Canadian Journal of Forest Research

Interaction of elevation and climate change on fire weather risk

Journal:	<i>Canadian Journal of Forest Research</i>
Manuscript ID	cjfr-2021-0137.R1
Manuscript Type:	Article
Date Submitted by the Author:	18-Aug-2021
Complete List of Authors:	Spittlehouse, Dave; BC Ministry of Forest, Lands and Natural Resource Ops, Dymond, Caren; Government of British Columbia
Keyword:	climate change, fire weather risk, elevation, weather generator, mountains
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

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Draft

Abstract

Most wildfire studies are regional to global in scale; however, many of the values of interest and the weather are local phenomenon that may give rise to large spatial variability in risk. We assessed the interaction of elevation and climate on fire weather for the Penticton Creek watershed in south-western Canada for historic weather, and five climate change scenarios. 100-year records of daily temperature and precipitation were generated using the LARS-WG5 weather generator, and used to calculate the Fire Weather Indices of the Canadian Forest Fire Danger Rating System. Fire season length, restricted activity season and fire season severity are all projected to increase by the 2050s and in some scenarios to increase further by the 2080s. Low and mid-elevations had substantially worsening risks, whereas at the highest elevations risks were mitigated by the continuation of the snowpack. Increasing temperatures lengthened the fire season while decreasing (increasing) precipitation exacerbated (ameliorated) the intensity of the fire risk. These results indicated more variable climate change effects than in the literature. Over 24 million km² globally of forestland have a similar or higher degree of slope highlighting the need for detailed topographic integration in fire studies to meet the needs of local planners.

Keywords: climate change, wildfire risk, fire weather risk, elevation, scale, wildfire, mountains, CFFDRS, weather generator, temperature, precipitation

1. Introduction

Wildfire risks in many parts of the globe are of interest to forest and fire managers because of the consequences to human security and health, the economy, and ecological goods and services (Johnston et al. 2020). Recent climate change is considered a driver of the increase in fire occurrence worldwide (Smith et al. 2020). In the province of British Columbia (BC), Canada, there was relatively low area burned annually through the middle of the 20th century, but it has increased since 2003 (Kirchmeier-Young et al. 2019). Kirchmeier-Young et al. (2019) concluded that that the almost doubling of maximum annual area burned in 2017 in BC (1.2 million ha) was made substantially more likely due to human-caused climate change. These fires, along with the preponderance of forests covering BC, highlight for the general public and policy makers the threat of wildfire to multiple values (Abbott and Chapman 2018). However, the effects of future climate change projections on fire risk metrics are uncertain, making it difficult to adapt.

Previous studies of climate change and fire indicators in BC have indicated the potential for increased future risks from wildfires in some areas, but not others and that the increase in risk depended on the climate change scenario. Large-scale modelling studies projected a small to moderate increase in fire occurrence likelihood in BC in the 2030s and 2090s (Wotton et al. 2010), a small increase in cumulative severity rating by 2040s but a large one by the 2090s (Flannigan et al. 2013), or an increase in annual area burned and increase or decrease in fire occurrence depending on the region (Boulanger et al. 2014).

Regional scale studies such as Haughian et al. (2012) projected changes in wildfire severity for the 2080s under a severe climate change scenario. Their results showed potential increased monthly mean severity index for the southern half of BC, but decreased severity in most of the northern half of the province. For a similar severe climate change scenario, a regional study of the Thomson-Okanagan

projected increasing climate change risk from fire weather, but that was offset by the possibility of moist forests expansion (Wang et al. 2016). A local study in the Okanagan of climate change and fire projected an increase in fires season length across all elevations under the A2 emissions scenario (Nitschke and Innes 2008). However, none of these studies show projections of fire weather risk due to climate change at the local scale typically used by municipal planners, in addition to larger scale information on fire risk (Wilbanks and Kates 1999) and water supply (Hering et al. 2015). The communication of climate change to decision makers has well-documented implications for action, or inaction (Markowitz and Guckian 2018). In general, local actions are more likely to be taken when the science is presented with local effects that people can connect to (Armstrong et al. 2018; Halperin and Walton 2018).

All of these studies rely on the Canadian Fire Danger Rating System (CFFDRS) and its Fire Weather Indices (FWI). The FWI system tracks the moisture content of different dead fuel layers and rate of spread and therefore indicates the likely difficulty in suppressing a fire (Van Wagner 1987). The CFFDRS is also used in several states in the USA, France, Indonesia, Malaysia, Mexico, New Zealand, and Spain (Dymond et al. 2005; Wang et al. 2017). Components of the FWI are correlated with fire occurrence and area burned (e.g. Amatulli et al. 2013; Carvalho et al. 2010).

The BC Wildfire Service uses components of the FWI system in their fire managements operations. As the Fire Danger Class (FDC) increases with dry weather, the risk of fire occurrence, area burned, and difficulty controlling the fires increases from easy to extremely difficult (BC 1983). Consequently, the FDC is used in the Wildfire Regulation to place restrictions on high risk activities (BC 2005). Even if there are no fires, under regulation there are economic and job implications of longer restricted activity seasons or more frequent severe fire seasons. For example, the forestry, fishing, mining and oil and gas industries would be subject to more restrictions. Although these costs are justified in preventing wildfires, they are still incurred. Other socio-economic effects, which are not as clearly defined in

regulation, include reduced recreational use of the forest in the spring and fall, and limitations on grazing use.

Topography can have a significant influence on the local weather (Dupire et al. 2017; Jain and Flannigan 2017). Specifically, elevation has been shown to affect fire weather due to decreasing temperature, increasing relative humidity and potentially increased rainfall as elevation increases. The purpose of this study was to evaluate the importance of the interaction of climate change and elevation on the risks from fire weather. To achieve this purpose our objectives were to: examine the role of elevation in fire weather and associated risks under current and a range of future climates; and determine how these influence indicators of fire risk relevant to municipal planners, timber companies and fire managers. The Penticton Creek watershed in south-western Canada (Winkler et al. 2017) offers the opportunity to study the interaction of elevation and fire weather in detail. Data from two long-term weather stations 1276 m apart in elevation and snowpack measurements at higher elevations allow detailed evaluation of current conditions and calibration of the LARS-WG5 weather generator (Semenov and Barrow 2013). We selected five climate projections that cover approximately 90% of the range of the CMIP5 projections for our area. The weather generator was used to create 100-year-long daily temperature and precipitation records of current and projected climates for the 2041-71 and 2071-2100 periods, and these data were used to calculate a selection of indicators of fire weather and associated risk.

