DROUGHT INFLUENCES MIXED-SEVERITY FIRE REGIMES ACROSS TEMPORAL AND SPATIAL SCALES IN THE MONTANE CORDILLERA OF CANADA

by

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Abstract

Understanding historical fire-drought associations, particularly in forests with mixed-severity fire regimes, is a research and fire management priority in western North America. My thesis investigates how drought variation across temporal and spatial scales drove such fire regimes in the Montane Cordillera of Canada. I developed three-interrelated studies written as independent chapters, all of which used crossdated fire-scars to represent historical fire years. The first two studies test fire-drought associations using monthly adaptations of the Drought Code (DC) from Canada's Fire Weather Index System. First, I compared three monthly drought codes during the 20th and 21st centuries for montane forests of southeast British Columbia. Accuracy of monthly DC increased after accounting for overwinter drying, early fire season starts, and effective precipitation. June–August drought codes were significantly associated with historical fires. Variation in fire-season drought influenced fire severity, connecting modern fire-weather indices with historical mixed-severity fire regimes. Second, I investigated how historical drought variation drove mixed-severity fire regimes in the same location by developing a tree-ring proxy reconstruction of summer DC. Comparing summer DC against a local summer Palmer Drought Severity Index provided a nuanced understanding of inter-annual fire-drought associations and moisture content among forest fuels, namely in deep compact organics in the soil and large woody fuels, versus the duff layer. Fire years were associated with coinciding and previous year summer drought; but limited by coinciding and previous year summer wet conditions. Summer moisture conditions during fire years likely influenced ignitions and led to variable combustion of forest fuels. The final study encompassed broader spatial coverage by including 17 fire-history sites across the Montane Cordillera, and by testing historical associations between climate and fire based on years with evidence of fire at multiple sites, i.e., fire synchrony. Fire synchrony was historically common, and associated with droughts at regional and subregional scales based on tree-ring proxy reconstructions of climate. My thesis provides information on drought as a driver of mixed-severity fire regimes across temporal and spatial scales. Ultimately, understanding how drought drove mixed-severity fire regimes across scales, helps fire managers anticipate how these fire regimes are shifting due to climate change.

Lay Summary

My research explores how drought influenced fires over time and space in western Canadian forests. I used weather and climate records, statistical models, tree-ring science, and fire-scar records to understand historical associations between droughts and fire. Using a suite of monthly drought indices, I found the onset, duration and degree of drought during the fire season influenced fire severity in montane forests of southeastern British Columbia. For these same forests, I used two different multi-century tree-ring reconstructions of summer drought, which represent moisture content in different forest fuels. I determined that the persistence and degree of drought influenced fire behaviour. Using networks of drought reconstructions and fire records from multiple sites across Central and Interior BC and western Alberta, I found that fires burning at multiple sites were common and occurred during droughts. Ultimately, my research helps fire managers foresee how future fires can be impacted by climate change.

Preface

Raphaël Chavardès was the main contributor to the identification, design, analyses and writing of this PhD thesis. The thesis was supported throughout by Drs. Lori Daniels, Ze'ev Gedalof, and Bianca Eskelson. Data were contributed by: Dr. Lori Daniels (fire-scar records in Chapters 2–4; tree cores in Chapter 3); Dr. Ze'ev Gedalof and Vesta Mather (scanned tree-core images in Chapter 3); Dr. Emma Watson (annual precipitation reconstructions in Chapter 4); Drs. Emily Heyerdahl and Jill Harvey, Rick Kubian, Gregory Greene, Hélène Marcoux, Alexandra Pogue, Eric Da Silva, Jed Cochrane, John Nesbitt, Theresa Dinh, Wesley Brookes, Olivier Villemaire-Côté, and Raphaël Chavardès (fire-scar records in Chapter 4). Supporting contributions included those by Dr. Paul Pickell (developing the initial R script to calculate the Monthly Drought Code, which Raphaël Chavardès modified and further developed into the adjusted Monthly Drought Code), Dr. Jill Harvey (minor editorial advice in Chapter 4), Dr. Tongli Wang (answering questions regarding daily weather and monthly climate data), Dr. Estelle Arbellay (friendly reviews of Chapters 2 and 3), Kelsey-Copes Gerbitz (friendly review of Chapter 3), Alice Cecile (answering questions on dendrochronological standardization), Nicole Prehn (measuring Douglas-fir tree-ring widths), and Xianda Guo (supporting a preliminary study on climatic variation at two locations across the Canadian Rocky Mountains).

Chapter 2 was published online by the International Journal of Wildland Fire on June 4th, 2019. Raphaël Chavardès generated the research questions and was the main contributor to the research design, analyses and writing of this publication. Dr. Lori Daniels provided the fire-scar data, advised on research approach and provided editorial advice. Dr. Bianca Eskelson helped develop the mixed-model statistical analyses and provided editorial advice. Dr. Paul Pickell co-developed the R script to calculate MDC and provided minor editorial advice.

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List of Abbreviations

adjMDC: adjusted MDC

ARIMA: autoregressive integrated moving average

asl: above sea level

B: average bias

BEA: bivariate event analysis

DC: Drought Code

DC_m: monthly mean DC

IDW: Inverse Distance Weighted

MDC: Monthly Drought Code

PC1: first principle component

$PC1_{PDSI}$: first principle component from summer PDSI reconstructions

$PC1_{PPT}$: first principle component from annual precipitation reconstructions

PCA: principle components analysis

PDSI: Palmer Drought Severity Index

predDC_m: predicted DC_m

RMSE: Root Mean Square Error

SEA: superposed epoch analysis

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Chapter 1: Introduction

1.1 Mega-fires Driven by Climate Change

Large forest fires driven by human-induced climate change have become increasingly difficult to manage (Bowman et al. 2009). Particularly large forest fires >10,000 ha, known as mega-fires, tend to include extreme fire behaviour, which can adversely impact socioeconomic factors (Stephens et al. 2014). For example, following persistent and extremely dry and warm weather that desiccated forest fuels, more than one million hectares burned in interior British Columbia, Canada, during each of the 2017 and 2018 fire seasons (Sankey 2019). These extreme fire-seasons in the region attributed to climate change (Kirchmeier-Young et al. 2019) resulted in high fire management costs, community evacuations, strained physical and mental health for many Canadians, damaged infrastructure, and disruptions to business and industry (Sankey 2019). Although these costs and effects are concerning, less well understood and possibly as important are the impacts that such fires have on ecological systems and the services that they provide.

1.2 Forest Fire Ecology

Ecologically, forest fires burn the vegetation with a range of severities over time and space (Agee 1993). The range of fire severity is the result of interacting drivers that include but are not limited to weather, climate, and fuels (Pausas and Ribeiro 2013). Interactions among the drivers are generally complex, hence it is often preferable to focus research on few drivers to gain an understanding of how these influence temporal and spatial characteristics of fires within a determined timeframe and over a delineated area, i.e., the fire regime (Turner 2010; Falk et al. 2011). Fire regimes are usually described according to the frequency and severity of the dominant fires (Stephens et al. 2013). Traditionally, research on fire regimes has focused on low- and high-severity fire regimes, at opposite sides of the fire-severity spectrum. Low-severity fire regimes have frequent surface fires causing minimal tree mortality and reducing surface fuels, hence the name stand-maintaining regimes (Halofsky et al. 2011). Conversely, high-severity fire regimes have infrequent crown fires causing high tree mortality and significantly reducing surface and canopy fuels, hence the name stand-replacing regimes (Halofsky et al. 2011).

1.3 Mixed-severity Fire Regimes

Among fire regimes, those of mixed severity were most recently identified and are thus the least well understood (Perry et al. 2011). Mixed-severity fire regimes are defined by successive fires that burn at one location with a range of severities over time, and by fires that burn with a range of severities across space either simultaneously or through time (Halofsky et al. 2011). These regimes include combinations of low-severity surface fires and higher-severity crown fires (Daniels et al. 2017). Mixed-severity fire regimes have been described in many forests of western North America (e.g., Hessburg et al. 2019), eastern North America (e.g., Bergeron et al. 2004; Drobyshev et al. 2011, 2012; Xu et al. 2018), western South America (e.g., González et al. 2005, 2010; Veblen et al. 2009; Holz and Veblen 2011; Cóbar-Carranza et al. 2014), and northern Europe (e.g., Lampainen et al. 2004; Kuuluvainen 2009). However, research on their drivers remains limited relative to that of low- and high-severity fire regimes (Halofsky et al. 2011). Further research investigating drivers of mixed-severity fire regimes, for example by focusing on how climate, and more specifically drought, i.e., persistent warm and dry weather, influenced these fire regimes, can provide fire managers with baseline information that would help assess current and future characteristics of mixed-severity fire regimes.

1.4 Fire-drought Associations

To test how drought influenced mixed-severity fire regimes, one can test associations between fire and drought. Fire-drought associations have been investigated in western North America, yet most have focused their efforts in the western United States (e.g., Westerling et al. 2006; Heyerdahl et al. 2008a; Littell et al. 2009; Trouet et al. 2010). To test fire-drought associations, distinct metrics and indices are commonly used (Littell et al. 2016). Most of these are related to temperature and precipitation, two climate variables which provide an indication of drought (Littell et al. 2016). Specifically, higher temperatures and lower to no precipitation increase the degree of drought (Heim 2002). Drought in turn decreases moisture content in forest fuels making them more susceptible to fire ignition, spread and combustion (Van Wagner 1987; Macias Fauria et al. 2011). Testing fire-drought associations using metrics and indices that were designed to account for changes in temperature, precipitation, and moisture content in forest soils and fuels across different temporal scales (e.g., monthly to interannual) and spatial scales (e.g., landscape to regional) can enhance the understanding of potential fire behaviour in mixed-severity fire regimes.

1.5 Overarching Hypothesis and Research Questions

Our current understanding of how drought influences mixed-severity fire regimes over time and space remains insufficient. Improved understanding can provide fire managers with baseline information that can support assessments of current and future characteristics of fires that burn at a range of severities. For my thesis research, I conducted three interrelated studies written as distinct chapters, to investigate drought as a driver of mixed-severity fire regimes at different temporal and spatial scales in the Montane Cordillera of Canada (Figure 1.1.). In the first study (Chapter 2), I use a suite of monthly drought indices and test fire-drought associations in montane forests of southeastern British Columbia to answer two questions: 1) How do monthly derivatives of the Drought Code differ over the fire? 2) How do fire-drought associations differ among these monthly derivatives? In the second study (Chapter 3), I test fire-drought associations in these same montane forests using two summer drought reconstructions, which represent moisture content in different the duff layer versus deep organics in the soil and large woody fuels. For this second study, I address two questions: 1) How related are summer Drought Code and summer Palmer Drought Severity Index reconstructions? 2) How do fire-drought associations differ between these reconstructions? The third study (Chapter 4) broadens its spatial scope by testing fire-drought associations in low- and mid-elevation forests across multiple locations in the Montane Cordillera. I use three summer and annual drought reconstructions to test associations between droughts and years with fires at multiple locations, i.e., fire synchrony. For this third study, I pose two questions: 1) How frequent was fire synchrony in the Montane Cordillera between 1746 and 1945? 2) What climate conditions were associated with such events at regional and subregional scales? Chapter 5 summarizes my main findings and explains the contributions of my thesis to research on drivers of mixed-severity fire regimes. I provide management implications and identify four directions for future research.

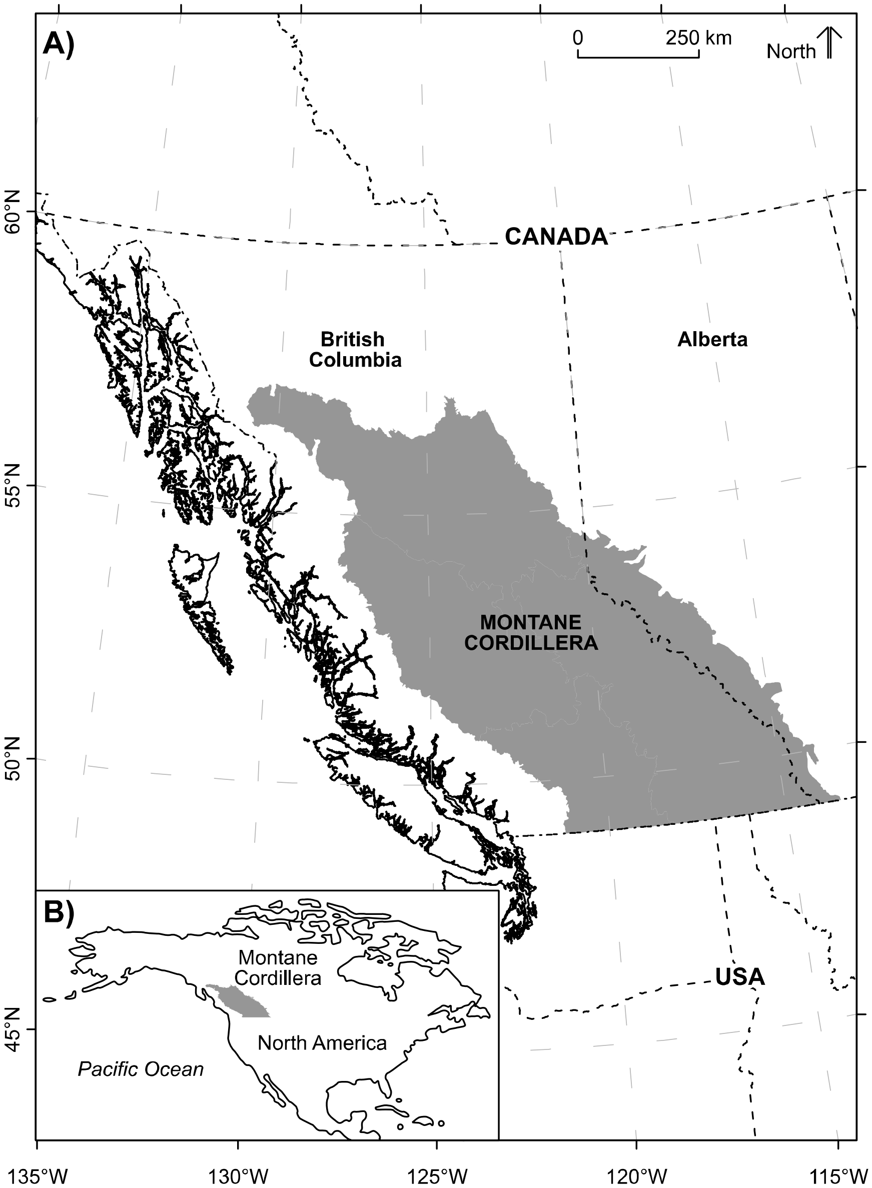

Figure 1.1 (A) Montane Cordillera of Canada in (B) western North America.

