99th percentile in 2050, the site will see an increase in rate of spread by 2 m/min. Also, in 2080, at SSP2-4.5 95th percentile, the research found a decrease in rate of spread by 1 m/min, considering that the rates of spread still ranged from 5-8 m/min. For the Intensity Classes, there was minimal change but with a few exceptions. The 99th percentiles saw no change from Intensity Class 5 for current and future years, while the 95th generally saw a decrease from Intensity Class 5 to 4 after harvest. The outlier at this percentile is in 2080 for SSP2-4.5 where the research found no change from Intensity Class 5. At the 50th percentile, the site remained consistent at Intensity Class 3.

The results of Aspen Parkland Block 3 were like the previous Aspen blocks. Despite the treatment on this site, the results found that there will still be Intermittent crowning post harvest at the 99th percentile weather variables for current and future years analyzed. This result may be because three of the four species remain on site post harvest (Douglas-fir, lodgepole pine, trembling aspen). Once again, the complexity of having multiple species dynamics and characteristics on site may have increased the changes of Intermittent crowning post harvest. Although the 95th percentile did not result in any type of crowning, increasing the forest floor fuel loads by up to ranges of 2.5-4.0 kg/m^2 will cause Intermittent crowning. For the sites rates of spread, the research concluded that there was a decrease across the 95th and 99th percentiles and for current and future years. These decreases ranged from 1-3 m/min, however, the rates of spread still ranged between 6-10 m/min. In terms of Intensity Classes, there was minimal change from pre harvest. The 99th percentiles saw a decrease from Intensity Class 6 to 5, the 95th saw no changes from Intensity Class 5, and the 50th percentiles saw no change from Intensity Class 3 for current and future years.

Shaded Fuel Break

Alternative treatments, including shaded fuel breaks, thinning, or a combination, are more appealing to the public as they have fewer visual consequences and are more widely accepted to homeowners in the WUI (Massada et al. 2011). Shaded fuel breaks are the removal of understory vegetation while keeping the overstory trees (Massada et al. 2011). The strategy of the shaded fuel break is to strengthen defensible areas and help suppression efforts for indirect tactics that can include backburning (Finney 2001). Current research shows that shaded fuel breaks have variable outcomes in effectiveness, but another known method being tested is called ‘green’ fuel breaks. Green fuel breaks are “strips of low-flammability vegetation planted at strategic locations across the landscape to slow or stop the progress of wildfires" (Cui et al. 2019). This multi-layered approach allows for better distribution of wildfire retardants and facilitating the treatment is less costly, but the difficulties need not only look at suitable tree species but also shrubs and herbaceous species (Cui et al. 2019). The Shaded Fuel Break is represented by differing overstory and understory removal of Douglas-fir. Planting 4000 stems of trembling aspen underneath the Shaded Fuel Break represents a variation of a green fuel break. The combination of the two another multi-tiered approach to fuel management.

The treatments on site were an arrangement of 50% and 80% removal of the Douglas-fir with non-planting and planting of trembling aspen scenarios. The rational behind testing non-planting vs. planting scenarios is to examine possible impacts of deciduous species on fire behaviour and intensity. Deciduous species have low flammability which can obstruct the spread of fire since it has a longer ignition time and releases less heat (Cui et al. 2019). Trembling aspen stands have been proposed to have 'high foliar moisture content, high understory vegetation moisture content, rapid decomposition of leaf litter, and fewer fine dead woody fuels' (Nesbit et al. 2023). This higher moisture content within the stand drives the common perception that trembling aspen within a stand reduces fire behaviour. Few research studies found that trembling aspen dominated stands reduced fire behaviour, occurrence, and severity except in the event of extreme weather conditions (Nesbit et al. 2023). The results from this research will look to see if trembling aspen in the understory reduces fire behaviour.

At 50% removal, planting trembling aspen diminished the type of fire from an intermittent crown fire to no crowning of any type at the 95th percentile. Unfortunately, this was the only scenario that experienced a decrease in the crown fire involvement on site. Between pre and post harvest, there was no change from a crown fire at the 99th percentiles. The 95th percentile in 2080 experienced a crown (SSP2-4.5) and intermittent crown (SSP3-7.0) fire respectively. The year 2050 at the 95th percentile did not experience any type of crowning however, for non-planting scenarios, increasing the forest floor fuel load by 0.5 kg/m^2 will cause a crown fire. Alternatively, for the planting scenario, increasing the forest floor fuel load from 1.1-4.0 kg/m^2 will cause intermittent crowning. For the rates of spread, the research hypothesized that spread rates will decrease in the planting scenario. The research found that planting decreased the rate of spread by 2-4 m/min except for current (baseline) conditions where rate of spread slightly increased by 1 m/min. On the other hand, the non-planting scenario saw an increase in rate of spread for all years tested by 1-2 m/min. Considering that at the 95th and 99th percentiles, planting scenarios had rate of spreads ranging from 8-15 m/min while non-planting scenarios had rates of spread ranging from 6-14 m/min. Regarding Intensity Classes, the planting scenario slightly decreased the Intensity Classes post harvest. The 99th percentiles went from Intensity Class 6 to 5 except for SSP3-7.0 remained at Intensity Class 6. The 95th percentile decreased from Intensity Class 6 to 5 while the 50th percentile remained at Intensity Class 3.