2. Methods

a. Study area

The study area is the 25,675 ha Penticton Creek watershed in south-eastern BC, Canada (Figure 1). The base of the watershed is at 342 m and the lower 200 m is relatively narrow and steep. It then opens up to the rolling south to southwest facing terrain of the Okanagan Plateau and reaches 2154 m at Greyback Mountain in the northeast. The city of Penticton is at the foot of the watershed and residents use the area for drinking water, irrigation of farms and wineries, and recreation. Industrial uses include timber harvesting and ranching. Most of the study area is on public land. The area is largely forested with ecosystems ranging from Ponderosa pine (*Pinus ponderosa*) savanna at the lowest elevations, transitioning into open-canopy Douglas-fir (*Pseudotsuga menziesii*) and Ponderosa pine, and closed-canopy lodgepole pine (*Pinus contorta*) and spruce (*Picea* spp.) at mid-elevations to lodgepole pine, spruce and subalpine fir (*Abies lasiocarpa*) at the top of the watershed (Table 1). Natural disturbances include wildfire and insects. Timber harvesting has been occurring in the area for many decades.

We established an elevation transect to evaluate the range of fire weather conditions in the watershed (Figure 1, Table 1). The average slope across the transect is 7.2% (4 degrees). Data for all sites are presented but for clarity some figures and the discussion are focused on low (point 1), mid (point 3) and high (point 5) elevations.

b. Calculating the Fire Weather Index

Operationally in this climate, the calculation of the FWI system begins when the area is snow-free and ends when the snow pack starts in the fall (Lawson and Armitage 2008). The input to the FWI system is

daily noon observations of temperature, relative humidity, wind speed, 24-hour accumulated precipitation and the previous-day's moisture codes. The first step in the methodology is the calculation of the fine fuel moisture code (FFMC) (litter layer), the duff moisture code (DMC), and the drought code (DC) (deeper organic soils and coarse woody debris). The DMC and DC indices are used to calculate the build-up index (BUI), which represents availability of fuels for burning, and the FFMC and wind speed are used to calculate the initial spread index (ISI) (Van Wagner 1987). FWI represents fire intensity and is calculated from the BUI and ISI. The BUI and FWI are used to define FDC which represents the potential fire load (Table 2 and S1) (BC 1983).

As described in the Introduction, the FWI System is used in conjunction with other tools in fire management; and by proxy in smoke, natural resource, and recreation management in BC. The FFMC is correlated with fire occurrence (Kiil et al. 1977) and fires are generally thought to be unlikely to occur below a FFMC of 72 (M. Alexander pers. comm.). In the Wildfire Act Regulation (BC 2005), the value of the FDC is used to restrict or prohibit activity on the land base for fire prevention (Table). Therefore, we defined our main variables of interest as: the BUI, the FWI, fire season length (the number of days at or above FFMC 72), restricted activity season (the number of days per year at or above FDC 3), fire season severity (the number of days per year with FDC 5 occurring) and seasonal severity rating (mean of the daily severity rating for June, July and August, Van Wagner 1987). Fire season severity is presented as an exceedance probability i.e. the likelihood that the number of days in a year with FDC of 5 will exceed the chosen threshold.

The *cffdrs* R package (R Core Team 2018; Wang et al. 2017) calculates the FWI codes, including the overwintering Drought Code. It uses a temperature threshold for starting and ending the calculations as a surrogate for a lack of information on the state of the snow pack. We used a modification of the

standard R package which allowed us to use 3 consecutive days of no snow pack and 3 consecutive days of snow depth >1 cm for calculation start and end dates, respectively (A. Cantin, pers. comm.).

There are various approaches to modelling fire weather statistics at the regional and local scale for climate change studies. Bedia et al. (2014) calculated historic and future indices at the 0.5° grid scale of their calibration data and regional climate models. Jain et al. (2020) calculated fire weather indices using 32 km gridded weather data and then downscaled the indices using a distribution-based scaling approach based on comparison with site specific indices. The calibrated downscaling algorithm was then used to downscale indices calculated with weather data from a regional climate change model. Yang et al. (2015) downscaled weather data using a distribution-based scaling approach and then calculated the fire weather indices for historic and regional climate model-based projections of climate change. Neither approach explicitly considered the influence of elevation on indices within the grids. Dupire et al. (2017) took account of elevation by using regional weather model output bias corrected with local weather station data to give the appropriate weather variables by elevation. They did not consider projections of future climate change. We used an approach similar to Yang et al. (2015) in using downscaled daily weather data to calculate historic and projected future indices. Like Dupire et al. (2017) we obtained elevational gradients of weather variables using local weather station data to account for the influence of elevation on fire weather. Similar to Bedia et al. (2014) we used an ensemble of 5 climate change scenarios spanning the range of projected climate changes for our area. These data were used to calculate a selection of indicators of fire weather and associated risk.

c. Historic weather data

Daily and hourly weather data for the higher elevations of Penticton Creek are available from the Upper Penticton Creek (UPC) Watershed Experiment (Winkler et al. 2017). Data start in October 1983 for the P1 weather station (49°39'05"N, 119°23'56"W, 1620 m). Only daily maximum and minimum air temperature (2 m height) and precipitation measurements were made from 1983 to 1991. Measurement of humidity (2 m height), wind speed (3 m height), and snow depth were added after this and hourly data start in 1996. Environment and Climate Change Canada's (ECCC) Penticton Airport station (49°27'47"N, 119°36'08"W, 344 m) ~21 km SW of P1 has daily and hourly values for these variables available from 1953 to 2018. Monthly temperature and precipitation data for 1981 to 1983 at P1 were estimated from the ECCC station at McCulloch (49°48'N, 119°12'W, 1250 m) ~20 km NE of P1 to allow calculation of the 1981 to 2010 normals. Following Vincent et al. (2002) coefficients to adjust McCulloch data to P1 were calculated with overlapping data (1984-1996). The resultant time series was checked for discontinuities and that it followed trends in Penticton Airport data, a station in ECCC's Adjusted and Homogenized Canadian Climate data base.