Chapter 2: Monthly adaptations of the Drought Code reveal nuanced fire-drought associations in montane forests with a mixed-severity fire regime

2.1 Introduction

Globally, forests are facing increased pressures due to climate change, especially during drought (Choat et al. 2012; Sommerfeld et al. 2018). Droughts, caused by persistent warm and dry weather, directly affect tree health and survival by lowering available moisture (Van Mantgem et al. 2009; Allen et al. 2010, 2015), and indirectly by influencing climate-mediated disturbances such as fire (Daniels et al. 2011; Moritz et al. 2014). To date, few studies have compared drought conditions between recent and historical fires in western Canadian montane forests (elevation up to 1500 m above sea level (asl)) with mixed-severity fire regimes. At watershed to landscape scales, these montane forests include even-aged stands resulting from fairly high-severity fires that last burned one to several centuries ago, intermixed with uneven-aged, mixed-conifer, structurally diverse stands (Marcoux et al. 2015; Daniels et al. 2017). The latter stands commonly include trees with single and multiple fire scars, and historical reconstructions using fire scars and forest demography reveal these stands burned at low- to moderate-severity once every 20–60 years, on average (Marcoux et al. 2013, 2015; Chavardès et al. 2016; Rogeau et al. 2016). Some montane forests in southeastern British Columbia have rich fire-scar records that extend throughout the 20th century (Cochrane 2007; Daniels et al. 2011). Testing how these fire-scar records are associated with drought over the instrumental record, can provide novel insights on mixed-severity fire regimes and influences of variable drought conditions within and among fire seasons.

In Canada, the daily Drought Code (DC) is a fire-weather index related to combustibility of slow-drying forest fuels, including deep compact organic matter and large-diameter woody fuels (Wotton 2009). The Monthly Drought Code (MDC) is a monthly adaptation of DC (Girardin and Wotton 2009). Both DC and MDC integrate cumulative effects of drought over the fire season (Girardin and Wotton 2009). A feature of DC is its capacity to account for fuel moisture depletion between fire seasons, called “overwintering”. In many high-latitude or high-altitude forests, where moisture is retained in frozen soils and insulated by a persistent snowpack, spring snowmelt saturates soils and overwintering effects are low, as is the degree of drought at the start of the fire season (Van Wagner 1987). In forests with dry climates, discontinuous or ephemeral snowpack, and moderately- to well-drained soils, fuels can dry over winter, increasing the degree of drought at the start of the fire season (Lawson and Armitage 2008). Under the latter conditions, a site-specific adjustment is applied to DC to account for overwintering (Van Wagner 1987); however, a comparable adjustment has not been developed for MDC owing to insufficient local soil properties information that can affect overwintering (Girardin and Wotton 2009).

To characterize 20th Century droughts during the fire season (May 1–October 31) across Canada, Girardin and Wotton (2009) developed two monthly adaptations of DC. The monthly mean DC (DC_m) is the average of daily DC values calculated from noon temperature and precipitation observations. MDC is an adaptation of DC_m calculated from the average of daily maximum temperatures and total precipitation over each month (Girardin and Wotton 2009). To calculate DC_m and MDC across a broad spatial network from 1901–2002, Girardin and Wotton (2009) assumed overwintering effects were low and set initial values of DC and MDC to 15 on April 30 of each year (i.e., one day prior to the start of the fire season on May 1). This approach resulted in mean July MDC values from 46–300 across Canada (Girardin and Wotton 2009). In contrast, DC calculated using daily fire-weather station records from southeastern British Columbia revealed higher mean July and August values. For example, fire-weather records from the Palliser (1989–2013), Johnson Lake (1986–2013), and Cranbrook (2001–2013) stations yielded July means of 338, 464, and 499 and August means of 472, 602, and 642, respectively (BC Wildfire Management Branch; unpublished data). I have sought to understand why the MDC values underestimated DC_m during peak fire season in this region.

I hypothesize that three factors explain the discrepancies between MDC and DC_m. The first factor is overwintering and how it affects the initial DC value. Typically, the default DC value at the start of the fire season is set to 15 (Lawson and Armitage 2008). However, overwintering results in DC values >15 at the start of many fire seasons in montane forests of southeastern British Columbia (British Columbia Wildfire Management Branch; unpublished data) and should thus be accounted for when calculating DC at the monthly scale.

The second factor influencing DC and MDC values is the date assigned to the start of the fire season. The specific date varies among locations and years depending on snow melt or temperature. Daily DC calculations begin either the third day after snow has melted in regions with persistent snow cover or the third day that noon temperatures are ≥12°C in regions where snow cover is not consistent (Lawson and Armitage 2008). Typically, May 1 has been the start date when calculating MDC (Girardin and Wotton 2009; Girardin et al. 2009, 2013; Mori and Johnson 2013). However, the median start date of actual fire-weather records from 1981–2010 for the Canadian Southern Cordillera was April 12th (Wang et al. 2015). Moreover, recent evidence points to the fire season starting earlier in many parts of North America owing to climate change (Flannigan et al. 2003; McKenzie et al. 2004; Westerling et al. 2016; Wotton et al. 2017). Therefore, initiating calculations of MDC on April 1 is justified to improve understanding of fire weather throughout the fire season now and in the future.

The way in which precipitation is incorporated into DC and MDC is the third factor. With DC, daily precipitation must exceed 2.8 mm before it is considered to have a wetting effect on deep organic and coarse woody fuels (Girardin and Wotton 2009). For days with precipitation >2.8 mm, DC is calculated using daily effective precipitation that accounts for canopy and surface fuel interception as follows: daily effective precipitation = 0.83 x (daily total precipitation >2.8 mm) - 1.27 mm (Girardin and Wotton 2009). With MDC, monthly precipitation is multiplied by 0.83 to calculate monthly effective precipitation (Girardin and Wotton 2009). Thus, MDC overestimates effective precipitation by including days with precipitation ≤2.8 mm and not subtracting 1.27 mm from each day that precipitation exceeds 2.8 mm. More accurate calculation of MDC on a monthly time scale depends on the frequency of days per month when precipitation exceeds 2.8 mm. In summary, when the subtle effects of overwintering, start date, and effective precipitation are combined, MDC underestimates DC in montane forests of southeastern British Columbia.

In the present study, my goal was to interpret drought conditions associated with historical fires in montane forests of southeastern British Columbia. Using fire-weather data from the Palliser station located in the montane forest, I computed and compared four monthly adaptations of DC (DC_m, MDC, adjusted MDC, and predicted DC_m) to address three questions. How does MDC differ from DC_m over the fire season? Do overwintering and early start of the fire season adjustments improve MDC accuracy relative to DC_m? Does predictive modelling to account for effective precipitation on a monthly scale further improve accuracy? To interpret historical fire-drought relations, I computed three monthly adaptations of the drought code

(MDC, adjusted MDC, and predicted DC_m) from 1901–2013 and tested their associations with a crossdated fire-scar record compiled from 20 sites in montane forests surrounding the Palliser station (Cochrane 2007; Daniels et al. 2011). Combined, these analyses provided a nuanced understanding of fire-drought associations in a montane forest with a mixed-severity fire regime.

2.2 Methods

2.2.1 Study area

The study area encompasses the Palliser fire-weather station (50°29’40”N, 115°39’59”W; 1100 m asl) and 20 fire-history research sites distributed along a 250 km north-south transect representing 255 400 hectares of mid-elevation montane forests (1100–1550 m asl) in southeastern British Columbia, Canada (Figure 2.1). These forests are dominated by interior Douglas-fir (*Pseudotsuga menziesii* var *glauca* (Beissn.) Franco), western larch (*Larix occidentalis* Nutt.), lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and white spruce (*Picea glauca* (Moench) Voss). Climate is continental, and precipitation is influenced by the rainshadow of the Purcell Mountains located west of the study area (Pojar and Meidinger 1991). Climate normals for 1981–2010 at Palliser were calculated using ClimateNA 5.30 (Wang et al. 2016). At Palliser, mean annual temperature was 3.5°C, with means of -7.9°C for January and 15.4°C for July. Mean annual precipitation was 433 mm, with 293 mm (68%) during the fire season from April–October, and 113 mm as snow from November–March. Lightning-ignited forest fires are most common from July–August (Natural Resources Canada 2019).

2.2.2 Daily and monthly fire-weather data

The British Columbia Wildfire Service operates circa 260 hourly fire-weather stations. The Palliser record is the longest and most continuous in montane forests of the study area. I acquired daily fire-weather records for Palliser from May 31, 1989, to September 30, 2013, including temperature (°C) and precipitation (mm, as water equivalent) measured at noon (British Columbia Wildfire Service, unpublished data). These records included the daily Drought Code (DC) values calculated by local authorities.

Acquiring monthly fire-weather data required multiple steps. I added 2.8°C to the daily noon temperature to generate maximum temperature (°C) (after Turner 1972; Van Wagner 1987; Girardin and Wotton 2009). Daily (April 1 to October 31) maximum temperature and DC for each month of the fire season were averaged. Daily precipitation for each month of the year was summed because monthly winter precipitation was also needed to initiate drought code calculations at the beginning of each fire season. I identified missing monthly maximum temperature and precipitation values, and monthly mean DC (DC_m) values using the criteria for the Adjusted and Homogenized Canadian Climate Data (Mekis and Vincent 2011; Vincent et al. 2012). From 1989–2013, 21 (12%) monthly maximum temperatures, and 28 (16%) DC_m values were missing from the beginning (April or May) or end (October) of the fire season. Seventy-six (26%) monthly precipitation values were missing from November–May, mostly during the months between fire seasons. To estimate missing values, I generated records of monthly maximum temperature from April–October, and monthly precipitation from January–December for 1989–2013 using ClimateNA (Wang et al. 2016). I used the ClimateNA-generated records to impute the monthly maximum temperature and precipitation values that were missing from the 1989–2013 Palliser monthly records.

2.2.3 Computing monthly adaptations of the daily Drought Code, 1989–2013

I computed two monthly adaptations of DC over each fire season from 1989–2013 using the Palliser station monthly maximum temperature and precipitation data as follows. Following Girardin and Wotton (2009), MDC was calculated for May–October assuming an initial value of 15 on April 30 in each year (Appendix A). Adjusted MDC (adjMDC) accounted for overwintering and an earlier start to the fire season. From an initial DC value of 195.7 measured on May 31, 1989, adjMDC was calculated for June–October of 1989. From 1990 to 2013, adjMDC was calculated from April–October with the April starting value accounting for overwinter drying between each fire season adapted to the monthly scale.

2.2.4 Predictive model of the monthly mean Drought Code, 1989–2013

I developed a linear mixed-effects model to predict DC_m from adjMDC:

$$\mathbf{Y}_i = \mathbf{X}_i\boldsymbol{\beta} + \mathbf{Z}_i\mathbf{b}_i + \boldsymbol{\varepsilon}_i$$

where i = month (April, May, …, October) or group of months (early fire season: April–May, mid–late fire season: June–October), $\mathbf{Y}_i$ is a column vector of length n_i of DC_m observations for each group i, $\mathbf{X}_i$ and $\mathbf{Z}_i$ are design matrices of dimension n_i x 2 containing adjMDC values as predictor variables, $\boldsymbol{\beta}$ and $\mathbf{b}_i$ are vectors of fixed- and random-effect coefficients, respectively, and $\boldsymbol{\varepsilon}_i \sim \mathbf{N}_{n_i}(\mathbf{0}, \boldsymbol{\sigma}^2_{\boldsymbol{\varepsilon}_i})$ is a column vector of length n_i of the errors for observations in i with covariance matrix $\boldsymbol{\sigma}^2_{\boldsymbol{\varepsilon}_i}$. During model development, I tested whether it was justified to include (a) random effects (intercepts and slopes) for each month versus a random effect for each group of months, and (b) AR(1) correlation and/or unequal variance structure to account for autocorrelation and heteroscedasticity, respectively. Model selection was based on minimizing

Akaike's information criterion, likelihood ratio tests and model simplicity (Bolker et al. 2009). To assess the fit of my model, I calculated for each month, and group of months, average bias (B) and root mean squared error (RMSE) using leave-one-out cross validation.

2.2.5 Comparing monthly adaptations of the daily Drought Code, 1989–2013

To assess the accuracy of MDC, adjMDC or predicted DC_m ($predDC_m$) relative to DC_m from 1989–2013, I used boxplots with Mann-Whitney rank sum tests and calculated Pearson product moment correlations (Gorvine et al. 2018). To evaluate discrepancies among these drought codes, I used daily precipitation records for Palliser to calculate the percentage of days per month when precipitation was 0 mm, >0 but ≤2.8 mm, and >2.8 mm. Monthly precipitation records missing >5 days or >3 consecutive days were excluded from this analysis (Mekis and Vincent 2011). I calculated effective precipitation during a given month in two ways: (1) summing all daily precipitation values and multiplying their total by 0.83, i.e., monthly effective precipitation; and (2) summing only the daily precipitation values >2.8 mm, multiplying their total by 0.83, and then subtracting 1.27 mm per day that precipitation was >2.8 mm, i.e., daily effective precipitation summed over the month (Girardin and Wotton 2009). Overestimation of effective precipitation during a given month was the relative difference between monthly effective precipitation and daily effective precipitation summed over the month.

2.2.6 Comparing monthly adaptations of the daily Drought Code, 1901–2013

I used the ClimateNA-generated monthly data to calculate MDC from May−October, 1901−2013, using an initial value of 15 on April 30 of each year (Girardin and Wotton 2009). adjMDC was calculated continuously from April 1901 to October 2013 from an initial value of

15 on March 31, 1901 (Canadian Forestry Service 1984). I applied the linear mixed-effects model coefficients to predict DC_m over the same period as adjMDC.