For the Shaded Fuel Break scenario of 80% removal of Douglas-fir with non-planting and planting of trembling aspen, planting slightly diminished the type of crown fire on site. When planting post harvest, the site can expect intermittent crowning at the 99th percentiles and only require 1.0-1.5 kg/m^2 of forest fuel accumulation to cause a crown fire. However, planting at the 95th percentile will not cause any type of crowning unless forest floor accumulations reach 4.5-6.0 kg/m^2 which will cause intermittent crowning. The 95th percentile with no planting only requires 0.5-3.5 kg/m^2 to have a crown fire. With respect to rates of spread, there was a decrease overall in the planting scenario. The current (baseline), 2050, and 2080 years saw a decrease for each year of 3-6 m/min. The non planting scenario saw a decrease in the current (baseline) conditions up to 5 m/min but saw increases in future years of up to 1 m/min. Despite decreases in the planting scenario, the rate of spreads still ranged from 5-14 m/min while the non planting variation still experienced ranges of 8-15 m/min. For Intensity Classes, the planting scenario had a minor difference in Intensity Classes than the non planting scenario. Planting had a decrease from Intensity Class 6 to 5 for the 95th and 99th percentiles. The non planting scenario only had a decrease at the 95th percentile from Intensity Class 6 to 5 but the 99th remained constant at Intensity Class 6 except for current (baseline) which saw a decrease to Intensity Class 5.

To summarize the post harvest results, at the current state of the stand, the research finds that the site will still experience intermittent crowning or crowning, increases in rates of spread, and minimal decreases in Intensity Classes at the two highest percentiles analyzed. In future years, the site will also experience the same characteristics as the current (baseline) conditions. Although there is one block and a few outliers that say otherwise, the entire research area will see minimal change from pre harvest conditions. intermittent crowning or crowning will impact how close fire suppression personnel can action the fire and increase the likelihood of short- and long-range spotting. Spotting causes concern because these embers may land on nearby structures which may influence structures ignitions adjacent. High rates of spread are important to note as fire suppression crews generally do not operate within and around fast paced, high intensity wildfires, as the fire behaviour uncertainties pose a threat to personnel safety. The importance of determining Intensity Classes is to have an overall value quantifying the sites pre and post harvest conditions which are easy to communicate and visualize for on the ground suppression crews and fire managers who generally reside in an office setting. Other than providing information on fire behaviour for this specific fuel treatment, fire and forest managers can look at the 95^{th} and 99^{th} percentile values calculated from this research and understand the type of fire behaviour that may occur on similar treatment areas. This will be crucial for deployment of resources and alerts or orders to evacuate nearby communities.

Pertaining to planting, this method did see positive outcomes in the results by decreasing rates of spread regardless of the percentage of Douglas-fir removed and the overall rates of spread. The outcomes of this research will be helpful for fire managers and for forestry personnel who facilitate fuel treatment projects that are considering implementing a ‘green’ component to their shaded fuel breaks. Understanding that from this research the deciduous species helped reduce the rates of spread, it is also important to note that high densities of green vegetation can increase wildfire spread upwards of 40%, which could also increase the production of simultaneous spotting (Cui et al. 2019). Cui et al. (2019) researched green fuel breaks in China, the world leader in green fuel break implementation, and found that while there is little evidence of effectiveness, the importance to further research could be of significance because green fuel breaks have lower long-term maintenance costs and can enhance biodiversity. Experimenting with green fuel breaks in multiple fuel types and locations across British Columbia can help better understand the true effectiveness of deciduous species across a diverse landscape.

Prescribed Fire

For this research, B.C. CanFIRE runs a hypothesized ‘wildfire’ or ‘prescribed fire’ during its simulations from current to 50 years in the future. The simulations ran every five years, therefore, the site both pre and post harvest assessed a burn event every 5 years into the future. The common knowledge with implementing prescribed fire on a fuel treatment area is that the process of prescribed burning reduces fuel loads, depths, and continuity (Finney 2001). This reduces the wildfire spread, intensity (Finney 2001), and decreases surface and ladder fuels, eventually reducing the potential for crown fires and spot wildfire ignitions (Vaillant et al. 2009). Prescribed burn areas (paired with fuel treatment areas) can allow firefighters to access the site, create a space for back burns, strengthen their control lines, and use fire (back burn) to redirect the main wildfire path (Vaillant et al. 2009). During fire suppression operations, a back burn is a strategy used to intentionally set a fire on the landscape, usually at the front of an active fire, that consumes combustible material and creates a strip of black (no vegetation) that the incoming wildfire will have difficulty crossing (IAFRS 2019).

A study conducted in Australia found that prescribed burning was only effective if it was conducted within the first few years after fuel treatments (Price et al. 2022). Essentially, 69% of prescribed burns within two years reduced wildfire severity which contradicts previous knowledge of 5-7 years (Price et al. 2022). In Canada, Klenner et al. (2008) also determined that the best approach to implementing a frequent and low severity prescribed burn within the dry forest ecosystem is after mechanical treatments. The argument has been made that to accomplish the reduction of wildfire behaviour and potential in fuel treatment areas, it may require multiple reintroductions of prescribed wildfire (Ziegler et al. 2017). Little information exists of the long-term temporal and spatial structures of a forest following prescribed burns (Ziegler et al. 2017). However, to increase the predictability, application of prescribed wildfire is necessary during benign and moderate wildfire conditions to monitor and adapt strategies to meet wildfire and fuel management goals (Hessburg et al. 2021).

With respect to the management objectives of the research area given by the 100 Mile House District, the site will be investing time and money into a prescribed burn within a few years of completing harvesting. The research area currently has not experienced a burn event, however, in the event this occurs, the results have shown that despite testing a burn event every 5 years, the intensities and rates of spread do not reduce fire behaviour. On the other hand, as described by Hessburg et al. (2021), experimenting with burning on the site and analyzing results physically in the field will provide further or better insight into the validity of this research's outcomes with respect to prescribed burning.

Suppression

One of the main goals of the fuel treatment area in South Green Lake, is to provide defensible ground for fire suppression personnel. The treatment area is adjacent to a paved roadway and in behind many residential yards in addition to hiking trails and some 4x4 networks. Regardless of these access points, access into the site also references the ability to conduct suppression efforts in and around the forest itself. Pre harvest conditions, with high stem/ha will reduce the maneuverability and visibility of personnel as well as reduce the impacts of retardant from the lack of penetration to the forest floor. Post harvest conditions are more conducive to successful suppression operations because of the larger openings between dominant species, better line of sight for incoming fire behaviour, and better penetration of retardant or water via aircraft to the forest floor.