The upper part of the watershed has cold, long winters and cool summers. This contrasts strongly with the milder winters and hot summers in the valley (Table 3). Annual precipitation at Penticton Airport is less than half that at the P1 weather station. The climatic range in the watershed is reflected in the vegetation communities (Table 1). There are no significant ($p<0.2$) increasing or decreasing trends in the seasonal precipitation or air temperature over the 1984 to 2016 period at Penticton Airport and P1 (calculated using the zyp R package Bronaugh and Werner 2013). The period includes cool and warm phases of the Pacific Decadal Oscillation (PDO). Cool phases have higher precipitation and cooler temperatures in winter and spring than the warm phase and the snow melt season starts later (Winkler

et al. 2017). The influence of the PDO can be modified in years with a strong El Nino Southern Oscillation (Fleming and Whitfield 2010).

d. Climate Change Scenarios

Our climate change scenarios were obtained from the Bias Corrected Constructed Analogues with Quantile mapping (BCCAQ-v1 and -v2) data sets (PCIC 2014, Sobie and Murdock 2017). These data are based on CMIP5 global climate model output (Taylor et al., 2012) of daily maximum and minimum air temperature and total precipitation, downscaled and bias corrected to 300 arc seconds (approximately 10 km grid). We chose five distinct scenarios (Table 4) that bound approximately 90% of the projections for the region (Figure S1). We used daily time series from 1950 to 2100 for each scenario for a grid cell centered at 48.625°N, 119.4583°W that includes the location of the study area. We calculated changes in monthly temperature and precipitation between the 1981-2010 normals of these data and normals for the 2041-2070 (2050s) and the 2071-2100 (2080s) periods (Tables 4 and S2). The changes in monthly temperature and precipitation were used in generating the 100-year long daily time series used in our analysis (described later).

The CSIRO-Mk3-6-0-r1 RCP8.5 scenario (CSIRO85) projects a climate with substantially warmer temperature and much drier summers and wetter winters than CNRM-CM5-r1 RCP4.5 (CNRM45) for the study area. CNRM45 projects minimal difference in climatic conditions between the middle (2041-2070) and end (2071-2100) of the century while CSIRO85 projects conditions to continue to get warmer and drier (summer) or wetter (winter) over the century (Table and S2). The MPI-ESM-MR-r1 RCP4.5 (MPI45) has a warmer spring than CNRM45 and generally wetter precipitation regime. As with CNRM45, MPI45 has similar climatic conditions between the middle and end of the century. A fourth scenario, CanESM2-r1 RCP8.5 (CanESM85), has a larger increase in temperature in all seasons, a greater amount of spring and summer precipitation and lesser amount of fall and winter precipitation than CSIRO85. The MIROC-

ESM-r1 RCP8.5 scenario (MIROC85) produces a climate with temperatures similar to CanESM85 but with greater precipitation particularly in winter and summer. As with CSIRO85, the CanESM85 and MIROC85 scenarios produce climates that continue to warm to the end of the century with MIROC85 producing the wettest climate.

We calculated the FWI statistics for the 2050s and the 2080s periods for each climate change scenario, though we focus discussion mainly on the 2050s period with most of the 2080s data provided in the Supplemental.

e. Data for fire weather calculations

100-year-long weather records for a stationary climate were required for fire frequency analysis to improve the statistics for determining 20- to 30-year return events and simulating extreme events. The GCM simulations were not used because their 30-year periods contain climate change trends. Consequently, records for the historic climate and climate change projections were created using the LARS-WG5 weather generator (Clarke et al. 2021; Semenov and Barrow 2013). It was calibrated with 33 years (1984 to 2016) of daily maximum and minimum air temperature and precipitation data for P1. We found that compared to the historic measured data, the simulated values tended to underestimate the distribution of the coolest temperature. Mehan et al. (2017) noted that the weather generators they evaluated had difficulty in fully matching the shape of the temperature distribution. The LARS-WG5 data were adjusted with a simple empirical quantile mapping procedure where quantiles of simulated temperature were directly mapped onto the quantiles of measured temperature (Sobie and Murdock 2017). The two data sets were divided into 5% quantiles and regressed against each other to generate a second-order polynomial equation that was used to adjust the simulated historic and the projected data from the weather generator. Our analysis was done with the quantile and regressions functions in base R (R Core Team 2018). Adjustment of daily values using seasonally-based second order polynomial

equations provided the best match to the measured data (Figure 2, Table S3). The adjusted r-squared for all months was >0.997 and standard error of the estimate was 0.1 to 0.3°C .

In contrast to temperature, the distribution of daily precipitation, monthly 1-day extreme precipitation and the length of the summer dry period (Figure 2, Table S3) were well simulated and no adjustment was required. A dry period is a number of continuous days without rain. We set a threshold of 0.3 mm d^{-1} as the cutoff because a comparison with P1 data showed that the BCCAQ data has a bias to more days with small amounts of rain. As a corollary, a wet period is the number of continuous days with $>0.3\text{ mm}$ of precipitation. The change in the length of a dry and wet period for each month used in the weather generator is calculated from the mean monthly maximum length of a dry or wet period.

Projected changes in temperature and precipitation from the base period were used with LARS-WG5 to produce 100-year daily records of a “stationary” climate for the 2050s and 2080s. The change from the base period (temperature) or the ratio of future to base (precipitation and wet and dry period length) are used by LARS-WG5 to adjust the statistical distributions of these variables (Semenov and Barrow 2013). The resulting time series were assessed to ensure that the mean monthly change in temperature and precipitation matched those projected by the climate models.

The fire weather calculations require daily weather data (temperature, humidity, precipitation, wind speed) at noon (Lawson and Armitage 2008), necessitating functions to estimate noon values from daily data. Equations were developed using hourly and daily data for P1 to allow the calculation of these variables from the daily data, similar to Bedia et al. (2014). Daily humidity and wind speed values are not available from the BCCAQ data and require methods to generate their daily and noon values. The best of the methods evaluated are described below and the success in using them in calculating fire weather metrics is reported in the following section.