To compare MDC, adjMDC, and predDC_m from 1901–2013, I categorized their values as low (<200), intermediate (≥200 and <400), or high (≥400) according to thresholds corresponding to relative moisture content in compact organics and coarse woody fuels (after Bergeron et al. 2010). When drought codes are low, fuels are fairly wet and least likely to combust, whereas high values indicate dry combustible fuels, which is supported by de Groot et al.'s (2009) findings that more forest floor fuels are consumed by fire as drought codes increase. To assess the onset of drought during each fire season, I compared the first month in each year when values were ≥200 for each code. To assess the magnitude of fire season droughts, I compared the proportion of months categorized as low, intermediate, and high during all fire seasons from 1901–2013. For each pair of monthly adaptations of DC, I derived two-way contingency tables of observed values from which I calculated expected values and assessed differences using chi-square goodness-of-fit tests (Whitlock and Schluter 2015).

2.2.7 Fire-drought associations, 1901–2013

I combined crossdated fire-scar records from 20 montane forest sites in the study area (Cochrane 2007; Daniels et al. 2011) and identified 17 years from 1901–2013 in which ≥2 trees were scarred (hereafter, "fire years"). I tested fire-drought associations in two ways. First, I used Superposed Epoch Analysis in the Fire History Analysis and Exploration System (Brewer et al. 2015), to test for associations between fire occurrence and the following monthly adaptations of DC: MDC, adjMDC, and predDC_m. I compared the mean value of each monthly adaptation during fire years relative to bootstrapped values from a Monte Carlo simulation of 1000 randomly selected years that provided 95.0, 99.0 and 99.9% confidence intervals (Sutherland et al. 2017). Second, to determine if MDC, adjMDC, and predDC_m represented the magnitude of droughts during fire years similarly, I compared the proportion of months categorized as low, intermediate, and high during the 17 fire years. For each pair of monthly adaptations, I derived two-way contingency tables of observed values from which we calculated expected values and assessed differences using chi-square goodness-of-fit tests (Whitlock and Schluter 2015).

2.3 Results

2.3.1 Model predicting DC_m

The graph of DC_m versus adjMDC revealed distinct slopes for two groups of months (group 1: April–May and group 2: June–October) (Figure 2.2). As a result, the final linear mixed effects model included random slopes by group of months representing the early fire season (April–May) and mid–late fire season (June–October). Among tested models, inclusion of an AR(1) correlation structure in the model resulted in the lowest AIC value. By definition of the fitted model, predictions by group of months were unbiased (Table 2.1). Across months, range of bias (B) was smallest over August and September ($-2 \leq B \leq 4$), largest over April and October ($-22 \leq B \leq 30$) and intermediate from May–July ($-15 \leq B \leq 7$). Root mean squared error (RMSE) across groups of months was greater over the early fire season (RMSE = 52) than mid–late fire season (RMSE = 43). Across months, RMSE was lowest from July–September ($36 \leq$ RMSE ≤ 42), greatest from April–June ($51 \leq$ RMSE ≤ 52) and intermediate over October (RMSE = 46).

2.3.2 Improved predictions of DC_m

Of the monthly adaptations of DC, MDC was least accurate and predDC_m was the most accurate representation of DC_m (Figure 2.3). Based on Mann-Whitney rank sum tests, medians of MDC were significantly lower than those for DC_m ($p < 0.001$); MDC ranges were also less than those for DC_m. Over May, the correlation between MDC and DC_m was weak and not significant ($r^2 = 0.29$, $p = 0.209$), but correlations were strong and significant ($r^2 \geq 0.78$, $p < 0.001$) from June−September. When comparing adjMDC with DC_m, medians were similar early in the fire season ($p = 0.841$ and $p = 0.091$ in April and May, respectively), but adjMDC values were significantly lower than DC_m for June−September ($p \leq 0.011$ for all months). Ranges of MDC were also less than those of DC_m later in the fire season. predDC_m and DC_m had similar medians and ranges for all months; medians did not differ significantly ($p \geq 0.351$). Correlations of adjMDC and predDC_m with DC_m were strong and significant ($r^2 \geq 0.87$, $p \leq 0.027$) for all months.

At Palliser fire-weather station, monthly precipitation was greatest in June, increased from April–June and decreased from June–October (Table 2.2). Precipitation was >2.8 mm and sufficed to have a wetting effect on deep organics and coarse woody fuels thus altering daily DC on 9–25% of days per month. Monthly effective precipitation averaged 19–64 mm, whereas it averaged 9–47 mm when calculated from daily effective precipitation summed over the month. Overestimation of effective precipitation during a given month ranged from 36–117% and was greatest in October and least in June.

2.3.3 Differences in monthly adaptations of the daily Drought Code, 1901–2013

The degree, onset, and duration of droughts during the fire season differed among monthly adaptations of DC (Figure 2.4). MDC indicated the least amount of drought conducive to fire. Over 113-years from 1901–2013, MDC was ≥200 in 4±1 months per year (mean ± s.d.; range 0–5). MDC first reached intermediate values in June in 3 years and July in 75 years. High values occurred in 42 years and persisted 2±1 months (range 1−3), for a total of 87 (13%) of 678 months assessed (i.e., May−October over 113 years). The adjMDC also was ≥200 in 4±1 months per year, with a wider range of 0−7 months. Compared to MDC, adjMDC reached intermediate values earlier: April or May in 11 years, June in 15 years, and July in 60 years. High values of adjMDC occurred in 47 years and persisted 2±1 months (range 1−4) for a total of 103 (13%) of the 791 months assessed (i.e., April−October over 113 years). Relative to MDC and adjMDC, $predDC_m$ indicated conditions more conducive to fire, with droughts that started earlier and were more pronounced. The $predDC_m$ was ≥200 in 5±1 months (range 3−7) per year. It reached intermediate values in April or May in 22 years, June in 61 years and July in 24 years. High $predDC_m$ values occurred in 95 years and persisted 3±1 months (range 1−6) for a total of 285 (36%) of the 791 months assessed.

Chi-square goodness-of-fit tests confirmed MDC and adjMDC had significantly fewer months with intermediate and high values and more months with low values than expected relative to $predDC_m$ from 1901–2013 ($\chi^2 = 104.6$, $p < 0.001$ and $\chi^2 = 115.8$, $p < 0.001$, respectively). MDC and adjMDC did not differ significantly across the proportion of months categorized as low, intermediate, and high from 1901–2013 ($\chi^2 = 0.7$, $p = 0.703$).

2.3.4 Fire-drought associations

The monthly adaptations of DC revealed fire years were associated with a higher degree of drought conditions over multiple months of the fire season; however, of these associations, the strongest were for adjMDC and $predDC_m$ (Figure 2.5). Fire years were associated with high MDC values in mid–late fire season, with the strongest and most significant associations in July and August ($p < 0.01$), followed by June ($p < 0.05$). For adjMDC, associations were strongest from April–August ($p < 0.001$), followed by September ($p < 0.05$). Associations with $predDC_m$ were strongest in June and July ($p < 0.001$), followed by April, May and August ($p < 0.01$), and September ($p < 0.05$).

The degree, onset, and duration of droughts during the 17 fire years varied among MDC, adjMDC, and $predDC_m$ (Figure 2.6). In 16 fire years, MDC values were intermediate or high for 3−5 months; MDC remained low throughout the 1903 fire season. MDC values were low in May and reached intermediate values in June, July, or August during 2, 13, and 1 fire years, respectively. High MDC values occurred relatively late in the fire season in August, September, and October during 5, 11, and 8 fire years, respectively. Intermediate and high values of adjMDC persisted 3−7 months in all fire years, except in 1903 when adjMDC remained low. Compared to MDC, intermediate and high values of adjMDC were reached earlier during fire years. Values were intermediate in April and May in 3 and 4 fire years, respectively; high values were reached in July, August, and October in 2, 8 and 9 fire years, respectively. Compared to MDC and adjMDC, $predDC_m$ had the most intermediate values, starting as early as April (n = 5). Intermediate or high values persisted 4−7 months of each fire year. High values were reached as early as May and June in 1 and 3 fire years, respectively, and occurred in July, August, September, and October during 10, 16, 14, and 13 fire years, respectively.

Chi-square goodness-of-fit tests confirmed MDC and adjMDC had significantly fewer months with intermediate and high values and more months with low values than expected relative to predDC$_m$ during the 17 fire years (χ^2 = 16.4 p <0.001 and χ^2 = 14.7, p <0.001, respectively). MDC and adjMDC did not differ significantly across the proportion of months categorized as low, intermediate, and high during fire years (χ^2 = 0.2, p = 0.898).

2.4 Discussion

2.4.1 adjMDC improved drought estimation in montane forests of southeastern British Columbia

In the Canadian Fire Weather Index System, the daily Drought Code (DC) is used alongside other fire-weather indices to forecast fire danger, potential fire behaviour (Stocks et al. 1989; Taylor and Alexander 2006), and the effort required to extinguish a fire (Terrier et al. 2013). I aimed to determine whether the monthly mean Drought Code (DC$_m$) was well represented by the Monthly Drought Code (MDC), an index commonly applied in boreal forests (Girardin et al. 2009; Bergeron et al. 2010; Drobyshev et al. 2013; Marchal et al. 2017), and adjMDC that accounted for overwinter drying and an earlier start to the fire season. For the Palliser station in montane forests of southeastern British Columbia, I found lower MDC values during April–May and lower MDC and adjMDC values during June–September relative to DC$_m$. I found that MDC underestimated the degree of drought throughout the fire season in the dry montane forests of southeastern British Columbia. Therefore, I raise caution when interpreting MDC values in other montane forests where overwinter drying is common. Because adjMDC included the adjustment typically applied to daily DC calculations in dry western and some northern forests of Canada (Van Wagner 1987; Lawson and Armitage 2008), ranges of adjMDC and DC_m were similar during the early fire season. Nevertheless, adjMDC like MDC, underestimated DC_m from June−September, when fires commonly burn in montane forests of British Columbia (Natural Resources Canada 2019).

Assessment of the Palliser station daily precipitation records illustrates subtle effects of daily precipitation on the monthly adaptations of DC. Over 25 fire seasons from 1989−2013, precipitation exceeded 2.8 mm, effectively wetting deep organic fuels and coarse wood, only 9−25% of days per month. Monthly effective precipitation used to calculate MDC and adjMDC exceeded daily effective precipitation summed over the month used to calculate DC_m by 36−117% per month, explaining the systematic underestimates of these two drought adaptations relative to DC_m. April and May effective precipitation overestimates averaged 67 and 51%, respectively. Evidently, accounting for overwinter drying countered the effect of overestimating April and May effective precipitation because adjMDC was more accurate than MDC early in the fire season. June was wettest and most variable, with the lowest effective precipitation overestimate (36%). In July, August and September, overestimates ranged from 50−53%. These inaccuracies are cumulative; consequently, differences between MDC and adjMDC relative to DC_m increased through the fire season.

2.4.2 Implications of improved drought predictions for montane forests of southeastern British Columbia

Combined effects of the subtle factors overestimating monthly effective precipitation and underestimating DC_m warranted the development of a predictive regression model for the Palliser station. The predDC_m more accurately represented DC_m than MDC or adjMDC and improved understanding of the onset and duration of droughts during fire years from 1901–2013. The shift from low to intermediate drought codes provides critical information about increasing fire danger and risk of a sustained ignition. The predDC_m revealed many years reaching intermediate values early in the fire season and improved detection of early-season drought making deep organic and coarse woody fuels more conducive to combustion. Given evidence of an earlier start to the fire season in recent decades (Jolly et al. 2015; Westerling et al. 2016; Wotton et al. 2017) with the trend expected to continue over the 21st century (Flannigan et al. 2013), my approach provides predictions of DC_m that allow a more accurate understanding of how drought conditions influenced the onset of historical fire years in montane forests of southeastern British Columbia. In turn, these historical drought conditions can be compared to modern observations and future predictions to assess potential changes in the onset and degree of drought during each fire season over time.

Droughts indicated by high predDC_m values at Palliser were common and of adequate magnitude and duration to sustain fire, had an ignition occurred. Specifically, predDC_m values for July and August from 1901–2013 averaged 345 and 452, respectively. These values are greater than mean July MDC values ≤300 reported across Canada from 1901–2002 (Girardin and Wotton 2009) and mean August MDC values <200 reported for the Montane Cordillera from 1901–2009 (Mori and Johnson 2013). These two previous studies suggested the likelihood of sustained fires remained intermediate or low even during peak fire season. In contrast, predDC_m calculated at a finer spatial scale in southeastern British Columbia indicated more frequent and persistent droughts of greater magnitude during peak fire season that had greater likelihood of sustaining fires over the same period.

2.4.3 Drought variability influenced the historical mixed-severity fire regime

Using crossdated fire-scar records in concert with the monthly adaptations of DC improved understanding of the range of variation in droughts that influenced the historical mixed-severity fire regime in the study area. Past fire-drought analyses assessed documentary records of area burned or number of large wildfires against MDC (Girardin et al. 2009; Bergeron et al. 2010; Girardin et al. 2013; Mori and Johnson 2013); however, this approach may be affected by documented fire suppression effects in British Columbia. Over the past 40 years, 92% of fires in British Columbia were suppressed before exceeding 4 ha in size (British Columbia Wildfire Management Branch 2012). As low-intensity fires are fairly easy to suppress (Arienti et al. 2006), fire-drought analyses based on modern area-burned records from British Columbia represent high-intensity fires that tend to burn under extreme fire-weather conditions (Johnson et al. 2001). Focusing on the subset of large intense fires that exceeded suppression capability biases interpretations of how drought variability influenced historical fire regimes. Using crossdated fire scars partly addressed this limitation. The fire-scar record does not overcome temporal effects of fire suppression. However, fire scars provide evidence of low- and moderate-severity surface fires, although scars can also form on the periphery of high-severity fires (Daniels et al. 2017). Therefore, fire-scar records are suitable for interpreting the range of drought conditions in which historical fires burned in montane forests with mixed-severity fire regimes.