A study conducted by Syphard et al. (2011), as mentioned briefly in the introduction, looked at the effectiveness of fuel treatments in the U.S. and the associated suppression efforts. Of the fifty-three events, 30 wildfires were not successfully contained within the fuel treatment (Syphard et al. 2011). Eleven of the thirty events (37%) were unable to provide access to suppression crews therefore permitting wildfire growth in the treatment (Syphard et al. 2011). The remaining 63% had suppression activities conducted but the wildfire still spread across the treatment (Syphard et al. 2011). In the events where the fuel break contained the wildfire, seven (13%) of the events changed the wildfire behaviour enough that suppression crews could operate in the vicinity of the treatment and successfully suppress the wildfire (Syphard et al. 2011). With wildfire crews present on scene, the fuel breaks success rate was around 46% (Syphard et al. 2011). These statistics do not allude to the condition at which the fuel breaks where under at the time of the wildfire but maintaining fuel breaks are an important part of effective wildfire management (Syphard et al. 2011). One assumption from this research is that wildfire size is correlated with rate of spread and found that small fires are more likely to be ceased by the fuel treatments than larger fires that are associated with faster, more erratic spread rates (Syphard et al. 2011).

With the fuel treatment, although relatively unsuccessful in reducing the overall fire behaviour, will provide access to ground personnel and create space for aircraft operations. Nevertheless, with the combination of the fuel treatment, planting in a portion of the site, and access for aerial and ground support will increase the chances of success in protecting the adjacent community. Well ahead of the fire front, aircraft can unload fire retardant in the fuel treatment, ground crews can deploy sprinkler systems and prepare for possible burn off operations. If resources are deployed to the area in a timely manner, this research expects greater success at managing the wildfire.

Considerations/Limitations

Throughout this research, there are some considerations the research identified prior and during analysis. Firstly, the research is assuming that the contractor conducting the initial site assessment has the highest level of expertise when assessing stand and site characteristics prior to harvest. This is important because their assessment provides guidance in creating the prescription for this research to analyze as well as guide the contracted company conducting the harvest. For this research, a consideration was made relating to how the prescription is written versus how the fire effects model can input information. The harvesting prescription reduces stems per hectare in layers (L1-lowest to L4-tallest), but this research removed stems/ha in a percentage relating to the entire block. For example, the harvesting prescription requires <15 cm DBH in L3 to be removed from site, but this research accounted for those stems removed to the total percentage of stems removed. The results may not truly reflect the impact fire behaviour has on the range and variety of all heights and stem diameters on site post harvest. Regarding outside contractors implementing the harvest, multiple contractors operating in the research area increase chances of missed information, improper harvesting, and missed site objectives. This along with prolonged timelines to complete the project may influence different fire behaviour. With the high volume of human influences on site and during the research analysis, the research identified that there is a high probability human error during multiple steps of this process.

Secondly, the data assumption is that TIPSY is accurate and relevant to today's forest landscapes. Data collection for TIPSY has occurred over a 70-year time frame but no information shows when the most recent study was conducted. For this research, some data manipulation was required to calculate actual biomass of the forest stand post harvest since TIPSY did not have the capabilities to calculate biomass with <69 stems/ha. These calculations for post harvest biomass are therefore another human error component in this research.

Another consideration that this research did not account for is understory vegetation growth and the type of vegetation that may rebound after harvest or prescribed burning. With respect to fuel management, differences post harvest may stem from new openings in the canopy, increase in sunlight, precipitation (snow and rain), and soil disturbance from machinery conducting the harvest. With respect to planting, it may change the biodiversity of the understory canopy, increase species competition between other tree saplings, and out compete native shrub and grassland species. Prescribed burning, on the other hand, can have a positive impact on site by removing excessive forest floor debris and increase nutrient influx to promote healthy understory vegetation. Alternatively, burning can overachieve a surface fire by burning deeper into the soil, destroying viable regrowth of native species. This also increases the introduction of invasive plant species that is detrimental to native or wanted species on site. Invasive species may be more flammable, increase forest floor biomass at faster rates, and be less desirable to forage on for cattle or ungulates.

Furthermore, the weather considerations for this research are that the accuracy during time of recording is proficient, and microclimate/microsite differences will not influence the data outputs. For the weather stations, historical weather data collection may not have been as accurate as today creating possible discrepancies or missing information. Microclimates in comparison to weather station location may also provide slight differences when assessing weather. This research chose the most representative weather station for analysis but acknowledges that there may be alternative methods to collecting weather data that could represent the site better. For future year calculations, taking the adjusted weather variables from ClimateBC and translating the new weather variables into the Fire Weather Index spreadsheet may have also incorporated a human error component in all calculation and transferring of data phases.

Lastly, there are considerations for the fire effects model used in this research. CanFIRE stems from the original model BORFIRE (Boreal Wildfire Effects Model), where it looked to study effects of shifting wildfire regimes and carbon storage in Canada's boreal forest (de Groot 2012). The new adaptation, CanFIRE, was developed for wildfire managers to understand wildfire behaviour, impacts of wildfire, and the contribution to carbon emissions under future climate change but still focused only on boreal tree species (de Groot 2012). The objective of CanFIRE was to enhance the CFFDRS, be user friendly and accessible, and to eventually be used across all provinces to provide rapid estimates of wildfire behaviour and potential prescribed burn scenarios (de Groot 2012). Furthermore, B.C. CanFIRE, is a new experimental version, testing CanFIRE's ability to adapt to new tree species, specially those found on this research site.