- 246 • Temperature ($^{\circ}\text{C}$) at noon ($T_{a,N}$) is calculated from the daily maximum air temperature ($T_{\max}$)

247 using $T_{a,N} = 0.95 * T_{\max} - 1.7$, $R^2 = 0.986$, $n=365$, $\text{se}_{xy} = 1.2^{\circ}\text{C}$, $p < 0.01$. Evaluation with data for

248 another year (Table S4) had similar agreement.
- 249 • Relative humidity (%) at noon (RH_N) is calculated from the daily vapour pressure (e_a) and the

250 saturated vapour pressure at $T_{a,N}$ ($e_s[T_{a,N}]$), i.e., $\text{RH}_N = 100 * e_a / e_s[T_{a,N}]$. We assume that the dew

251 point temperature equals the minimum air temperature and the daily vapour pressure equals

252 the saturated vapour pressure at the minimum air temperature (EWRI ASCE 2005). Compared to

253 measured noon values, the calculated RH_N had a standard error of $\pm 8\%$ (Table S4). A sensitivity

254 analysis to the assumption the dew point temperature equals the minimum temperature at the

255 high elevation reference site indicated that a $\pm 1^{\circ}\text{C}$ change in dew point temperature during the

256 summer resulted in a ± 3 to 4% change in the calculated noon humidity. This resulted in a $\pm 6\%$

257 change in the average number of days in a year with FDC 4 or 5 at the low elevation site.
- 258 • Daily average wind speed showed no correlation with the daily temperature and precipitation

259 and there was negligible day-to-day serial correlation. Measured daily and noon values at P1

260 were used to produce a model for noon wind speed (km h^{-1}) adjusted from 3 m to 10 m using

261 the power law with a coefficient of 0.143. Daily wind speed (u_{day}) is sampled from a lognormal

262 distribution ($\ln(\mu) = 0.628$, $\ln(\sigma) = 0.245$, 0.469 , November-March and April-October,

263 respectively) (Figure S2). The noon wind (u_N) is calculated from a mean relationship between it

264 and the daily wind ($1.46 * u_{\text{day}}^{0.914}$) plus the variability around the mean calculated using a normal

265 distribution ($\mu = 0.255$, $\sigma = 0.427$). Distributions of measured (simulated) wind speed (Figure S2)

266 had the mean and 90th and 10th percentiles of 10.3 km h^{-1} , 15.4 km h^{-1} and 5.6 km h^{-1} and (10.6

267 km h^{-1} , 16.3 km h^{-1} and 5.6 km h^{-1}), respectively. An advantage of this approach is that the shape

268 and scale parameters can be adjusted to simulate other wind regimes.

- Precipitation (mm d^{-1}) at noon (P_N) is assumed equal to the daily precipitation.
- The fire season starts 3 days after the snow pack disappears and ends on the day when the snow pack is established late in the year (Lawson and Armitage 2008). The date of snow pack appearance and disappearance are calculated using a snow accumulation and melt model (Buttle 2009, Gergel et al. 2017). The model is run for each elevation point on the transect using the projected daily maximum and minimum air temperature, precipitation, humidity and wind speed for that elevation. The model agreed well with measurements of the start and end dates of the snow pack (Table S5) and tracks the evolution of the pack over the winter (Figure S3).

f. Extrapolation of weather data over the elevation transect

Monthly gradients calculated from monthly normals were used to adjust the daily weather data to various elevations within the Penticton Creek Watershed using P1 as the reference location (*c.f.* Thornton et al. 1997). Data for P1 and Penticton Airport were used in the determination of these elevational gradients. Lapse rates for the monthly maximum and minimum air temperature ranged from 0.29 to 0.77 and 0.51 to 0.69 °C/100 m, respectively, with an average annual temperature lapse rate of 0.6°C/100 m. The monthly vapour pressure gradient varied from 0.013 to 0.029 kPa/100 m.

Kolmogorov-Smirnov similarity test indicate no difference between the distributions of measured at Penticton airport and simulated from P1 noon air temperature and noon relative humidity (Figure S4).

Monthly precipitation elevation gradients were calculated as a percentage change in precipitation with elevation using P1 as the reference and ranged from 2.7 to 4.9 %/100 m depending on the month. The temperature and precipitation gradients are in agreement with regional gradients (Pacific Climate Impacts Consortium https://data.pacificclimate.org/portal/bc_prism).

There is no elevation gradient for wind speed and the simulated value at P1 is used at all elevations in the watershed. Wind speed can vary with the local terrain; however, the P1 reference station is well exposed to the wind and likely represents conditions typical of the Okanagan plateau. Considering the terrain on the elevation transect we would not expect any large differences from our reference location. A sensitivity analysis of wind speed indicated that a 10% and 20% increase or decrease in the distribution of the noon wind speed resulted in a small change (± 2 and ± 4 days, respectively) in the average number of days with FD class >3 compared to the base case using the historic noon wind speed distribution.

We assume that environmental gradients do not to change with a changing climate, similar to the approach used in creating the BCCAQ data base (Sobie and Murdock 2017). Other downscaling methods and assumptions are available but there is no consensus on the best method (Maraun et al. 2017).

The relatively gently sloping terrain and predominance of south to south-west aspect of the watershed indicates that elevation would be the major driver of variation in the spatial temperature, precipitation and snow pack. Large differences in slope and aspect from our use of relatively flat terrain would ameliorate or exacerbate the influence of elevation on weather conditions and fire risk. For example, steep south facing slopes in the lower elevations would likely melt out sooner by a few days than the on relatively flat terrain we are considering. However, this should not affect the relative change in fire statistics resulting from the climate change scenarios.

g. Evaluation of synthetic weather data to calculate fire weather metrics

The 100-year historic and climate change daily temperature and precipitation time series are generated for the P1 site. The temperature data are used to calculate the daily vapour pressure. The elevational

gradients are then used to adjust the daily values of temperature, vapour pressure and precipitation to points on the transect and noon values for each point are then calculated. The daily and noon wind speed values generated for P1 are applied at all points. Daily values at each point are used to model the snow pack. Daily noon weather data during the snow free period are used to calculate the fire weather indices using the cffdrs R package.

This approach to determining fire weather metrics was evaluated by comparing values calculated with measured noon weather data and simulated weather data for P1 and Penticton Airport. The simulated values for P1 are based on the daily temperature and precipitation from the weather generator, simulated wind speed and the equations for calculating noon values. Those for Penticton are from the simulated P1 daily weather data adjusted to Penticton using the elevation gradients and then applying the equations for estimating noon values. Table 5 illustrates the success of our methodology for predicting the length of the fire season, days in high fire danger classes (class 4 and 5) and summer severity rating. Although there is a tendency to slightly underestimate the most extreme values of some variables, the agreement in fire statistics for measured and synthetic weather data for Penticton is encouraging and indicates that our methodology is robust.