Combining fire-scar records with the monthly adaptations of DC provided novel insights into the duration and magnitude of droughts influencing historical fires. Among the monthly adaptations, adjMDC provided the strongest significant fire-drought associations, particularly during April, May and August. Fire-drought associations were also strong with $predDC_m$, and drought conditions were more accurately represented by $predDC_m$ than adjMDC over the fire season. I found both adjMDC and $predDC_m$ values were predominantly low during the early-fire season, indicating wet and/or cool conditions limited fuel combustibility. Six fire years, 1903, 1905, 1917, 1925, 1938, and 1971, had low and intermediate adjMDC and $predDC_m$ values from April–July. Fires burning under these conditions would have been low in severity; higher-severity fires would have been limited to later in the fire season when drought values increased. In contrast, springs with little precipitation and high temperatures, such as 1906, 1926, 1931, 1937, and 2001, resulted in intermediate to high adjMDC and $predDC_m$ values early in the fire season. As the fire season progressed and drought increased, more combustible fuels became available exacerbating the potential for high-severity fire. Corroborating these interpretations, montane forests of the study area include strong evidence of historical fires of a range of severities, including even-aged tree cohorts that established following moderate- to high-severity fires and uneven-aged forests with abundant fire-scarred trees recording lower-severity fires (Daniels et al. 2011; Marcoux et al. 2013, 2015). My findings provide an opportunity for future research that uses adjMDC and $predDC_m$ alongside fire-scar seasonality to test the hypothesis that early- versus late-season fires differed in severity, depending on the onset and duration of fire-season drought.

2.5 Conclusion

Monthly adaptations of DC provided a nuanced understanding of the variability in drought within and among fire seasons in montane forests of southeastern British Columbia. Adjusting for overwintering and an early start to the fire season improved adjMDC relative to MDC estimates of DC_m, particularly early in the fire season. Regression modelling based on adjMDC accounted for differences between total and effective precipitation, yielding predDC_m values that most accurately reproduced DC_m. Hence, predDC_m most accurately represented the degree, onset, and duration of droughts during fire seasons from 1901–2013. I found numerous and significant associations between fire-scar dates and adjMDC and predDC_m for months throughout the fire season. Both adjMDC and predDC_m showed variability in drought within and among fire seasons influencing historical fires in the study area.

Two monthly adaptations of DC, adjMDC and predDC_m, provide fire scientists and managers with a practical connection between modern drought indices used to determine fire danger and historical droughts that were conducive to fires of a range of severities. Given growing evidence of mixed-severity fire regimes, I recommend continued investigation of these drought codes. Because precipitation varies along elevation gradients and among montane forests, comparative analyses among stations are warranted to determine the degree to which patterns observed at Palliser may be generalized and where they are not applicable.

I acknowledge that calculating predDC_m elsewhere requires daily fire-weather records, a substantive limitation due to spatial and temporal paucity of local records, as originally noted by Girardin and Wotton (2009). In contrast, adjMDC can be calculated for more locations and over broader areas using modelled monthly climate data. However, adjMDC remains less accurate than predDC_m in the mid–late fire season owing to differences in how precipitation is integrated into these two monthly drought indices. I conclude that adjMDC and predDC_m are practical indices of drought conditions conducive to fires of a range of severities and have strong potential to enhance understanding of historical fire-drought relations in forests where overwintering conditions dry fuels between fire seasons.

Table 2.1 Statistics of the linear mixed-effects model to predict the monthly mean Drought Code (DC_m) from the adjusted Monthly Drought Code (adjMDC). Statistics included n_i as the number of observations per month or group of months, B as average bias, and RMSE as root mean square error.

Statistic	Group		Month						
	Apr–May	Jun–Oct	Apr	May	Jun	Jul	Aug	Sep	Oct
n_i	25	118	5	20	25	25	25	25	18
B	1	0	-22	7	-15	-9	4	-2	30
RMSE	52	43	51	52	51	52	36	40	46

Table 2.2 Summary of daily and monthly precipitation at the Palliser fire-weather station during 25 fire seasons including 1989–2013. Monthly precipitation records missing >5 days or >3 consecutive days were excluded. Effective precipitation during a given month was calculated in two ways: (1) by summing all daily precipitation values and multiplying their sum by 0.83, i.e., monthly effective precipitation; and (2) by summing the daily precipitation values that exceeded 2.8 mm, multiplying their sum by 0.83, and then subtracting 1.27 mm per day that precipitation was >2.8 mm, i.e., daily effective precipitation summed over the month. The relative difference between (1) and (2) is the overestimate of effective precipitation that causes the Monthly Drought Code (MDC) and the adjusted MDC (adjMDC) to underestimate the monthly mean Drought Code (DC_m). Numbers in parentheses indicate standard deviations.

Month	Sample size (n)	Daily precipitation (% of days)			Effective precipitation (mm)		Overestimate (%)
		0mm	>0 and ≤2.8mm	>2.8mm	(1)	(2)	
Apr	12	66 (11)	20 (11)	14 (9)	26 (16)	16 (14)	67
May	20	56 (8)	27 (8)	17 (6)	42 (16)	28 (15)	51
Jun	25	47 (12)	28 (10)	25 (10)	64 (32)	47 (29)	36
Jul	25	65 (13)	22 (9)	16 (8)	36 (17)	23 (13)	53
Aug	25	69 (14)	21 (9)	13 (9)	32 (23)	22 (19)	50
Sep	25	68 (15)	19 (10)	13 (8)	28 (17)	19 (13)	52
Oct	18	67 (11)	23 (8)	9 (5)	19 (8)	9 (5)	117

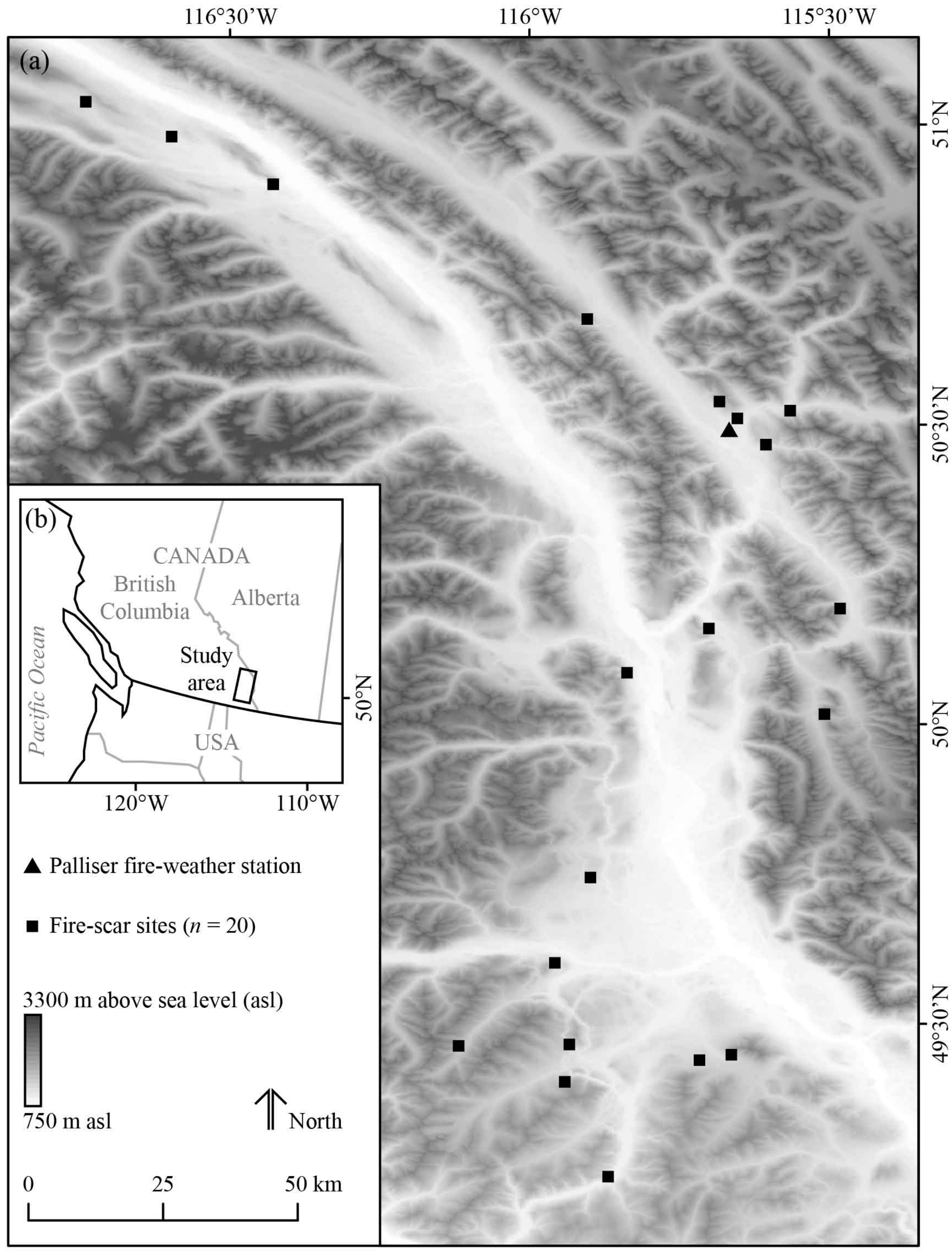

Figure 2.1 (a) Palliser fire-weather station and fire-scar sites within montane forests of (b) southeastern British Columbia, Canada.

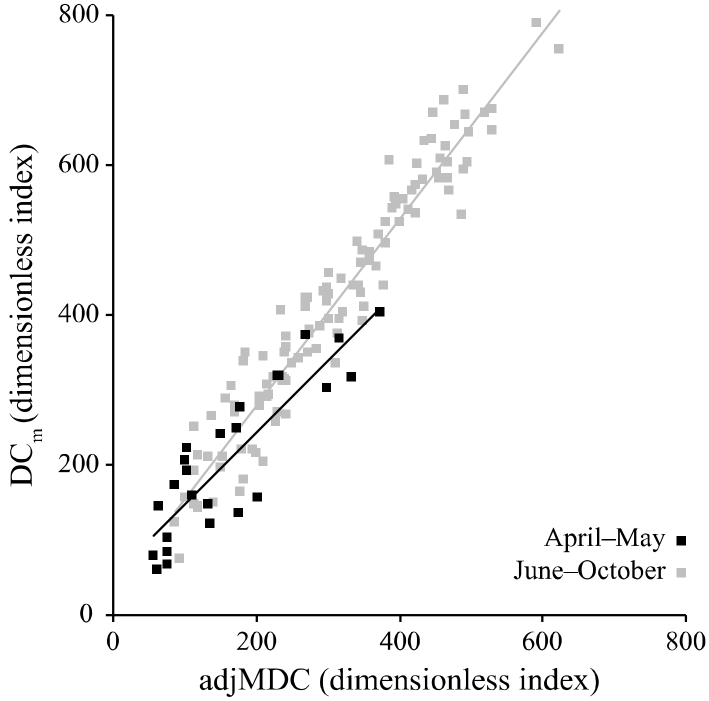

Figure 2.2 Monthly mean Drought Code (DC_m) versus adjusted Monthly Drought Code (adjMDC) including overwintering and an April 1 start of the fire season at the Palliser fire-weather station during 25 fire seasons including 1989–2013.

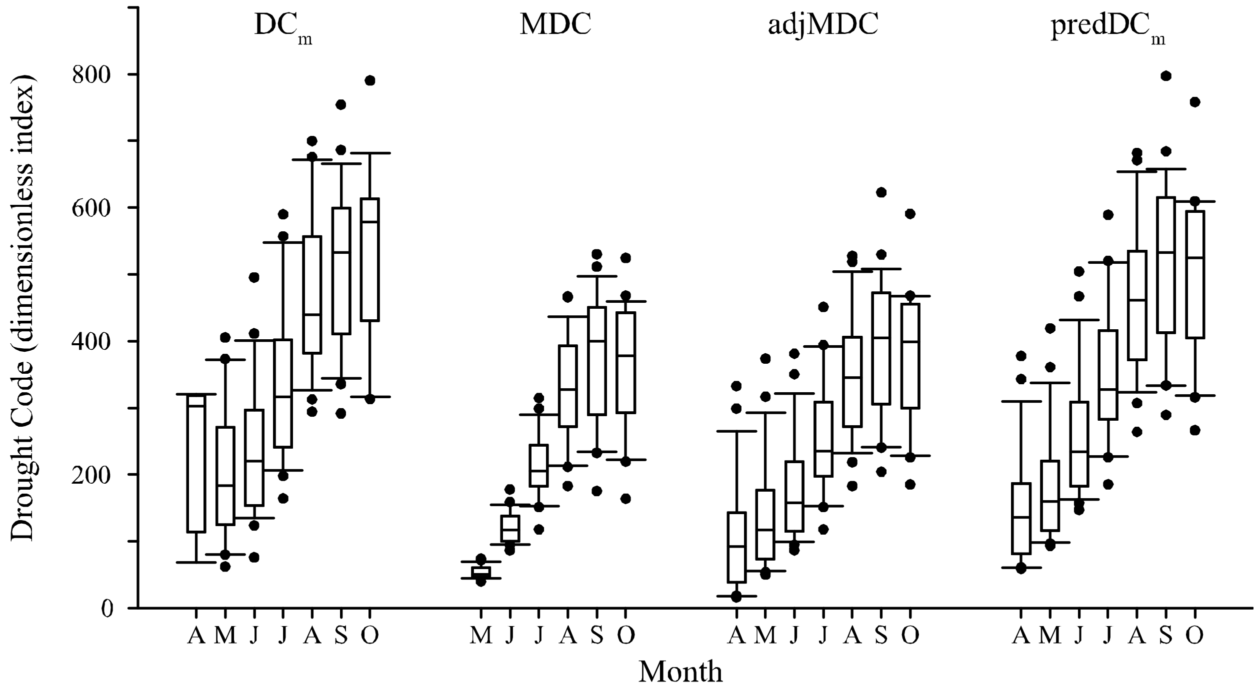

Figure 2.3 Boxplots of the monthly mean Drought Code (DC_m), Monthly Drought Code (MDC), adjusted MDC (adjMDC), and predicted DC_m ($predDC_m$) at the Palliser fire-weather station during 25 fire seasons including 1989–2013. In each boxplot, the horizontal line represents the median; box boundaries are the 25th and 75th percentiles; bars are the 10th and 90th percentiles; and, dots are outliers.