In previous versions of CanFIRE, an experimental wildfire conducted in Alaska compared CanFIRE with two other online wildfire behaviour prediction models called BehavePlus and RedApp. BehavePlus is a PC based model that is used for wildfire management applications that model wildfire behaviour and some wildfire effects (FRAMES 2022). RedApp is a PC based decision support tool that simply estimates wildfire behaviour (McLoughlin 2019). The results from the experimental wildfire showed that CanFIRE and RedApp were able to produce reasonable, slightly higher, predictions of head wildfire intensity than observed in the experiment (Drury 2019). CanFIRE also had near exact values of rates of spread, 1.8 m/min over 4.8 m/min given by the CFFDRS (Drury 2019). Slight overprediction from CanFIRE suggests that this model could be utilized in predicting potential wildfire growth but should be used conservatively because it is a newly developing model (Drury 2019). Regardless, overpredicting wildfire behaviour is preferential to underpredicting when assessing risks and hazards of areas burning, especially when there are community and resource influences nearby (Drury 2019). Although this experimental wildfire was not conducted in a fuel treatment area and it used an older version of CanFIRE, the benefits of using more detailed forest stand composition from fuel management surveys will be able to depict more accurate site conditions and realistic wildfire behaviour outputs. This research assumed that despite the change in species inputs in the model, that outcomes slightly overpredicted fire behaviour like previous research.

Future Work

The areas of future work with this research looks at B.C. CanFIRE model development, accessibility to multiple agencies, and future development of the model and fuel treatments.

The development of B.C. CanFIRE fire effects model should look to test and compare results to other sites within the IDF as well as expanding into other BEC Zones. For this research, some species used algorithms of similar species, therefore a suggestion would be to find or conduct research to determine algorithms that are specific to the species on site. This can also include adding more tree species algorithms that are found within British Columbia to the input page of the model.

Future efforts with B.C. CanFIRE (as per Bill De Groot 2022) can be further developed to calculate:

- detailed Dead Woody Debris and slash fuel consumption by size class,
- slope-adjusted rate of spread,
- aspen leaf-flush and leaf-fall dates based on location and,
- crown bulk density in crown fire equation.

By increasing the capabilities of B.C. CanFIRE, this research expects increased success at predicting fire behaviour both in treated and untreaded stands.

For accessibility, introducing the model to fire and forest managers, B.C. Wildfire Service staff, contracting companies, and other ministries involved in natural resources will foster collaborative coordination with fuel treatments and information sharing. In addition, the results of this research and the model can improve First Nation partnerships and collaboration with implementing treatments within and around their territories. This information can contribute further insight into the fire hazard abatement goals set for their communities while providing possible outcomes of burning in those areas. Information sharing can include development of prescriptions, treatment efficacies, vegetation consumptions, resource sharing, and prescribed burning tactics to achieve multiple site and land ownership objectives. Additionally, private, and commercialized companies can look at treatments adjacent to their infrastructure and values (e.g., hydro lines, mills, cell towers, etc.) and look to use this information in protecting their structures from wildfire threats.

Future work with B.C. CanFIRE can look at analysing and incorporating the other aspects of the model. These include fuel consumption for the varying fuel depths and types, Emission Rates, and tree mortality. These components may provide more depth information on the overall fire behaviour across the site. While considering more outcomes, future work can also investigate other harvesting treatments and interpretations of harvesting prescriptions. For example, testing out different species compositions, combinations, and concepts that may alter fire behaviour better while keeping true to natural species on site. This example is found in this research where only one block saw a reduction in fire behaviour that happened to have less than 3 different species present on site post harvest. This information would be important to test in future research to ensure these results are viable in similar treatment units. For further context, this research can not provide a blanket statement for the IDF but can give insight to other treatment areas like this research.

Chapter 5 . Conclusion

Fire behaviour is a function of both fuels (type, size, moisture, and distribution) and weather (wind, relative humidity, precipitation etc.) each providing an elaborate outcome that is marginally touched upon in this research. With the manipulation of fuels and weather, the results found that numerically the site overall did see a reduction in Rates of Spread, Final Head Fire Intensities, and Intensity Classes post harvest as per the initial hypothesis. It is important to mention that, despite the statistical differences between the untreated and treated sites, the research area still exhibited extreme fire behaviour with low fuel loads and continued to burn at Intensity Classes 4 to 6. This means that there is little difference between treating and leaving the site in its ‘natural’ state. Additionally, the research can’t understand the closeness of the final datasets and the difference between pre and post harvest results will likely not be discernable in the field. What this means is that, numerically, pre and post harvest Intensity Classes are different, but on site during the event of a wildfire, Intensity Class 6, 5 and arguably 4, are hard to distinguish. This is also true for Final Head Fire Intensities without a measurable device on site. Future climate change variables were tested throughout this research and identified that current weather at the extremes is relatively equal to predicted weather for 2050 and 2080. Discerning between Intensity Class 5 and 6 with the associated Final Head Fire Intensities again show minimal change between untreated and treated sites despite growing concerns of a warming climate.

The results of this research are a depiction of specific site conditions and are not a blanket statement for all fuel treatments within the Interior Douglas-fir Biogeoclimatic Zone of British Columbia. Consequently, there is no simple solution to the best treatment type and research will have to continue to explore possible avenues of treatments in numerous locations. This research does, however, provide some tools that address the changes in fuel management treatments while under different climatic changes both present and future. This research is valuable to the field of both wildfire and fuels management providing evidence that with the assistance of a fire effects model managers can make well informed decisions on location and type of treatment dependent on hazard abatement goals. To conclude, this research can provide a insight to fire and forest managers about how British Columbia manages their Wildland Urban Interface and the benefits of fuel management for fire suppression staff and adjacent community safety.