3. Results

As expected, under the historic climate the colder and wetter conditions at the high elevation result in a fire season that is about half that at the low elevation (Table 6). There are also substantially less days in higher BUI categories than at lower elevation (Figure 3). The climate change scenarios create different projections of the BUI in a 2050s climate. The CSIRO85 and CanESM85 scenarios have a relatively greater increase in BUI compared to CNRM45 and MPI45 due to the projected warmer and much drier summers

(Table 4). The wetter climate projected by MIROC85 ameliorates the influence of the projected increase in temperature and change in humidity resulting in summer BUI values similar to CNRM45 and MPI45. However, it has a snow free season similar to CanESM85 and CSIRO85.

Elevation and scenario interact in influencing the length of the fire season (Table 6). The high elevation site had under half the increase in fire season length (14 versus 32 days) compared to the low site for the warming of the CNRM45 and MPI45 scenarios in the 2050s. The warmer RCP8.5 scenarios produced an average of 28 and 39 days increase at the high and low elevation sites, respectively. The smallest percent change for the 2050s was the mid-elevation point under the CNRM45 scenario (13%) while the largest percent change was also the mid-elevation point but under MIROC85 (30%). The RCP4.5 scenario results do not change by 2080s while the RCP8.5 scenarios result in an increase fire season length by up to 69 days (51%) (Table S6). Changes in fire season length are related to a longer snow free season (Table 7) due to later start of the snow pack in the late fall and the earlier melt out of the pack in spring (Figure 4).

Historically the length of the restricted activity season decreased with increasing elevation by 5.3 days 100 m^{-1} on average (Figure 5). The average restricted activity season length was projected to increase by 12 to 40 days by the 2050s depending on elevation and climate scenario. Or put another way, the restricted activity season experienced at the low elevation point moved uphill 280 m (CNRM45) or 640 m (CSIRO85) by the 2050s. The maximum increase was 46 days in the 2080s under the CSIRO85 scenario for the mid elevation point (Figure 5). The CNRM45 and MPI45 provide similar changes to the length of the restricted activity season in the 2050s and 2080s but different absolute values. The lower values for MPI45 are a result of the increase in precipitation in summer and fall compared to a decrease for CNRM45 (Table 4). The influence of summer precipitation also results in a divergence in response of the three RCP8.5 scenarios. The wetter summer conditions of MIROC85 produce a restricted activity season

similar to the RCP4.5 scenarios (Figure 5) even though it projects temperatures that are 1 to 2°C warmer (Table 4). CanESM85 is intermediate between the other two RCP8.5 scenarios. MIROC85 is similar to the RCP4.5 scenarios in the 2080s while the CanESM85 scenario moves closer to the values from CSIRO85 as the influence of increased warming in CanESM85 offsets its greater precipitation (Table S2).

The FWI time series distributions show the influence of temperature, precipitation and snow pack on severity of the fire weather (Figure 6). As with the fire season length, the CNRM45 and MIROC85 have similar maximum values for FWI while the CSIRO85 has more days in higher FWI classes. The wetter summers of MIROC85 moderate the effect of its higher temperatures on FWI. Kolmogorov-Smirnov tests comparing FWI distributions between historic and future conditions were all significantly different ($n=100$, $P<0.001$).

Weather conducive to wildfires that are very difficult to control is shown here using days with FDC=5 (Figure 7). Under historic conditions 10 or more days in a year with FDC=5 is likely to occur about 5% of the time at the low elevations and is nonexistent at the mid and high elevation sites. The CNRM45, MPI45 and MIROC85 scenarios in 2050s and 2080s have minimal change in probability of 10 days for FDC=5 at the mid to high elevations and increase the probability to 15% at low elevations. The CSIRO85 and CanESM85 climates also have a low risk of these extreme conditions at mid and high elevations and approximately 50% and 75% in the low elevations for the 2050s and 2080s, respectively (Figure 7).

Changes in both temperature and precipitation (Table 4) were driving the changes in fire season severity. This is most obvious with the MIROC85 scenario which projects temperatures similar to that of CSIRO85 but also projects an increase in precipitation in all seasons. Snow pack dynamics were likely a contributing mechanism to the differential effect of climate change at different elevations (Figure 4).

The detail underlying the fire season severity statistics is the probability distributions of FDC (Figure 8 and S5). These show many days of the snow free period are in Class 1 or 2 even for low elevation sites

and reflect the warm spring temperatures of MPI45, MIROC85 and CanESM85 (Table 4). Warm summer temperatures and low precipitation for the CanESM85 and CSIRO85 result in a greater amount of time in FDC class 4 and 5 (Figure 8). As expected, conditions get more severe for the CanESM85 and CSIRO85 scenarios in the 2080s (Figure S6).

As expected, the seasonal severity rating (SSR) increases with a decrease in elevation for the historic climate and increases at all elevations under future conditions with the CanESM85 and CSIRO85 scenarios giving the largest increase (Table 8). Extreme years have the SSR 10 to 20% greater than the mean. The CNRM45, MPI45 and MIROC85 show minimal change in the 2080s from the 2050s while the CanESM85 and CSIRO85 scenarios produce an approximately 20% increase in the mean SSR.

4. Discussion

The results quantify the change in fire weather metrics over an elevation gradient and a wide range of possible future climates. Fire risks decrease substantially with increasing elevation historically and are projected to behave similarly in the future. This decrease with elevation is in large part because of the substantial snow pack and colder temperatures at higher elevations. However, fire risks are projected to increase under a changing climate due to shifts of the frequency distributions of summer dry periods towards longer spans and increasing temperatures (Table 4).

The relationship of fire season length with elevation is not well quantified in the literature, likely because wildfire studies are typically done over large areas often with subdued topography. Dupire et al. (2107) showed differential response to changes in fire weather in high and low elevations of the French Alps. A study of Mediterranean forests showed that fire season length decreased with increasing elevation at a rate of -34 to -0.7 with a median of -6 days 100 m⁻¹ (Moriondo et al. 2006). The median is similar to the rate for the restricted activity season historically in this study. A large-scale study

estimated Potential Spread Days ($\text{FWI} \geq 19$ and $\text{DMC} \geq 20$) for the region that includes our study area as 36.5 to 63 days per year historically (Wang et al. 2014). These values are similar to our restricted activity season estimates at the top of the watershed, but much less than our lower elevation results. Their range of Potential Spread Days across all of Canada (6 to 63 days) was smaller than the variability in the restricted activity season length across our elevation transect. Another study of BC and Alberta reported approximately 75 to 90 spread days in 1990-2000, and 120-140 days in 2050-60 decade for the area including the Penticton Creek watershed (obtained from map based on an ensemble of scenarios in Jain et al. 2020). Compared to our results their values are similar to the restricted activity season at lower elevations but higher than we found at the mid or high elevation points. This clearly illustrates the need for detailed topographic integration in fire studies to meet the needs of local planners in areas with moderate to large changes in elevation.