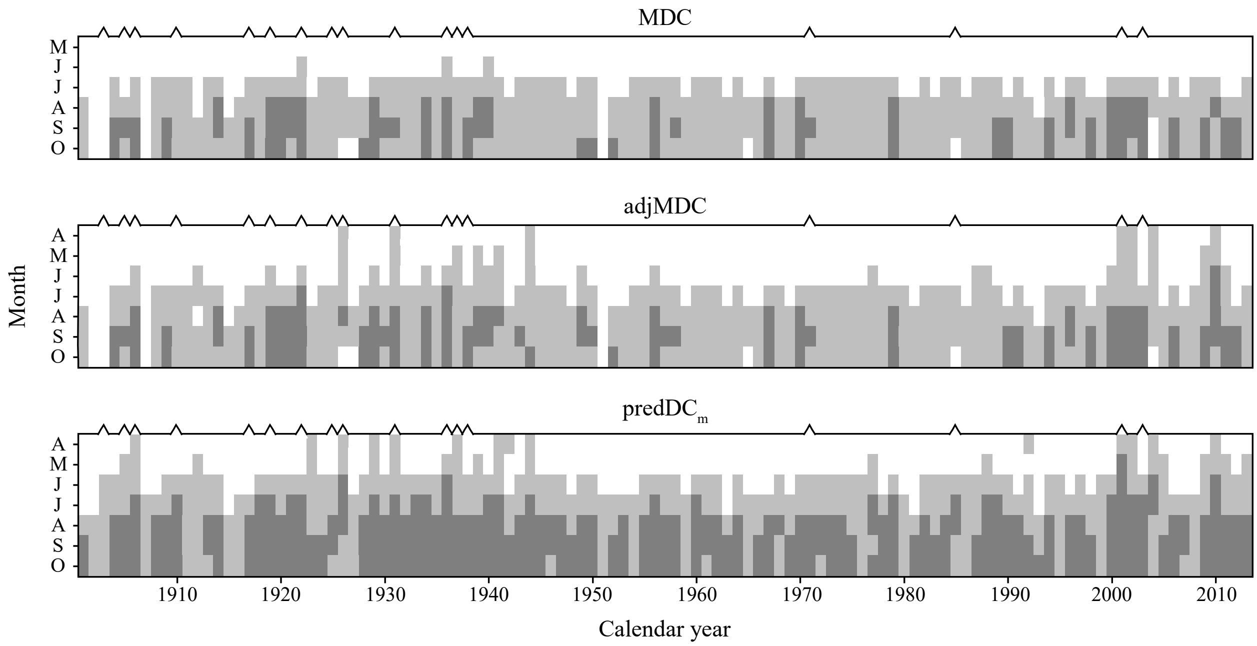

Figure 2.4 Months during each fire season with low (<200; white areas), intermediate (≥200 and <400; light grey areas), and high (≥400; dark grey areas) values of the Monthly Drought Code (MDC), adjusted MDC (adjMDC), and predicted monthly mean Drought Code ($predDC_m$) from 1901–2013 for the Palliser fire-weather station. Peaks at the top of each graphic represent the 17 fire years indicated by fire scars.

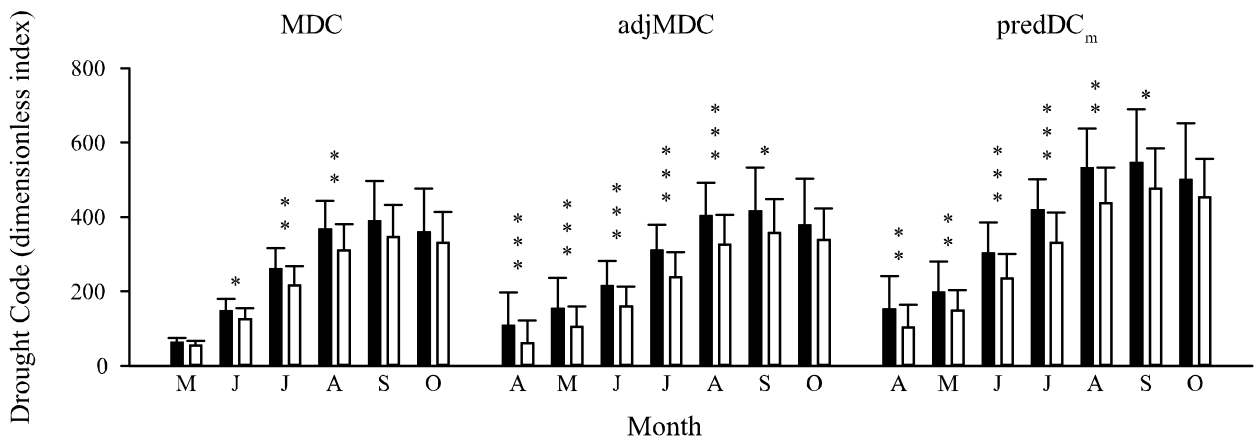

Figure 2.5 Fire-drought associations for the Monthly Drought Code (MDC), adjusted MDC (adjMDC), and predicted monthly mean Drought Code (predDC$_m$) for the Palliser fire-weather station. Black (white) bars represent mean values during fire (non-fire) years. Stars depict significant associations with fire years (1, 2, and 3 stars indicate the 95, 99, and 99.9 % confidence levels, respectively).

Fire year	MDC						adjMDC							$predDC_m$						
	May	Jun	Jul	Aug	Sep	Oct	Apr	May	Jun	Jul	Aug	Sep	Oct	Apr	May	Jun	Jul	Aug	Sep	Oct
1903	64	158	170	141	137	144	14	77	168	177	144	139	146	57	120	247	257	218	211	219
1905	43	82	169	326	403	343	150	168	154	216	365	434	364	194	211	229	305	485	569	484
1906	43	115	258	364	416	407	175	197	218	339	425	459	440	219	241	306	454	557	598	575
1910	77	163	287	371	363	339	32	111	191	308	387	373	347	75	155	274	416	512	495	463
1917	44	96	228	368	413	413	71	81	118	246	382	423	421	114	124	185	340	505	555	552
1919	64	188	337	411	432	427	19	86	207	353	422	440	433	62	129	293	470	554	576	568
1922	76	210	366	459	480	464	74	124	252	402	485	497	476	117	167	348	529	631	645	620
1925	73	163	261	340	306	257	28	111	193	283	356	315	264	70	155	276	385	474	425	362
1926	67	153	275	330	229	168	202	268	309	389	406	268	193	246	312	417	514	534	367	276
1931	65	129	226	367	400	374	217	240	259	316	439	451	410	261	284	357	426	575	590	540
1936	83	201	345	471	522	515	126	199	297	421	530	565	547	169	243	402	553	685	727	706
1937	64	135	203	286	332	305	165	203	241	274	336	368	331	208	247	334	375	450	489	443
1938	51	137	258	377	465	471	21	76	156	273	389	474	477	64	119	232	374	514	617	621
1971	65	138	238	375	424	366	18	84	153	250	384	431	370	60	127	228	345	508	564	491
1985	57	147	300	364	260	165	83	121	198	342	393	275	174	126	165	282	457	518	376	253
2001	73	158	245	413	530	524	332	373	381	391	527	623	590	377	419	504	516	682	797	758
2003	51	127	271	465	511	424	112	100	164	300	490	529	434	155	143	242	406	637	684	569

MDC, adjMDC, and $predDC_m$ values: <200 = [white] ≥200 and <400 = [light grey] ≥400 = [dark grey]

Figure 2.6 Comparison of low (<200), intermediate (≥200 and <400) and high (≥400) Monthly Drought Code (MDC), adjusted MDC (adjMDC), and predicted monthly mean Drought Code ($predDC_m$) values for the Palliser fire-weather station during 17 fire years indicated by fire scars.

Chapter 3: Using complementary drought proxies improves interpretations of fire histories in montane forests of southeastern British Columbia

3.1 Introduction

Drought-driven fire risk is expected to increase over the 21st century across many forests of western North America due to climate change (Stephens et al. 2013; Moritz et al. 2014). As a result of drought intensified by warmer temperatures and lower precipitation (Diffenbaugh et al. 2015), forest fuels have low moisture content making them more susceptible to ignite and burn at higher intensities and consequently with more severe impacts (Littell et al. 2009; Flannigan et al. 2013). Unfortunately, specific drought influences on fuels, including their ignition and combustion, remain insufficiently understood in montane forests of western North America characterized by mixed-severity fire regimes (Halofsky et al. 2011).

Mixed-severity fire regimes are comparatively more complex than low- and high-severity fire regimes (Schoennagel et al. 2004; Halofsky et al. 2011). Low-severity fire regimes are dominated by frequent surface fires that cause minimal tree mortality but reduce surface fuels, whereas high-severity fire regimes are dominated by infrequent crown fires with high tree mortality that significantly reduce surface and crown fuels (Agee 1993). For mixed-severity fire regimes, fires burn with a range of severities across spatial and temporal scales (Schoennagel et al. 2004; Halofsky et al. 2011), resulting in forest stands that are compositionally and structurally diverse (Hessburg et al. 2016; Daniels et al. 2017). Fluctuation in fire severity is caused by interacting top-down drivers including weather and climate, which influence drought, and bottom-up drivers including topography, and vegetation composition and structure (Turner 2010;

Perry et al. 2011). An improved understanding of the interactions between drought and fires by investigating fire-drought associations (see Chapter 2; Chavardès et al. 2019) can assist fire managers in anticipating impacts of climate change in montane forests with mixed-severity fire regimes.

Research on contemporary relationships between fire occurrence and drought have used documentary fire records with instrumental drought records in the 20th and early 21st centuries in western North America (e.g., Westerling et al. 2006; Littell et al. 2016), including western Canada (e.g., Xiao and Zhuang 2007; Meyn et al. 2010a, 2010b). Yet, this period includes advances in fire suppression technologies (Morgan et al. 2008; Flannigan et al. 2009), which can impact fire-drought associations (Williams and Abatzoglou 2016). To address this limitation, multi-century proxy reconstructions of drought based on tree-ring chronologies have been developed (Cook et al. 2004; Girardin et al. 2004a). Such reconstructions are based on climate-growth analyses that test the relationship between specific monthly drought variables over the instrumental period against tree ring-, earlywood-, and/or latewood-width chronologies (Fritts 1976; Watson and Luckman 2002).

In western North America, interior Douglas-fir (*Pseudotsuga menziesii* var *glauca* (Beissn.) Franco) (hereafter "Douglas-fir") radial growth is limited by low moisture availability according to climate-growth analyses (Chen et al. 2010). Within montane forests of western Canada, climate-growth analyses were conducted across multiple Douglas-fir ring-width chronologies (Griesbauer and Green 2010) and earlywood- and latewood-width chronologies (Watson and Luckman 2002). Specifically, Watson and Luckman (2002) found that intra-annual Douglas-fir growth was limited by low moisture availability, which is consistent with findings from the northwestern USA (Littell et al. 2008; Crawford et al. 2015). Seasonally, low moisture availability during the months of June and July in the current growing season significantly decreased latewood widths (Watson and Luckman 2002; Crawford et al. 2015). Low moisture availability also influences fire activity during peak fire season in July and August within montane forests of western Canada (Natural Resources Canada 2019). Thus, conducting climate-growth analyses using a moisture-sensitive Douglas-fir latewood-width chronology is justified to better understand how drought historically varied over the fire season in these montane forests.

Researchers have commonly used the Palmer Drought Severity Index (PDSI; Palmer 1965) in North America to conduct climate-growth analyses (e.g., Watson and Luckman 2002; Littell et al. 2008; Carnwath et al. 2012) and reconstruct historical droughts (e.g., Stahle et al. 2000; Cook et al. 2010). Based on PDSI records and moisture sensitive tree-ring chronologies, Cook et al. (2004) developed multi-century 2.5° x 2.5° gridded reconstructions of summer (June–August) PDSI over North America. These chronologies included those developed by Watson and Luckman (2004) for montane forests of western Canada. The multi-century depth and continental extent of the gridded reconstructions of summer PDSI made them suitable to test fire-drought associations at different spatial scales (e.g., Hessl et al. 2004; Trouet et al. 2006, 2010; Heyerdahl et al. 2008b), even though PDSI was originally developed as an agricultural index (Palmer 1965) and not as a fire-weather index.

The Drought Code (DC) is a daily fire-weather index used in the Canadian Forest Fire Behaviour Prediction System to indicate the moisture content in deep compact organics in the soil and coarse woody fuels (Girardin and Wotton 2009; Podur and Wotton 2010; Chavardès et al. 2019). High DC values indicate that these fuels have low moisture content and are more likely to combust (de Groot et al. 2009). To investigate the associations between DC and historical fires in montane forests of southeastern British Columbia, Canada, Chavardès et al. (2019) developed and compared several monthly adaptations of the DC (see Chapter 2). The predicted monthly mean Drought Code (hereafter, "monthly DC") most accurately represented the onset, duration, and degree of drought during the fire season, and exhibited several strong and significant fire-drought associations in surrounding montane forests. A unique feature of the monthly DC is its capacity to adjust for soil moisture depletion between fire seasons, a condition common in many forests of western Canada (Lawson and Armitage 2008). Depletion of soil moisture can lead to sufficiently dry fuels that have the potential to burn even during the months of April and May in some forests (Chavardès et al. 2019). Given these particularities, the monthly DC is an ideal index to test climate-growth relationships using drought-sensitive Douglas-fir latewood-width chronologies. I hypothesize that its development into a reconstruction of summer DC (average monthly DC from June–August) predating instrumental records can facilitate comparisons to the nearest gridded reconstruction of summer PDSI.