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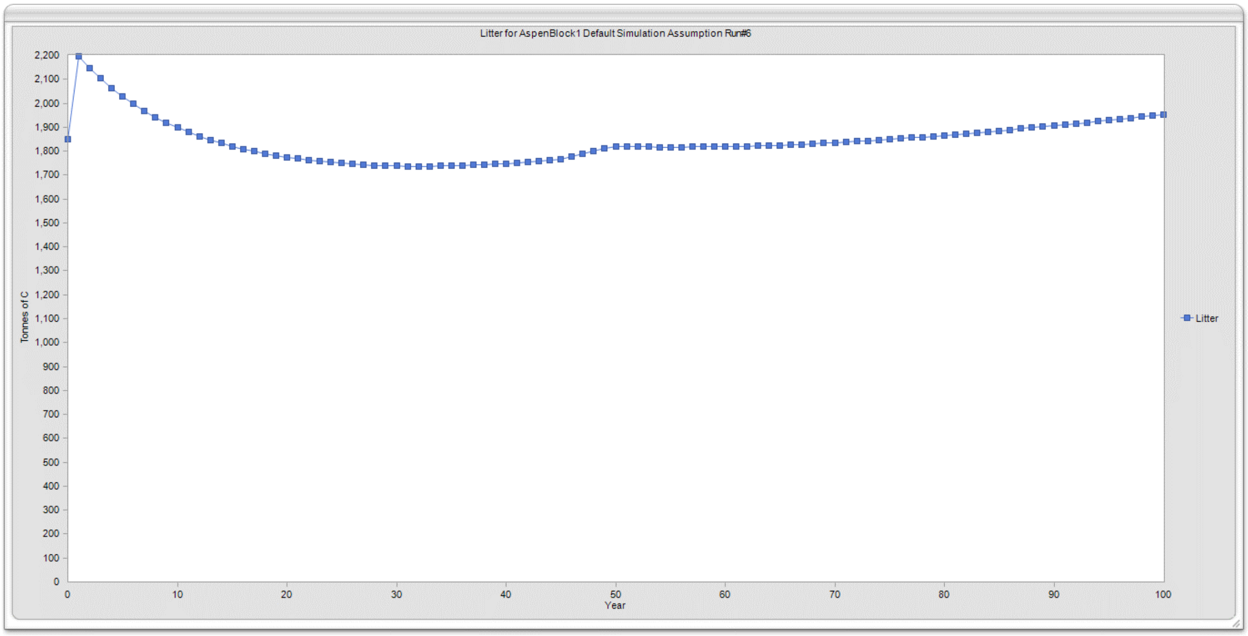
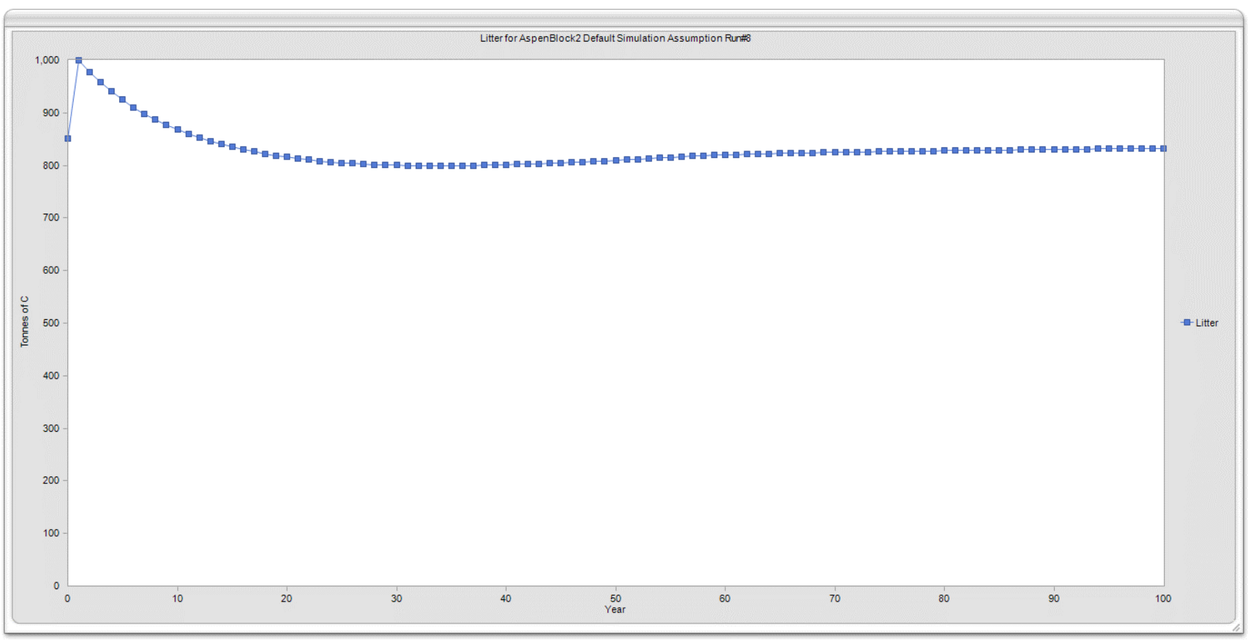
Appendices