Fire season length is projected to increase due to climate change. For a landscape near to our study area, Nitschke and Innes (2008) project an increase in 17 days, mostly in the spring, by the 2050s. Compared to our FFMC-based fire season, their change is substantially smaller than our result. However, their estimate is likely an average of all elevations (430 to 1492 m) because there was no snow melt model and FWI calculations were started on January first of each year (C. Nitschke pers. comm.). In contrast, climate change effects on all fire season indicators varied with elevation in our results. Again, this comparison highlights the impact of elevation on fire weather and the power of detailed climate and snow modelling.

Like fire season length, the inverse relationship of probability of fire season severity to elevation is not well defined in literature. Moriondo et al. (2006) describe current and future projected FWI-based severity indices decreasing with elevation class and show that elevations from 0 to 1200 m were the most affected by climate change. Comparing our SSR values to those from Haughian et al. (2012), for the

Penticton Airport, our results range from similar to higher; although comparing the mean severity ratings is complicated by the different historic years and future climate scenarios. There is greater uncertainty because of the range of future scenarios we have used. Another study in this part of BC projected increasing seasonal severity rating of 95% for June, July and August by 2100 (Nitschke and Innes 2008). For comparison, our study found increases in seasonal severity rating by 2080s ranged from $32\% \pm 27\%$ at the low elevation point to $45\% \pm 39\%$ at the high elevation point averaged across climate scenarios, underscoring the uncertainty of future climates.

A partial explanation for the differential climate change effects at low and high elevations is due to snow pack dynamics. An increase in the warming of the air increases the length of the snow free season (Figure 3, Table 7). The main reasons for this are that the snow pack starts to melt sooner and form later in the year (Figure 4), and more of the winter precipitation falls as rain rather than snow (Gergel et al. 2017; Rasouli et al. 2014). Consequently, the increased winter precipitation in the scenarios is not sufficient to compensate for the increase in temperature. Snowmelt occurs when air daily temperature is close to or above 0°C . Lower elevation temperatures are much closer to this threshold than upper elevations under current conditions. Consequently, lower elevations are more sensitive to the 2 to 4°C warming of the scenarios than upper elevations. Not only will melt start sooner at the lower elevations they may also experience melt though the winter resulting in a shallow pack and sooner melt out in the spring. Gergel et al. (2017) report a similar sensitivity to temperature change between warmer coastal and cooler interior environments in the western US and the resulting influence on fuel moisture content.

The CFFDRS indices are frequently correlated with area burned, fire frequency, or fire severity, (e.g. Amatulli et al. 2013; Magnussen and Taylor 2012). Our results indicate that there is currently a higher

447 risk of wildfires at lower elevations and an increased risk in the future under climate change. Thus, we
448 expect that area burned, fire frequency, and fire severity will increase into the future.

449 Climate change can lead to vegetation and fuel load changes. A contributing factor to selecting the
450 greater Penticton Creek watershed as our study area was the climate-envelope modelling of Wang et al.
451 (2012) that projects expanded grassland and low-density Douglas-fir habitat at lower to mid elevations.
452 Although higher elevations are projected to remain closed canopy forest, the species may change. We
453 were unable to integrate forest dynamics in our study, but expansion of grasslands and more open
454 forest canopies can shift the fire regime to more frequent, faster moving fires of lower intensity
455 (Forestry Canada Fire Danger Group 1992).

456 The results of this study have relevance well beyond the Penticton Creek watershed and the local
457 community. Similar terrain, ecosystems and human activities can be found in most of the Okanagan
458 Valley and surrounding mountains, an area of approximately 8,000 km² and climate change projections
459 for the whole area are similar to those used here. Similar changes in climate are projected for large parts
460 of the globe and there are approximately 24 million km² of forest land with 4° or greater slope between
461 60° N and 60° S (Farr et al. 2007; Hansen et al. 2013 updated to 2020), further emphasizing the need to
462 consider the scale of analyses to aid management.

463 The implications of more fire are first and foremost risks to human health and security. The Okanagan
464 has a population of 349,500 (Statistics Canada 2017) with many people living at lower elevations in the
465 wildland-urban interface (integrated into or near the forest). Economic losses would occur through
466 impacts on the tourism and forest industries. Furthermore, wildfires are a large source of carbon
467 emissions, potentially creating a feedback to climate change (Kurz et al. 2008). Substantial change in
468 tree cover can increase the risk of floods and drought (Goeking and Tarboton 2020).

469 As with any study, there are limitations to our results. We have assumed that the current
470 environmental gradients of temperature, humidity and precipitation and the wind speed distribution
471 will remain the same under a changing climate. Components of a landscape such as slope, aspect, fuels,
472 land use and management influence the fire risk and there will be sites that may have lower or higher
473 fire risk embedded within the risk profile of the larger terrain. Fuel loads vary within our landscape as it
474 ranges from low elevation savanna to closed canopy sub-alpine forest to semi-open woodland at the top
475 of the watershed (Table 1) and are influenced by harvesting and grazing. Our 33-year calibration period,
476 30-year averages of projected data and 100-year simulations allow us to assess a wide range of future
477 conditions. However, rare events that can have significant consequences, such as happened in BC in
478 2017 (Abbot and Chapman 2018; Kirchmeier-Young et al. 2019), are difficult to simulate. For example,
479 the summer of 2017 at Upper Penticton Creek was the warmest in its 35-year record and consistent with
480 the regional assessment of Kirchmeier-Young et al. (2019). This, combined with by far the driest summer
481 (5 mm of precipitation between mid-June and mid-September) on record at Upper Penticton Creek
482 resulted in fire season severity at high elevations of FDC=5 for 5 days and a summer severity rating of
483 13. This was an extremely low probability event historically, and only slightly more likely under the
484 CSIRO85 2050s climate scenario (Figure 6). This highlights the difficulty of modeling rarely occurring
485 season-long extreme weather events.