Compared to monthly and summer DC, monthly PDSI and its summer reconstructions indicate moisture content in the surface and underlying soil layers (Hu and Willson 2000). Moisture is removed from these two layers through a temperature driven evapotranspiration algorithm whereas precipitation is added using a water balance method (Thornthwaite 1948; Palmer 1965). According to their description, the surface and underlying soil layers are best represented by the duff to uppermost soil mineral horizon (Miyanishi 2001). The duff layer is highly susceptible to ignition and combustion when dry (Wotton et al. 2005) thus monthly PDSI and its summer reconstructions are commonly used to test fire-drought associations in North America (Littell et al. 2016). Given the subtle difference in fuels represented by monthly and summer DC compared to monthly PDSI and its summer reconstructions, I hypothesize that testing their associations with past fires has the potential to enhance understanding of fire behaviour in montane forests of southeastern British Columbia with mixed-severity fire regimes.

In this research, I test the hypothesis that using two proxy reconstructions of drought provides a more nuanced understanding of the type and degree of droughts associated with mixed-severity fire regimes. Specifically, I addressed three questions. (1) How do climate-growth relationships using monthly DC compare with monthly PDSI? (2) How does a reconstruction of summer DC based on monthly DC compare with the nearest gridded reconstruction of summer PDSI? (3) Do fire-drought associations differ among summer DC and summer PDSI reconstructions? To answer these questions, I developed a new summer drought reconstruction based on monthly DC using a moisture-sensitive Douglas-fir latewood-width chronology. I tested and compared fire-drought associations using this reconstruction and a reconstruction of summer PDSI representing an extensively used proxy-drought record in North America (e.g., Stahle et al. 2000; Cook et al. 2010). Practical outcomes from this research for fire managers include a nuanced understanding of fire ignition and fuel combustion in montane forests with historical mixed-severity fire regimes.

3.2 Methods

3.2.1 Study area

This research focused on montane forests (circa 1100–1550 m above sea level (asl)) of southeastern British Columbia, Canada (Figure 3.1). These mid-elevation forests are dominated by conifers, including Douglas-fir, western larch (*Larix occidentalis* Nutt.), lodgepole pine (*Pinus contorta* Dougl. ex Loud.), white spruce (*Picea glauca* (Moench) Voss), and ponderosa pine. Such forests contain legacies of mixed-severity fire regimes (Cochrane 2007; Daniels et al.

2011; Marcoux et al. 2015), including fire scars and even-aged tree cohorts, providing evidence of low-, and moderate- to high-severity fires, respectively (Marcoux et al. 2013).

Climate in the study area is continental (Pojar and Meidinger 1991). Between 1981 and 2010, the Palliser fire-weather station (50°29’40”N, 115°39’59”W; 1100 m asl) recorded a mean annual temperature of 3.5°C, with mean monthly temperatures of -7.9°C for January and 15.4°C for July, and mean annual precipitation of 433 mm, with 293 mm (68%) from April–October, and 113 mm as snow from November–March (Chavardès et al. 2019). Despite most of the precipitation falling from April–October, peak activity of lightning-ignited forest fires was common from July–August (Natural Resources Canada 2019).

3.2.2 Monthly drought indices

I calculated two monthly drought indices for the Palliser fire-weather station from 1901–2004 as follows. I compiled monthly maximum temperature (°C) and total monthly precipitation (mm; as water equivalent) from daily weather records and monthly climate data following procedures described in Chavardès et al. (2019). To generate monthly average temperature (°C), we used ClimateNA 5.30, a program that applies bilinear interpolation and elevation adjustments to downscale baseline gridded climate data to scale-free point data (Wang et al. 2016). For each fire season (April–October), I computed monthly DC and monthly PDSI.

I calculated monthly DC from monthly precipitation and maximum temperature data following procedures described in Chavardès et al. (2019). Higher (lower) monthly DC values represent drier (wetter) moisture contents in deep compact organics in the soil and coarse woody fuels (Turner 1972).

I calculated monthly PDSI following Wells et al. (2004), using the monthly precipitation and average temperature data, average temperature normals calculated from 1901–2004, and available water-holding capacity of the soil of 480 mm corresponding to forested areas (Meyn et al. 2010b). Positive (negative) monthly PDSI values represent wetter (drier) moisture content conditions in surface and underlying soil layers (Palmer 1965), which comprise the duff to uppermost soil mineral horizon.

3.2.3 Developing the Douglas-fir latewood-width chronology into a detrended residual chronology

I analyzed latewood widths of 147 Douglas-fir increment cores collected from six sites located in montane forests of southeastern British Columbia (Daniels et al. 2007). Cores were sanded and subsequently scanned at high resolution (1200 or 2400 dots per inch) to measure latewood widths using CooRecorder with a threshold of 70 to determine boundaries between earlywood and latewood (Larsson 2011).

To develop a latewood-width chronology, I crossdated ring dates using the programs COFECHA (Holmes 1983) and CDendro (Larsson 2011). Only series with correlations ≥0.54 over the lifespan of the tree (n = 29) were combined into the latewood-width chronology to represent average latewood-width growth in the study area. To describe the latewood-width chronology I calculated statistics including the mean series intercorrelation (r), mean sensitivity (MS), and first order autocorrelation (AC1) (Cook and Kairiukstis 1990).

Using the Climatic Research Unit Standardization of the Tree-ring data program (Melvin and Briffa 2014), I applied signal-free detrending (Melvin and Briffa 2008) with a 100-year 50% frequency response to remove age- and stand-related growth trends (Cook and Peters 1981). We computed the detrended chronology as a pre-whitened residual chronology to reduce temporal autocorrelation (Fritts 1976). I also stabilized variances and calculated the mean chronology as the weighted robust mean of the detrended chronology (Melvin and Briffa 2008). For the resulting detrended residual chronology, I calculated the expressed population signal (Wigley et al. 1984) from 1901–2004, the common period among the chronology and drought indices.

3.2.4 Climate-growth analyses

To identify the strength of the climate-growth relationships between the detrended residual chronology, and the monthly drought indices, I conducted correlation function analyses (Fritts 1976) with the "treeclim" R package (Zang and Biondi 2015). I conducted these analyses over the 7-month window corresponding to the fire season (current year April–October) from 1901–2004. I calculated Pearson's product moment correlation coefficients between the detrended residual chronology and each monthly drought index using 95% confidence intervals derived from 1,000 random bootstrapped samples (Zang and Biondi 2015).

3.2.5 Reconstructions of summer drought

I used two reconstructions of summer drought: a reconstruction of summer (June–August) DC, which I developed in this study, and a published reconstruction of summer (June–August) PDSI for the nearest grid point from the Palliser fire-weather station (GP 67, 50°N, 115°W; Cook et al. 2004).

I applied a linear model using the "lm" function in R (R Core Team 2018) to model summer DC as a function of the detrended residual chronology. To verify model assumptions were met with regards to normality, homoscedasticity, and serially independent data, I used

Shapiro-Wilk, Breusch-Pagan and Durbin-Watson tests, respectively, in addition to quantile-quantile and residual plots (Everitt and Skrondal 2010). The residual plot and Breusch-Pagan test revealed heteroscedastic error terms, which was accounted for by fitting a generalized least squares model (Fox and Weisberg 2019) with the error variance $\ln(\boldsymbol{\varepsilon}^2) = \ln(\mathbf{X})$.

To assess model fit over 1901–2004, I calculated R^2, reduction of error (RE) (Fritts 1976; Macias-Fauria et al. 2012), and root mean squared error (RMSE). To verify model consistency over time, I used the following split-sample periods: 1901–1952, 1953–2004, 1901–2003 every other year, and 1902–2004 every other year (after Littell et al. 2016). Validation statistics included R^2 for the sub-sample models and RE for the sub-sample validations (after Littell et al. 2016).

I tested the association between the reconstructions of summer DC and summer PDSI over their common period, hereafter the "period of analysis". To test the association between both reconstructions, I calculated over the period of analysis their Pearson product moment correlation with associated p-value.

3.2.6 Fire-drought associations

I followed three approaches to explore fire-drought associations during the period of analysis. Superposed epoch analysis was applied to determine whether fire years or non-fire years occurred after and during significantly drier or wetter than average summer conditions (Sutherland et al. 2015), bivariate event analysis was applied to determine whether fire years or non-fire years occurred after and during extremely dry or wet summer conditions (e.g., Harvey and Smith 2017), and logistic regression was applied to determine the summer drought thresholds that corresponded to presence or absence of fire years. For the historical fire records, I used crossdated fire-scars collected from montane forests of southeastern British Columbia (Cochrane 2007; Daniels et al. 2011). I composited all site-level fire records, then filtered them to identify years in which ≥2 trees were scarred for a total of 68 fire-scar years (hereafter, "fire years") over the period of analysis.

I applied SEA in the Fire History Analysis and Exploration System (Brewer et al. 2015). To meet the assumptions of SEA, I used autoregressive integrated moving average (ARIMA) procedures to test for and remove autocorrelation (after Heyerdahl et al. 2008b) from the reconstruction of summer PDSI. ARIMA procedures showed that the reconstruction of summer PDSI was not white noise ($p < 0.001$ up to six lags). I applied an AR(1) model to derive white noise residuals of the reconstruction of summer PDSI ($p \geq 0.547$ up to 24 lags). I standardized the reconstruction of summer DC to z-scores (Salkind 2007) and calculated mean values for these z-scores and the reconstruction of summer PDSI residuals for fire years, non-fire years, and each of their preceding three years. To assess statistical significance of these years, I compared their mean values against bootstrapped values derived from a Monte Carlo simulation of randomly selected years that provided 95%, 99%, and 99.9% confidence intervals (Sutherland et al. 2015).

I applied BEA using the K1D software (Gavin 2010) to test whether extremely dry/wet summers (±1 standard deviation) were temporally synchronous, independent or asynchronous relative to fire years, non-fire years, and each of their preceding three years. Compared to SEA, BEA focuses on extreme rather than average conditions, and it presents the comparative advantage of avoiding problems due to serial autocorrelation because it does not rely on continuous drought records (Gartner et al. 2012). I conducted BEA over the period of analysis with forward selection such that fire years and non-fire years were preceded by extremely dry/wet summers, and I generated 95% confidence intervals based on 1000 randomized Monte Carlo simulations (after Harvey and Smith 2017).

As a third approach, logistic regression was applied to predict the probability of a fire year based on the reconstructions of both summer DC and summer PDSI. An optimal pair of threshold values for summer DC and PDSI was derived from the cutoff probability at which the received operating characteristic (ROC) curve minimized the sum of false positives and false negatives (Toms and Villard 2015).

3.3 Results

3.3.1 Reconstruction of summer drought from Douglas-fir latewood widths

The Douglas-fir latewood-width chronology was robustly crossdated with a high mean series intercorrelation ($r = 0.62$). Chronology statistics indicated low variation but high correlation between latewood-width measurements from year to year (mean sensitivity = 0.33 and first order autocorrelation (AC1) = 0.70, respectively), which were analogous to Watson and Luckman's (2002) chronology statistics from Interior British Columbia. The detrended residual latewood-width chronology spanned from 1686–2004 and it achieved an expressed population signal >0.85 over 1901–2004, the common period among monthly drought indices.

Increased drought during the fire season was significantly correlated with decreased Douglas-fir latewood width (Figure 3.2). Both monthly drought indices showed significant correlations with the chronology ($p < 0.05$) during each month of the fire season; with negative correlations for monthly DC and positive correlations for monthly PDSI. Correlations with monthly DC were stronger from April–August, but weaker in September and October relative to monthly PDSI.

The model used to reconstruct summer DC met the assumptions of linear regression. The model showed moderate performance yielding an R^2 of 0.46, RE of 0.45, and RMSE of 59.04 (Table 3.1). Validation statistics revealed similar values of R^2 ranging from 0.41–0.49, and of RE ranging from 0.37–0.45. Over the common period of analysis spanning from 1686–2004, the summer DC reconstruction revealed a moderate negative Pearson product moment correlation with the summer PDSI reconstruction ($r^2 = -0.50$; $p < 0.001$) (Figure 3.3).

3.3.2 Fire-drought associations

Summer drought was a driver of historical fires (Figure 3.4). From 1686–2004, the 68 fire years burned during summers with significantly drier conditions in the year of fire according to both drought reconstructions ($p < 0.001$), and the year preceding fire according to the summer PDSI only ($p < 0.05$). During the 251 non-fire years, summers were significantly wetter only during the coinciding year according to summer DC ($p < 0.05$) and summer PDSI ($p < 0.01$).

As expected, fire years were synchronous with extremely dry summers and asynchronous with extremely wet summers (Figure 3.5). Fires were synchronous with extremely dry summers during the year of and prior year to fire according to summer DC ($p < 0.05$), and year of and up to three years prior to fire according to summer PDSI ($p < 0.05$). Corroborating these findings, fires were asynchronous with extremely wet summers during the year of and up to three years prior to fire according to summer DC and PDSI ($p < 0.05$). Non-fire years remained independent ($p \geq 0.05$) from extremely dry and wet summers.

Based on the pair of identified thresholds, fire years were more likely to occur when summer DC ≥344 and summer PDSI ≤0.08 (Figure 3.6). Over 319 years, these conditions were met for 100 distinct years, 41% of which were fire years that were recorded at the greatest percentage of sites (maximum 32% mean ±SD 9 ±6%). In contrast, when summer DC <344 and summer PDSI >0.08, only 5 of 109 years were fire years recorded at a lower percentage of sites (maximum 11% mean ±SD 7 ±4%) than under more pronounced and persistent drought conditions.

3.4 Discussion

3.4.1 Monthly DC and PDSI reveal subtle differences in drought influences on montane forests

Subtle differences in climate-growth correlations across the fire season indicate that monthly DC and PDSI can be used together to better understand drought effects on historical fires in the montane forests of southeastern British Columbia. Compared to monthly PDSI, monthly DC was more strongly correlated with latewood-widths in the early months of the fire season. Monthly DC, developed as a fire-weather index, accounts for soil moisture depletion between fire seasons (Chavardès et al. 2019). Soil moisture can be partly retained between fire seasons by discontinuous frozen ground and insulating snowpack or it can be depleted by dry winters with early snowmelt (Van Wagner 1987; Lawson and Armitage 2008). The latter phenomenon is known as "overwintering" and is common in the study area. The capacity to account for overwintering likely explains the stronger climate-growth correlations from April–August for monthly DC than monthly PDSI. In contrast to monthly DC, monthly PDSI poorly accounts for snowfall (Riley et al. 2013), snowmelt, or frozen ground which can be problematic when using PDSI at high-latitudes and mountainous areas (Alley 1984). Nonetheless, during September and October, monthly PDSI displayed higher climate-growth correlations than monthly DC, which was consistent with correlations between monthly PDSI and soil moisture that were strongest during late summer and autumn in the western USA (Dai et al. 2004). Combined, my findings provide support for the application of monthly DC along with monthly PDSI to improve interpretations of the effects of drought throughout the fire season in montane forests of southeastern British Columbia.