Appendix A. Carbon Budget Model – Litter Accumulation Projections Post Harvest

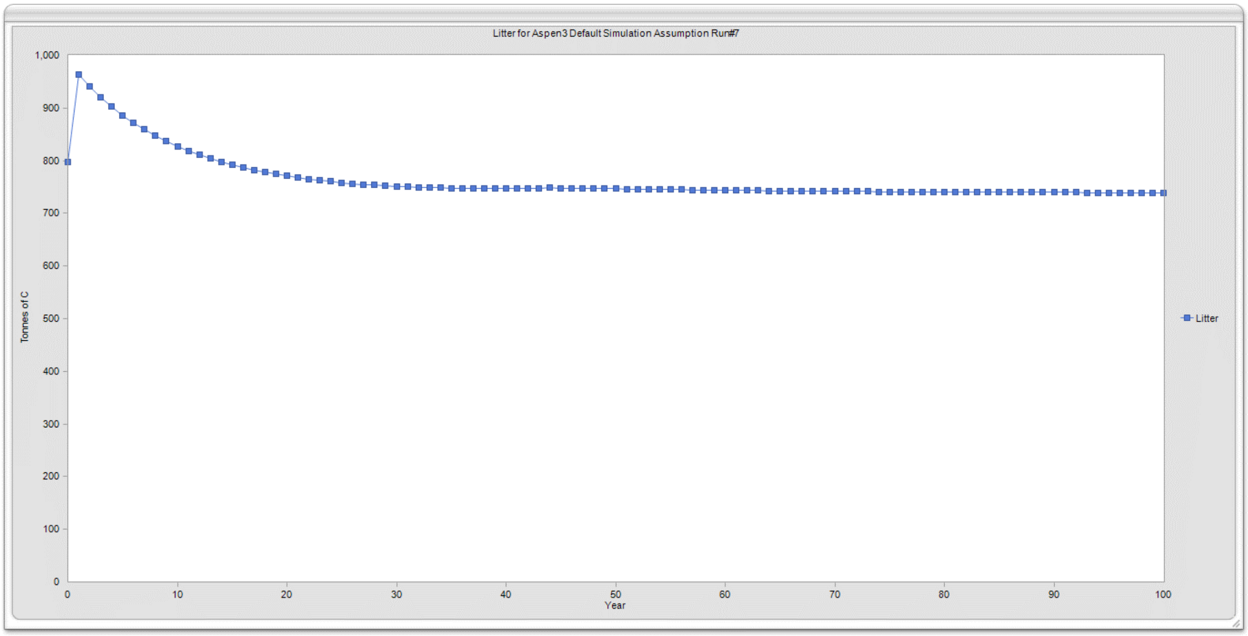
Aspen Parkland Block 1. Litter Accumulation 100 years Post Harvest



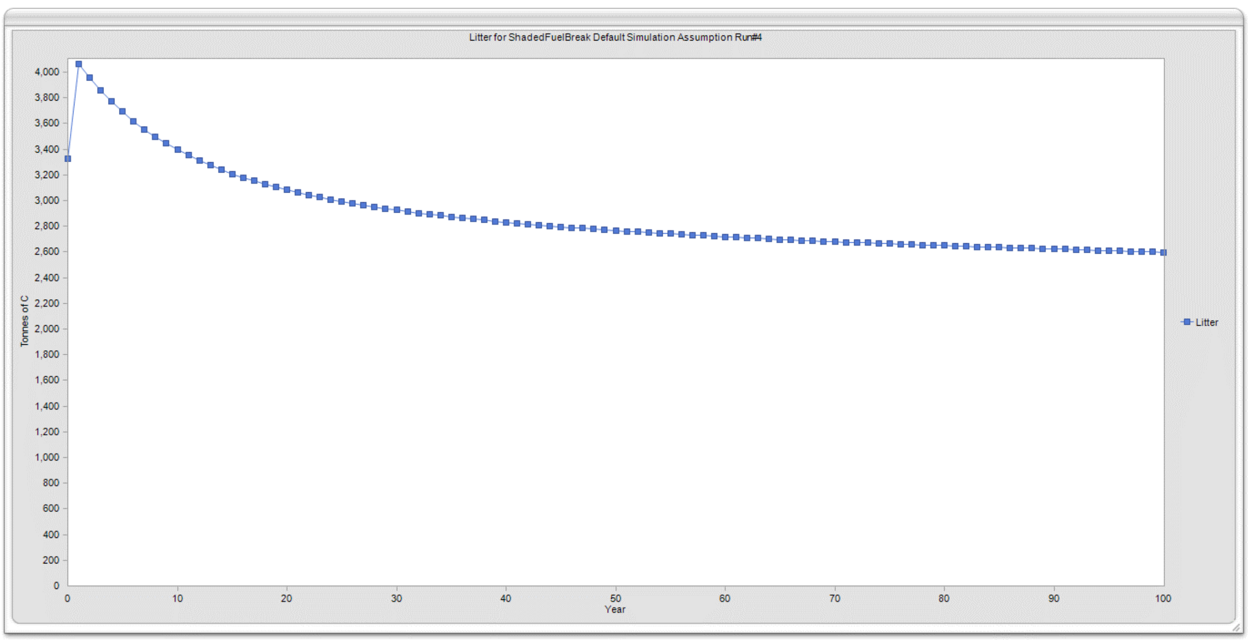
Aspen Parkland Block 2. Litter Accumulation 100 years Post Harvest



Aspen Parkland Block 3. Litter Accumulation 100 years Post Harvest



Shaded Fuel Break. Litter Accumulation 100 years Post Harvest



Appendix B. Frequency distributions for Fire Weather Index variables.

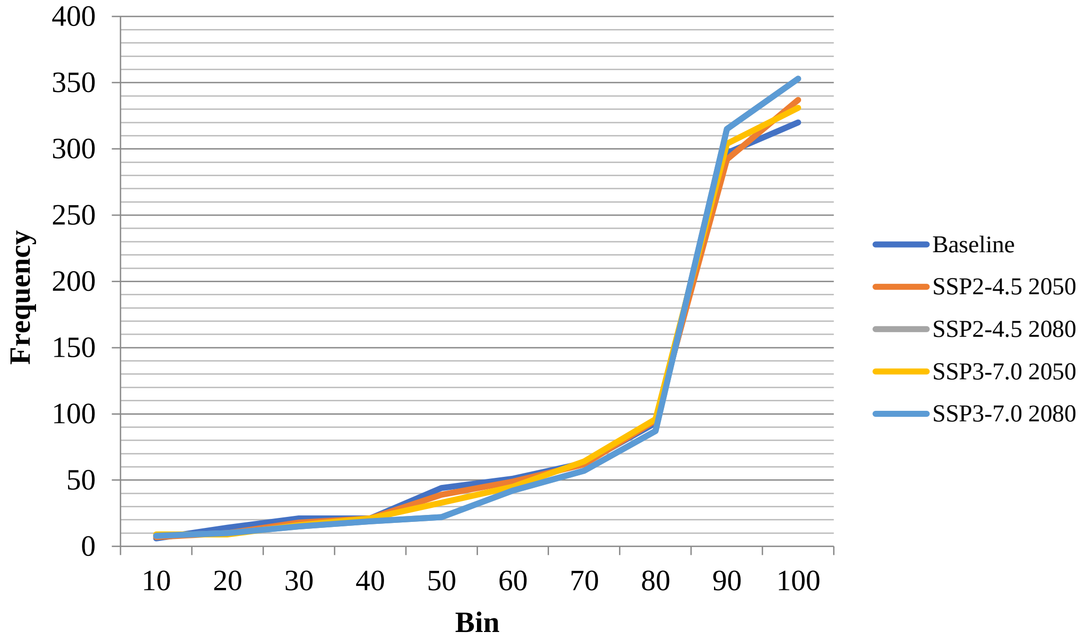


Figure 6. 1. Frequency graph of the Fine Fuel Moisture Code (FFMC) for July 1991-2021 from baseline, 2050, and 2080 adjustments with Shared Socioeconomic Pathways (2-4.5 and 3-7.0).