486 All climate change projections presented here indicate a significant increase in the risk of wildfires by
487 2050s. Future risk will depend on a combination of how warm it gets and how dry or wet the seasons
488 become. An ensemble of 21 GCM projections in the BCCAQv2 data set project an annual warming by
489 2050s of $2.3 \pm 0.6^\circ\text{C}$ and $3.1 \pm 0.7^\circ\text{C}$ for RCP4.5 and RCP8.5, respectively, compared to current conditions.
490 Projections of precipitation are quite variable and the ensembles do not offer a definitive guide for the
491 future. As shown by this work, impacts of warmer temperatures on fire weather metrics can be
492 somewhat offset by increase in precipitation. Until we have a clearer view of the future greenhouse gas

emissions and the resulting climate, planning needs to consider that the CanESM85 and CSIRO85 projections are plausible for the 2050s. Even if globally we achieve the goals of the Paris Agreement (Rogelj et al. 2016), the future fire climates of the RCP4.5 projections in the 2050s are conditions that managers will have to address. Clearly, the faster society reduces its emissions, the slower the fire risk will increase.

Acknowledgements

We would like to thank Giselle Bramwell, Environment and Climate Change Canada, for providing the Penticton Airport weather data, Eric Meyer, Government of British Columbia, for FWI system start up values, Alan Cantin, Natural Resources Canada, for help and customization of the cffdrs R package, Barbara Zimonick, Zimonick Enterprises for canopy closure measurements and Alexander Bevington, Government of British Columbia for estimating the amount of forestland at or above 4° slope. Furthermore, we acknowledge funding support from the Government of British Columbia and constructive comments from colleagues and reviewers of earlier drafts of this paper.

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664

665 Tables

666 *Table 1 Elevation point descriptions. Three points indicated as low, mid and high are focused on in the*
 667 *results for clarity. Data for all points are in the Supplemental.*

Point	Elevation (m)	Biogeoclimatic subzone*	Predominant landcover type	Average canopy openness (%)
Penticton airport	344	Bunch grass, very dry, hot	Urban	
Transect pt. 1 (Low elevation)	615	Ponderosa pine, very dry, hot	Open canopy <i>Pinus ponderosa</i> and <i>Pseudotsuga menziesii</i>	35
Transect pt. 2	755	Interior Douglas-fir, very dry, hot	Open canopy <i>Pseudotsuga menziesii</i> and <i>Pinus ponderosa</i>	13
Transect pt. 3 (Mid elevation)	1292	Interior Douglas-fir, dry, mild	Open to closed canopy <i>Pseudotsuga menziesii</i> , <i>Pinus ponderosa</i> , and <i>Pinus contorta</i>	19
Transect pt. 4	1436	Montane Spruce, dry, mild	Closed canopy <i>Pinus contorta</i> , <i>Picea engelmannii</i> , <i>Picea</i> hybrids, <i>Abies</i>	10

lasiocarpa,
Pseudotsuga menzesii
and Larix occidentalis

Transect	1700	Englemann	Closed canopy <i>Abies</i>	17
pt. 5 (High elevation)		Spruce-Subalpine Fir, dry, cold	<i>lasiocarpa, Pinus contorta, Picea engelmannii, and Picea hybrids</i>	
Transect	2009	Englemann	Open to closed canopy	
pt. 6		Spruce-Subalpine Fir, dry, cold woodland	<i>Abies lasiocarpa, Picea engelmannii, and Picea hybrids</i>	
P1	1620	Englemann	Closed canopy <i>Abies</i>	17
		Spruce-Subalpine Fir, dry, cold	<i>lasiocarpa, Pinus contorta, Picea engelmannii, and Picea hybrids</i>	

*Lloyd et al. 1990

670 *Table 2 Fire Danger Class (FDC) definitions based on fire weather index and build up index for the region*
 671 *of BC that includes the study area (modified from BC 2005). FDC 3 = Fire watcher required for 1 hour*
 672 *after work ends. FDC 4 = Fire watcher required for 2 hours after work ends; after 3 consecutive days,*
 673 *cease activity between 1 p.m. and sunset. FDC 5 = After 3 consecutive days, cease activity. Complete*
 674 *details on restrictions in Table S1.*

FIRE WEATHER INDEX					
BUILD UP INDEX	0-4	5-16	17-27	28-46	>46
0-50	1	2	2	3	3
51-90	2	2	3	3	4
91-140	2	3	3	4	5
140-200	2	3	4	4	5
>200	3	3	4	4	5

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678 *Table 3 1981-2010 normals of seasonal average air temperature (°C) and precipitation (mm) at Penticton*
679 *Airport and Upper Penticton Creek (P1). Snow free days at P1 are for 1992-2010.*

	Average temperature (°C)				Total precipitation (mm)				Snow free days
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	
Penticton									
Airport	-0.2	9.3	19.7	9.0	75.5	88.8	104.1	78.7	339
P1	-6.0	1.0	10.9	1.9	187.6	197.8	185.6	185.0	167

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683 *Table 4 Projected changes in seasonal average air temperature (°C) and precipitation (%) from 1981-*684 *2010 normals (Table 3) to 2050s period for the CNRM45, MPI45, MIROC85, CanESM85 and CSIRO85*685 *climate scenarios for the region encompassing the Penticton Creek watershed. Projections for the 2080s*686 *are presented in the Supplemental (Table S2).*

Climate scenario	Average temperature (°C)				Total precipitation (%)				Summer dry period
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	(%)
CNRM45	2.3	1.8	1.6	1.5	2	8	-4	-4	6
MPI45	2.4	2.3	1.7	1.7	5	7	14	11	4
MIROC85	3.8	3.8	3.4	3.9	19	11	9	11	-3
CanESM85	3.8	3.4	5.1	3.4	11	25	-3	12	1
CSIRO85	2.9	2.0	3.9	3.4	4	1	-30	10	22

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Table 5 Fire season length (days per year), days per year in fire danger classes 4 and 5 and seasonal severity rating (SSR) for the P1 weather station and Penticton Airport (Pen A). Data are calculated with measured noon weather data (1997-2016) and calculated from P1 weather data simulated (100 years) with LARS-WG5, equations for calculating noon conditions and lapse rates to apply P1 weather to Penticton Airport. Mean, standard deviation and maximum one-year values are presented.