3.4.2 Fire-drought associations highlight differences in moisture content over time

Fire-drought associations for summer DC and PDSI reflected the capacities of these two drought indicators to integrate moisture content over time in different forest fuels. Deep organics and coarse woody fuels have slow drying rates and hence long moisture content lag-times because of the low atmospheric influences on deep organics, including lack of influence by light precipitation events ≤2.8 mm (Van Wagner 1987; Girardin and Wotton 2009), and the small surface-area-to-volume ratio of coarse wood (Flannigan et al. 2016). In comparison, the duff layer responds more quickly to changes in moisture and is not influenced by overwintering effects (Wotton 2009). Differences in drying rates and overwintering effects meant that summer DC was significantly drier during fire years only. Summer DC during fire years and preceding years was also influenced by antecedent moisture conditions during and between prior fire seasons. Because average conditions were wetter two and three years prior to fire years, I found summer DC was drier, but not significantly so, during the preceding year. This difference in lagged response was reproduced when testing fire-drought associations during extremely dry summers. Summer PDSI showed synchrony during the year of and up to three years prior to fire, summer DC only revealed synchrony with extremely dry summers during the year of and one year prior to fire. Consequently, I conclude that for montane forests of southeastern British

Columbia, summer DC is a more suitable indicator of the degree and persistence of droughts across successive fire seasons than summer PDSI.

3.4.3 Fire severity indicators in montane forests with mixed-severity fire regimes

In montane forests with mixed-severity fire regimes, summer DC and PDSI can be applied together with the fire scar record to make inferences on historical fire types and effects. Historically, fire years were most likely when moisture content was low in the duff layer and deep organic and coarse woody fuels. These conditions occurred during 100 distinct years between 1686 and 2004, implying high potential for sustained ignitions and fuel combustion. During 41 of these years, fire-scars were recorded at the greatest percentage of sites indicating low- to moderate-intensity fires that burned but did not necessarily kill trees. Because fire severity is related to the amount of combustible fuel (Keeley 2009), I would expect some fires burned at high severities given that most fuels had low moisture content. However, spatial variation in moisture gradients and the amount of combustible fuels likely influenced fire severity over space as found in other montane forests with mixed-severity fire regimes in western North America (Halofsky et al. 2011; Daniels et al. 2017). Despite mostly dry fuels, the spatial variation implied some fuels still had enough moisture or that the amounts of fuel were quite low in some stands. Alternatively, it is possible that these fires were of mixed severity, and that fire-scarred trees sampled were survivors in patches of low- to moderate-severity fires or at edges of high-severity fires.

Increased moisture content across fuels led to considerably fewer fire years relative to non-fire years and fewer sites recording fires. For 104 distinct years, when summer DC remained below 344 and summer PDSI was above 0.08 and ranged from ‘near normal’ to ‘extremely wet’ (see Table 11 in Palmer 1965), no fire scars were detected across the study sites. Only five fire years were recorded under such mild drought conditions indicating forest fuels including the duff layer were less susceptible to sustain ignitions (Falk et al. 2007; Abatzoglou et al. 2016). When ignitions were sustained, higher moisture content across fuels likely limited the combustion of these fuels and the formation of fire scars at different sites. As a result, fire years were recorded at fewer sites than during years with more pronounced and persistent drought conditions coinciding with a fire year.

Over the past 319 years, fire years were not common when summers coincided with low moisture content in deep organics and coarse woody fuels, but higher moisture content in the duff layer. Of the 55 years that coincided with summer DC ≥344, and summer PDSI ranging from 'near normal' to 'very wet' conditions, only 6 were fire years recorded at a maximum of 14% of sites (mean ±SD 6 ±4%). Daily and monthly DC values above 300 imply deep organics and coarse woody fuels are moderately to very dry and more likely to burn according to fire managers in Canada (Girardin and Wotton 2009). Combined, these conditions suggest deep organics and coarse wood had comparatively lower moisture content than the duff layer which may have been the result of two factors. First, it is possible that these six fire years followed a drought in the previous year and that overwintering conditions also led to moisture content remaining low in deep organics and coarse wood (Lawson and Armitage 2008). Second, given that moisture content in these fuels requires daily precipitation events that exceed 2.8 mm (Van Wagner 1987), it is also possible that these six years had relatively frequent light precipitation events over the summer that were <2.8 mm. If this were the case, then such precipitation events would have provided some moisture to the duff layer but not to deep organics and coarse woody fuels (Van Wagner 1987). Consistent with my interpretations, I found that all six years had summer DC values that were >300 in the previous year, and had summer PDSI corresponding to 'near normal' to 'incipient wet spell' conditions during the fire year.

Sustained ignitions were more likely, but combustion of deep organics and coarse woody fuels less likely, when summer PDSI ranged from 'near normal' to 'severe drought', and summer DC was <344. Out of the 55 years, 16 were fire years recorded at a maximum of 20% of sites (mean ±SD 7 ±4%). Fires burning under these conditions emphasize the importance of a dry duff layer to sustain ignition and combustion (Wotton et al. 2005). However, because summer DC during the 16 fire years indicates that deep organics and coarse woody fuels were less combustible than under pronounced and persistent drought conditions, fires were more likely low- to moderate-severity fires. Similar findings were documented in other montane forests of western North America with evidence showing low- to moderate-severity fires burning during less pronounced and persistent droughts (Perry et al. 2011; Hessburg et al. 2016).

3.5 Conclusion

Using the reconstructions of summer DC and PDSI in concert provided nuanced insights on the range of drought conditions driving mixed-severity fire regimes in montane forests of southeastern British Columbia. The development of a summer DC reconstruction in particular provided a practical connection between historical fires and a modern fire-weather index derived from empirical research on fire behaviour. Comparisons between summer DC and PDSI reconstructions revealed how moisture content among forest fuels, namely deep organics and coarse woody fuels versus the duff layer, can offer indications on the susceptibility to fire ignition and combustion. Distinct lag-times according to fire-drought associations reflected different drying rates, wetting susceptibility, and overwintering capacity among forest fuels represented by each summer drought reconstruction. Variable fuel moisture conditions across fuels during fire years likely led to fires igniting and burning with a range of severities. Such information can be used by fire managers to understand how climate change could affect fire ignition and fuel combustion susceptibility in montane forests with historical mixed-severity fire regimes.

Table 3.1. Detrended residual latewood-width chronology-based reconstruction of the summer Drought Code (DC; dimensionless index) at the Palliser weather station including reconstruction, model and validation statistics.

Reconstruction coefficients	r (summer DC)	Estimate	Std. Error	t-value	P(>|t|)
Intercept		603.1	30.2	19.940	<0.001
Detrended residual latewood-width chronology	-0.66	-258.7	27.8	-9.303	<0.001

Model diagnostics	Sub-sample model	R^2	Sub-sample validation	RE
$R^2 = 0.46$	1901–1952	0.48	1901–1952	0.38
F-statistic = 86.54 on 1 and 102 df, p <0.001	1953–2004	0.41	1953–2004	0.37
RE = 0.44	1901–2003, every other year	0.49	1902–2004, every other year	0.38
RMSE = 59.04	1902–2004, every other year	0.41	1901–2003, every other year	0.45

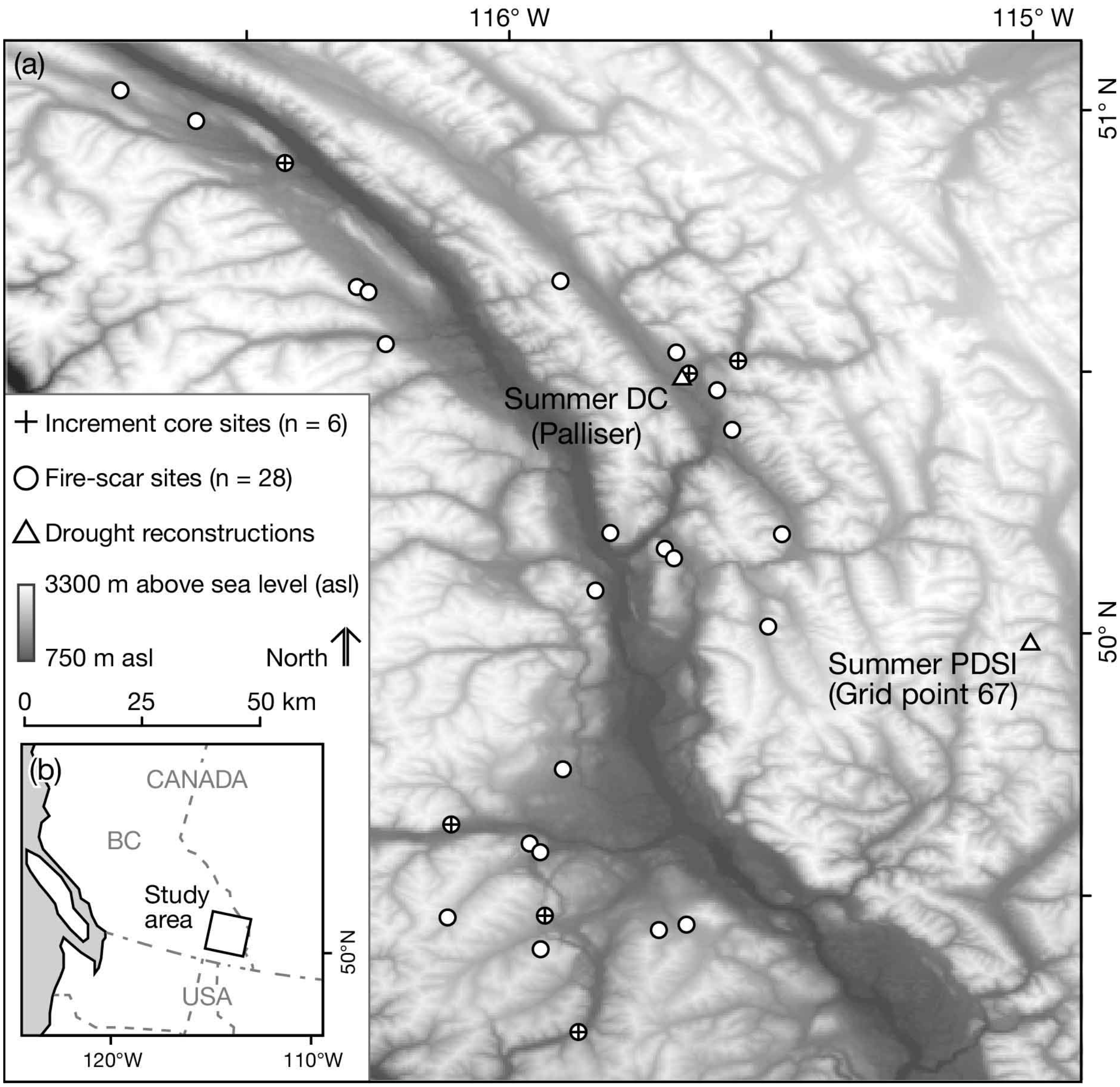

Figure 3.1 (a) Location of the sampling sites for Douglas-fir increment cores (Daniels et al. 2007), and fire-scar records (Cochrane 2007; Daniels et al. 2011), (b) in montane forests of southeastern British Columbia (BC), Canada. (a) Also shown are the location for the summer Drought Code (DC) reconstruction at the Palliser fire-weather station, and the summer Palmer Drought Severity Index (PDSI) reconstruction (Cook et al. 2004) at grid point 67.

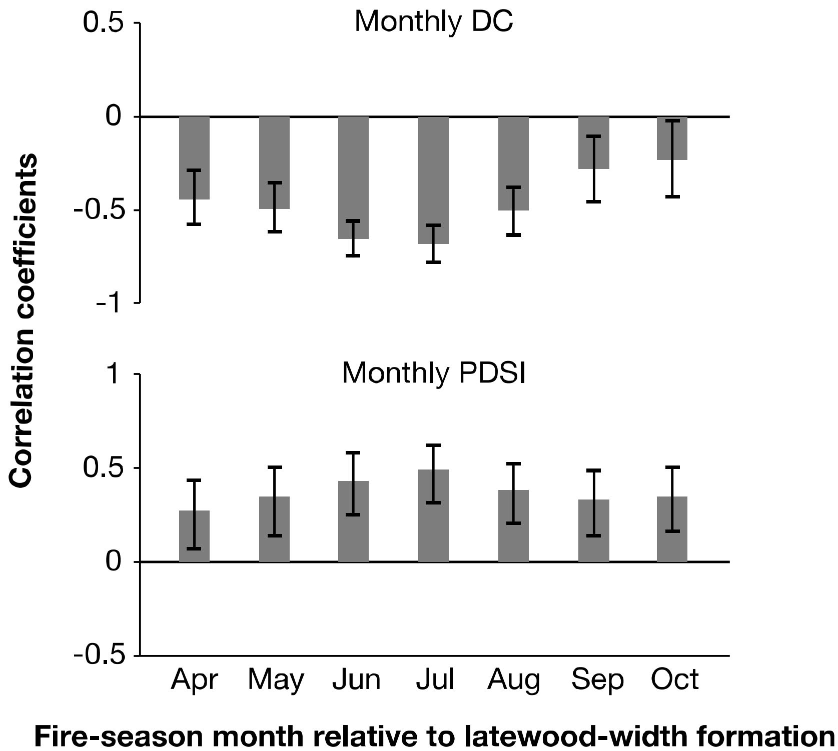

Figure 3.2 Bootstrapped correlation coefficients of the detrended residual latewood-width chronology against the monthly Drought Code (monthly DC; dimensionless), and monthly Palmer Drought Severity Index (monthly PDSI; dimensionless) at the Palliser fire-weather station. All correlation coefficients shown as grey bars were calculated for the period 1901–2004 and over April–October, the months corresponding to the fire season. Whiskers represent 95% confidence intervals.