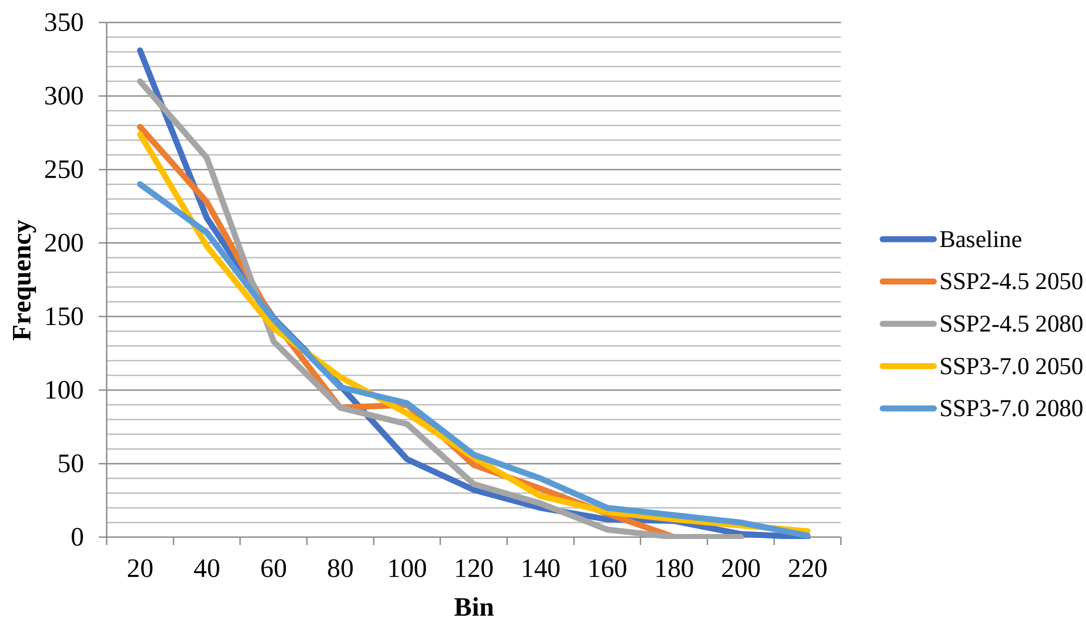


Figure 6. 2. Frequency graph of the Drought Moisture Code (DMC) for July 1991-2021 from baseline, 2050, and 2080 adjustments with Shared Socioeconomic Pathways (2-4.5 and 3-7.0).

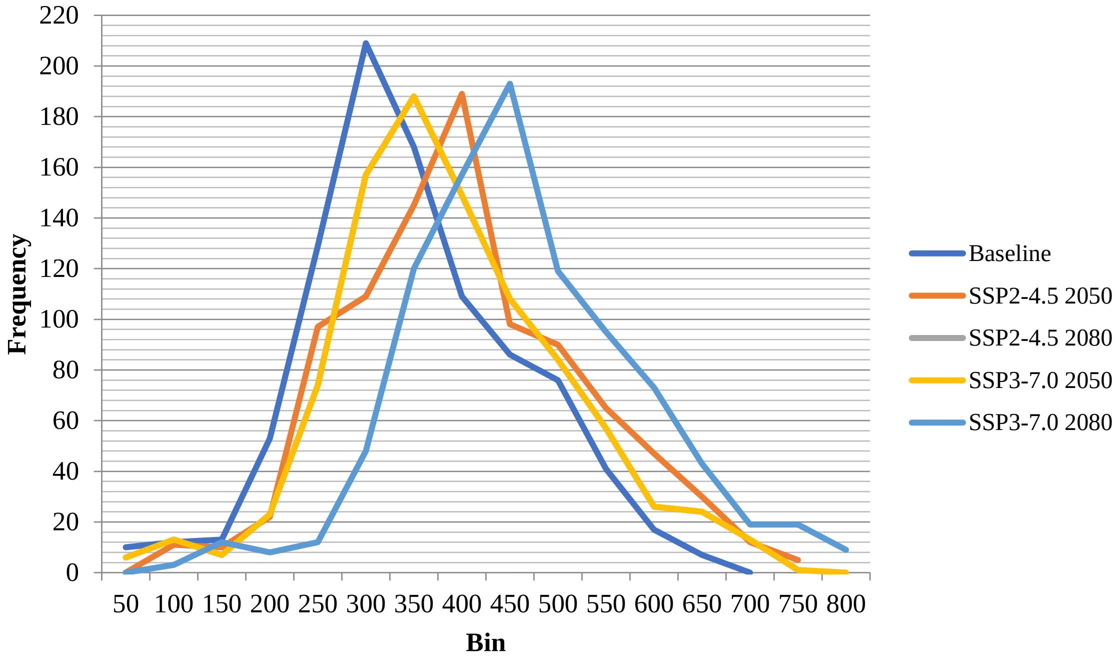


Figure 6. 3. Frequency graph of the Drought Code (DC) for July 1991-2021 from baseline, 2050, and 2080 adjustments with Shared Socioeconomic Pathways (2-4.5 and 3-7.0).