	P1 Measured	P1 Simulated	Pen A Measured	Pen A Simulated
Fire season length	107 ± 14, 154	111 ± 12, 139	259 ± 17, 294	245 ± 14, 290
FDC 4 & 5	8 ± 12, 43	6 ± 10, 46	62 ± 29, 130	62 ± 22, 139
SSR	4 ± 2, 11	3 ± 1, 6	11 ± 4, 18	11 ± 3, 16

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700 *Table 6 Mean and standard deviation of the fire season length at low medium and high elevation sites*701 *from 100 years of synthetic data for the historical reference period and the CNRM45, MPI45, MIROC85,*702 *CanESM85 and CSIRO85 climate scenarios for the 2050s for 3 elevations along the transect.*

Period	Climate scenario	Elevation		
		Low	Moderate	High
1984-2016	Historic	209 ± 14	135 ± 12	107 ± 12
2050s	CNRM45	241 ± 15	152 ± 12	122 ± 11
	MPI45	243 ± 15	157 ± 13	121 ± 13
	MIROC85	248 ± 12	175 ± 13	135 ± 14
	CanESM85	248 ± 13	168 ± 12	133 ± 12
	CSIRO85	250 ± 15	167 ± 10	136 ± 10

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Table 7 Mean and standard deviation of snow free days at low medium and high elevation sites from 100 years of synthetic data for the historical reference period and for the CNRM45, MPI45, MIROC85, CanESM85 and CSIRO85 climate scenarios in the 2050s. 2080s results are presented in the Supplemental (Table S7).

Period	Climate scenario	Elevation		
		Low	Moderate	High
1984-2016	Historic	263 ± 15	182 ± 12	144 ± 11
2050s	CNRM45	306 ± 16	202 ± 11	162 ± 10
	MPI45	325 ± 12	224 ± 13	169 ± 13
	MIROC85	339 ± 11	254 ± 14	196 ± 14
	CanESM85	330 ± 13	240 ± 16	187 ± 11
	CSIRO85	319 ± 15	221 ± 12	176 ± 10

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713 *Table 8 Mean, standard deviation and maximum summer severity rating at low, mid, and high elevation*714 *sites for the historical reference period and for the CNRM45, MPI45, MIROC85, CanESM85 and CSIRO85*715 *climate scenarios in the 2050s. 2080s results are presented in the Supplemental (Table S8).*

Scenario	Low	Mid	High
Historic	9 ± 2.3, 14	5 ± 1.5, 8	3 ± 1.1, 6
CNRM45	10 ± 2.5, 16	5 ± 1.7, 9	4 ± 1.3, 7
MPI45	10 ± 2.7, 16	5 ± 1.9, 10	4 ± 1.5, 8
MIROC85	10 ± 2.4, 17	5 ± 1.7, 11	3 ± 1.3, 8
CanESM85	12 ± 2.6, 20	6 ± 1.8, 11	4 ± 1.4, 9
CSIRO85	13 ± 2.3, 19	7 ± 1.7, 12	5 ± 1.4, 9

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Figures

Figure 1 Location of the Penticton Creek study area in south-west Canada, showing the points on the elevation transect, P1 weather station (star) and Penticton airport weather station (plane). Study area boundary: Government of BC (2010), digital elevation model: Government of BC (1996), North American political boundaries: Government of Canada (2006), and Vancouver and Penticton city locations, Government of Canada (2013).

Figure 2 LARS-WG5 calculated (100 years) and measured values (1984-2016) at Upper Penticton Creek, P1. Panels A and B show the distribution of daily maximum and minimum air temperature ($^{\circ}\text{C}$) after adjustment using quantile mapping, panel C shows the distribution of monthly maximum 1 day precipitation (mm d^{-1}) and panel D maximum length of a summer dry period (days). LARS-WG5 data in panels C and D are not adjusted.

Figure 3 Daily Build Up Index (BUI) for 50 years of synthetic weather data at high (A), mid (B) and low (C) elevations for the historic climate and the CNRM45, MPI45, MIROC85, CanESM85 and CSIRO85 climate scenarios in the 2050s. Areas in white indicate conditions outside the FWI calculation window (e.g. snow on the ground). BUI class limits are shown in Table 2.

Figure 4 Three-day average distribution of the snow water equivalent of the snowpack for three elevations for the historic climate and the CNRM45, MIROC85 and CSIRO85 climate scenarios in the 2050s. The median, maximum and minimum and 75th and 25th percentiles for the 100-years of daily data are shown.

Figure 5 Influence of elevation on the mean length of the restricted activity season for the historic climate and the CNRM45, MPI45, MIROC85, CanESM85 and CSIRO85 climate scenarios in 2050s (left panel) and the 2080s (right panel). Standard deviation on all points is approximately ± 20 days.

742 *Figure 6 Three-day average distribution of the Fire Weather Index (FWI) for three elevations for the*
743 *historic climate and the CNRM45, MIROC85 and CSIRO85 climate scenarios in the 2050s. The median,*
744 *maximum and minimum and 75th and 25th percentiles for the 100-years of daily data are shown. Dotted*
745 *horizontal lines indicate the thresholds for 4 classes of FWI severity.*

746 *Figure 7 Exceedance probability of fire season severity (days per year in fire danger class 5) at the high*
747 *mid and low elevation points on the transect for the historic climate and the CNRM45, MPI45, MIROC85,*
748 *CanESM85 and CSIRO85 climate scenarios in 2050s (left panel) and 2080s (right panel).*

749 *Figure 8 Daily Fire Danger Class (FDC) probability distributions for the low mid and high elevations for the*
750 *historic climate and the CNRM45, MPI45, MIROC85, CanESM85 and CSIRO85 climate scenarios in 2050s.*
751 *Results for all elevations in 2050s and the 2080s are presented in the Supplemental (Figures S5 and S6).*

Figure 1 Location of the Penticton Creek study area in south-west Canada, showing the points on the elevation transect, P1 weather station (star) and Penticton airport weather station (plane). Study area boundary: Government of BC (2010), digital elevation model: Government of BC (1996), North American political boundaries: Government of Canada (2006), and Vancouver and Penticton city locations, Government of Canada (2013).

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© The Author(s) or their Institution(s)

— Median — Max & Min — 75th & 25th %tile

3-day Average Fire Weather Index

© The Author(s) or their Institution(s)

— Median — Max & Min — 75th & 25th %tile

Exceedence probability

Mid 2050s

Mid 2080s

Low 2050s

Low 2080s

Scenario

- Historic
- - CNRM45
- · MPI45
- · MIROC85
- · CanESM85
- - CSIRO85

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Days per year with FDC=5

Historic CNRM45 MPI45 MIROC85 CanESM85 CSIRO85

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FD Class 1 2 3 4 5