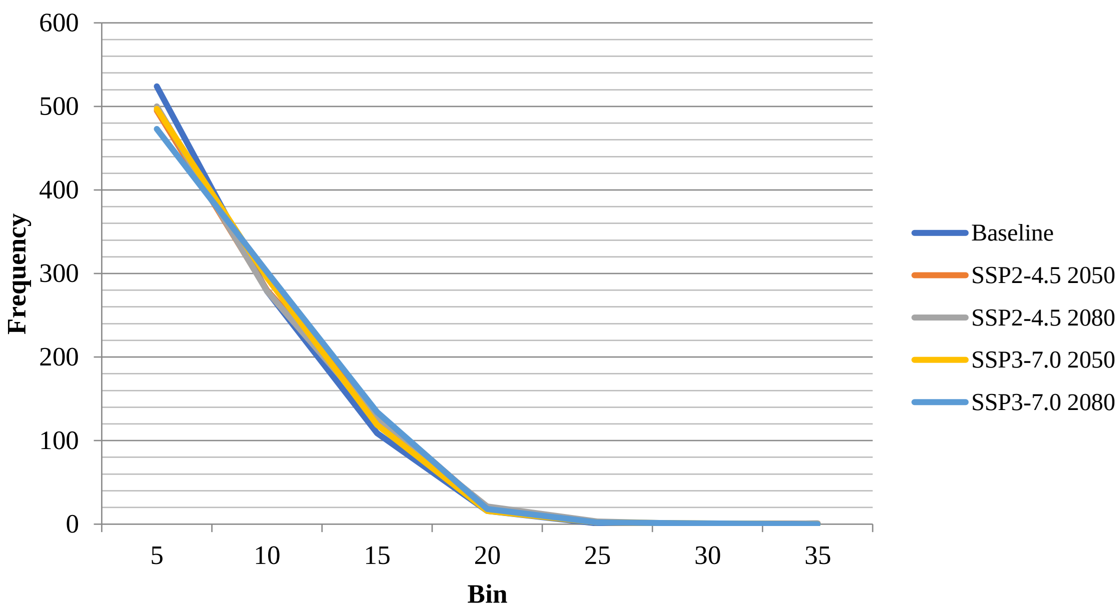


Figure 6. 4. Frequency graph of the Initial Spread Index (ISI) for July 1991-2021 from baseline, 2050, and 2080 adjustments with Shared Socioeconomic Pathways (2-4.5 and 3-7.0).

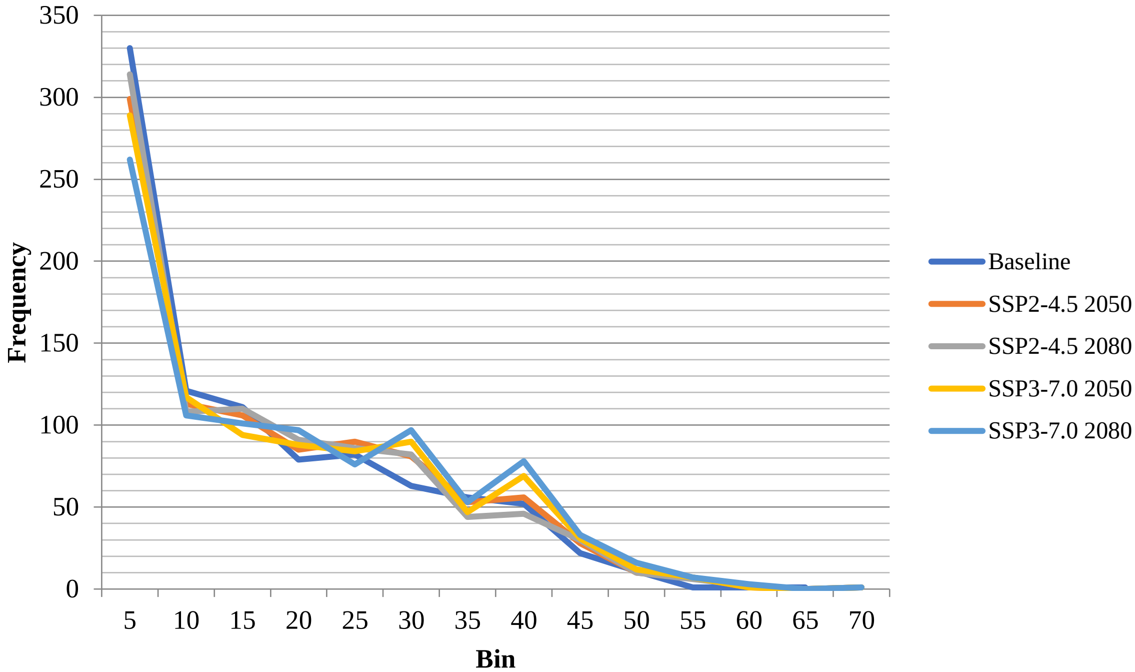


Figure 6. 5. Frequency graph of the Fire Weather Index (FWI) for July 1991-2021 from baseline, 2050, and 2080 adjustments with Shared Socioeconomic Pathways (2-4.5 and 3-7.0).

Appendix C. Fire Weather Indices and Hazard Ratings with Head Fire Intensities represented by Rank (Government of Alberta 2023).

Hazard Rating	**FFMC** Fine Fuel Moisture Code	**DMC** Duff Moisture Code	**DC** Drought Code	**ISI** Initial Spread Index	**BUI** Build Up Index	**FWI** Fire Weather Index	**HFI** Head Fire Intensity
Low	0-76	0-21	0-79	<1.5	0-24	0-4	1-2
Moderate	77-84	22-27	80-189	1.5-4.0	25-40	5-10	3
High	85-88	28-40	190-299	4.1-8.0	41-60	11-18	4
Very High	89-91	41-60	300-424	8.1-15.0	61-89	19-29	5
Extreme	92+	61+	425+	>15.0	90+	30+	6