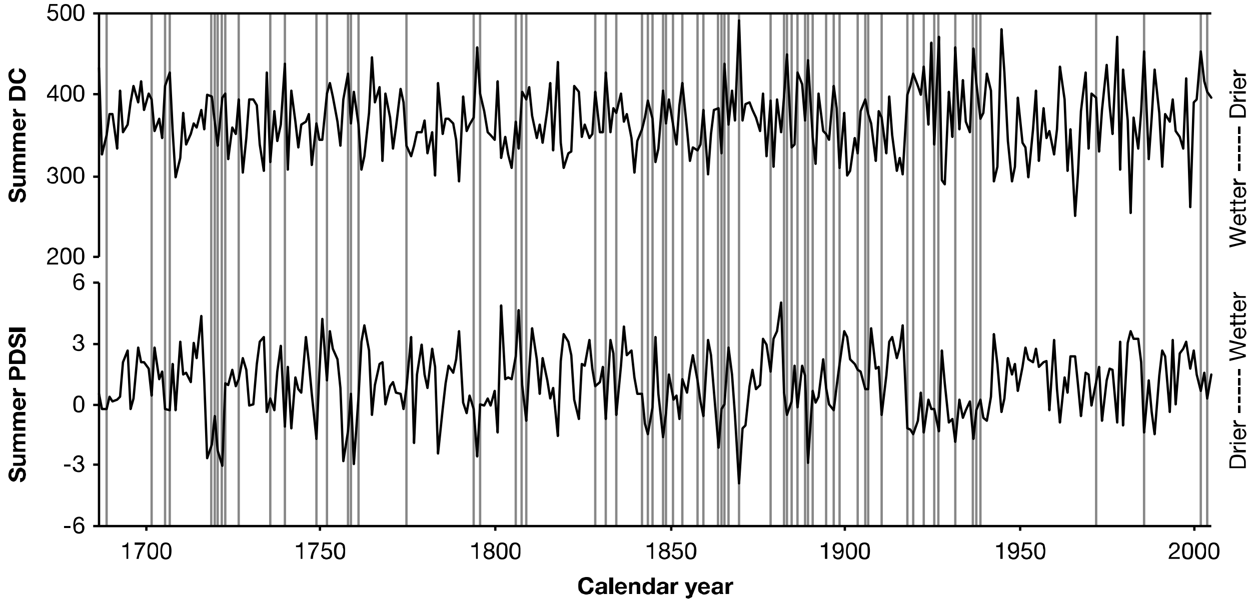

Figure 3.3 Association between reconstructions of the summer Drought Code (DC) and summer Palmer Drought Severity Index (PDSI) from 1686–2004. The 68 fire years are shown as vertical grey bars.

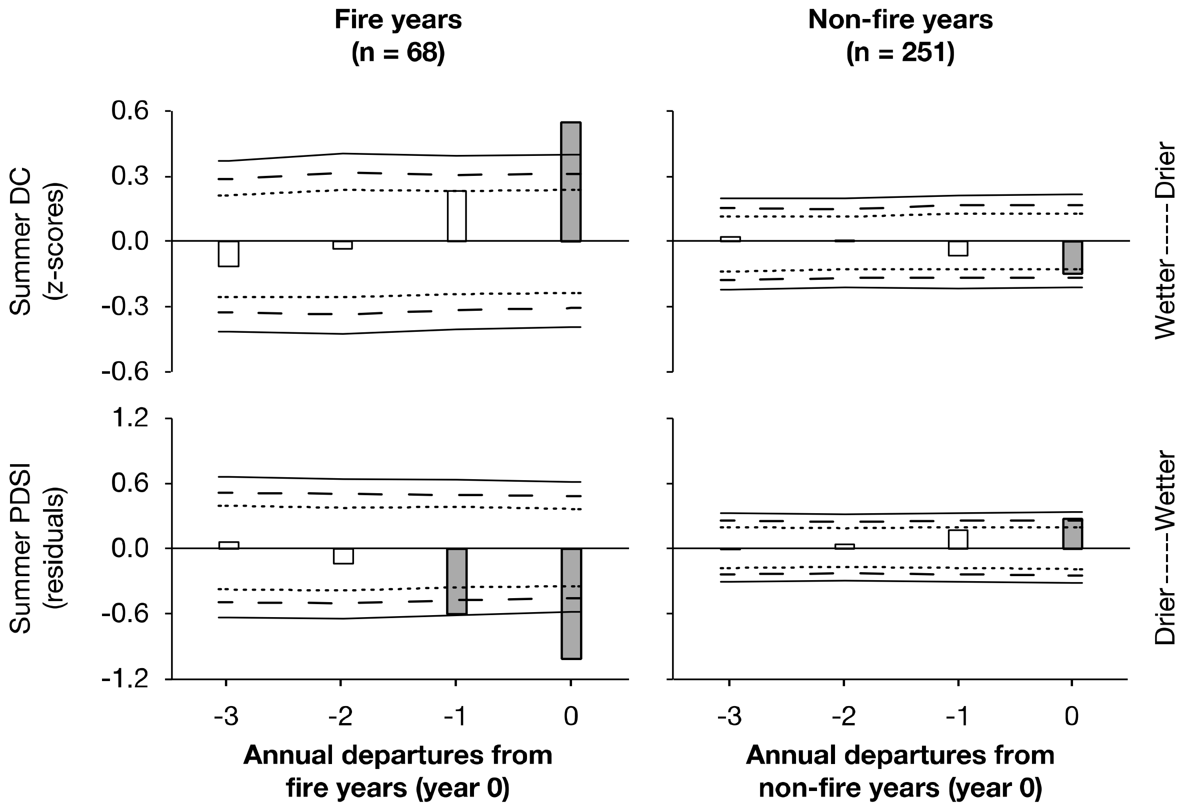

Figure 3.4 Superposed epoch analyses showing associations for the reconstructions of the summer Drought Code (DC) and the summer Palmer Drought severity Index (PDSI) during fire years and non-fire years. Solid, long- and short-dashed lines represent confidence intervals of 99.9%, 99%, and 95%, respectively. Gray bars indicate statistically significant departures from the mean ($p < 0.05$).

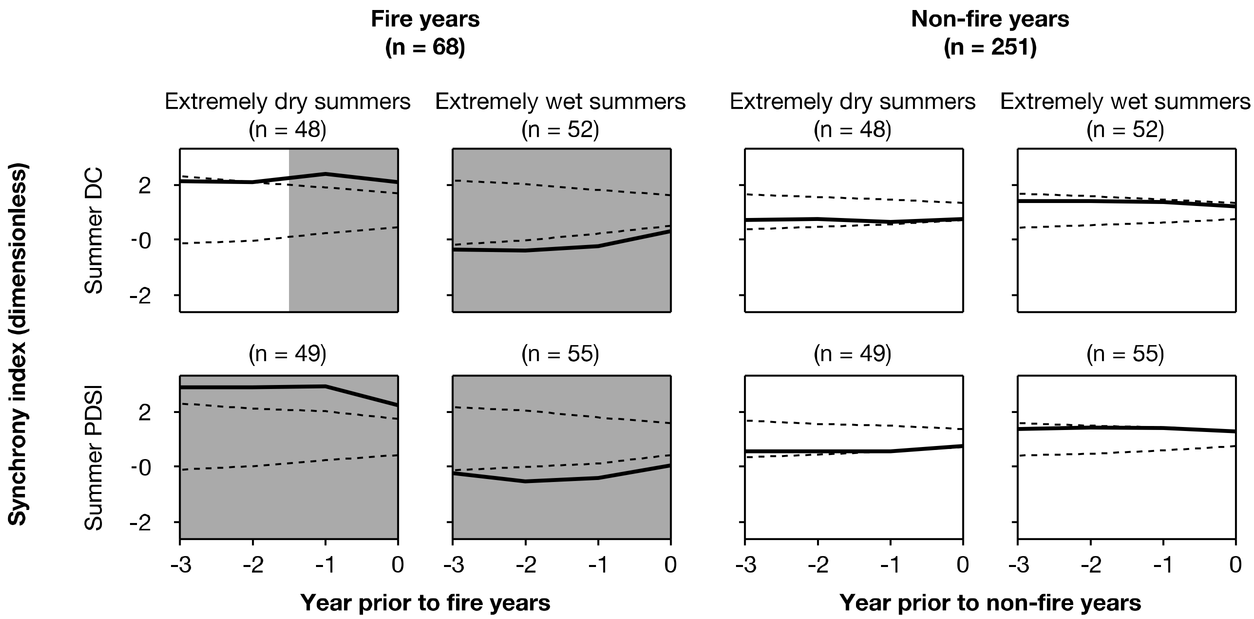

Figure 3.5 Bivariate event analyses showing associations for fire years and non-fire years during coinciding and preceding extremely dry or wet summers (±1SD) according to the reconstructions of the summer Drought Code (DC) and summer Palmer Drought severity Index (PDSI). Solid black lines represent reconstruction indices and dashed lines the 95% simulation envelopes, respectively. Reconstruction indices above the upper envelopes indicate synchrony with fire years or non-fire years. Reconstruction indices values falling between envelopes are statistically insignificant and indicate independence from fire years or non-fire years. Reconstruction indices below the lower envelopes indicate asynchrony with fire years or non-fire years. Portions highlighted in grey denote statistical significance ($p < 0.05$).

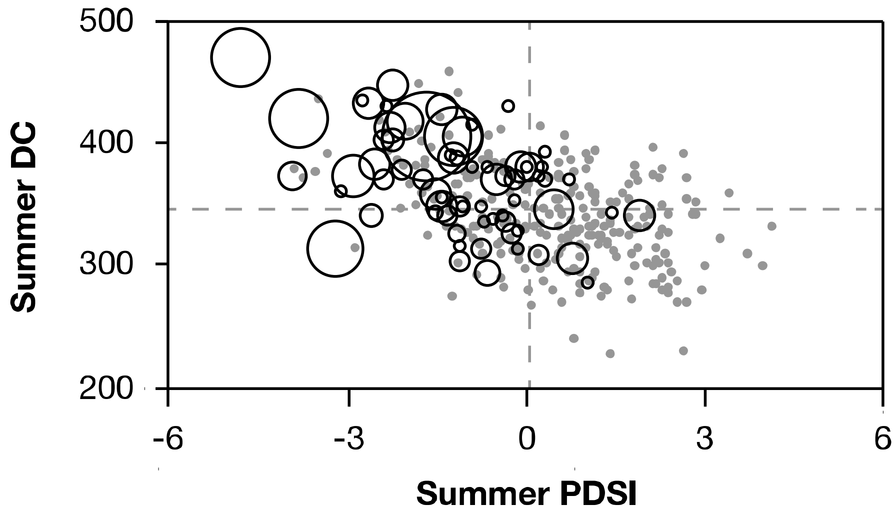

Figure 3.6 Scatterplot for the reconstruction of the summer Drought Code (DC) versus reconstruction of summer Palmer Drought Severity Index (PDSI) during fire years (black circles) and non-fire years (grey points). The percentage of sites recording each fire year is represented by the size of each circle. Dashed lines correspond to summer DC = 344 and summer PDSI = 0.08.

Chapter 4: Fire-climate associations in the Canadian Montane Cordillera: Climate drives fire synchrony in forests with mixed-severity fire regimes

4.1 Introduction

Anthropogenic climate change is leading to prolonged drought conducive to fire occurrence with high-severity impacts in forests of western North America (Flannigan et al. 2009; Westerling 2016; Wotton et al. 2017). Ultimately, this will result in more frequent fires placing human communities at risk (Moritz et al. 2014; Sankey 2019). For example, within the Montane Cordillera ecozone of Canada (hereafter, Montane Cordillera), many large (>200 ha) forest fires, including mega-fires (>10 000 ha), overwhelmed the deployment and control capabilities of fire suppression organizations during the 2017 and 2018 fire seasons (Natural Resources Canada 2019). Across the region, these fire seasons coincided with record breaking persistent warm and dry weather conditions corresponding to drought driven by anthropogenic climate change (Kirchmeier-Young et al. 2019). Such conditions over the fire season lower forest fuel moisture content, and thus facilitate the ignition, combustion and spread of fires (Gedalof 2011; Macias Fauria et al. 2011). The high number of widespread fires burning across a single fire season within the region has been described as historically unprecedented. Determining whether there is historical precedence for similar widespread-fire synchrony across the region is an important question that needs to be addressed to support fire managers in anticipating potential climate change impacts on fire regimes.

Associations between modern fire records and climate (i.e., weather averaged over monthly to annual scales) have been investigated across multiple regions of western North

America, largely focusing on the mid-20th to early 21st centuries given the availability of modern fire records and instrumental climate and drought records (e.g., Morgan et al. 2008; Littell et al. 2009; Meyn et al. 2010a, 2010b; Westerling et al. 2016). However, this period overlaps with changes in fire management including improvements in fire suppression technology (Bowman et al. 2009; Flannigan et al. 2009), which can confound fire-climate associations (Williams and Abatzoglou 2016). To avoid the confounding effect of fire management, dendropyrochronologists test fire-climate associations over longer periods using crossdated fire-scar chronologies and multi-century proxies of summer temperature or drought or annual precipitation that extend prior to the 20th century (Swetnam and Anderson 2008; Littel et al. 2016; Williams and Abatzoglou 2016). Individual fire-scar chronologies and climate proxies provide site-level baseline information on the frequency of years with fire and the past conditions in which they burned. When sites are combined into regional networks, evidence of historical fire synchrony (Swetnam 1993; Falk et al. 2011) and interannual associations between synchronous or widespread fires and climate can be deduced (Heyerdahl et al. 2008a, 2008b; Trouet et al. 2010; Margolis and Swetnam 2013). Historical fire-climate associations can also be investigated at finer spatial scales through spatially explicit prediction models applied to networks of climate reconstructions (e.g., Heyerdahl et al. 2008b; Trouet et al. 2010). Thus, analyzing historical fire-climate associations across spatial scales can provide key insights on climate conditions under which synchronous fires burned, and the potential for future fire synchrony within the region.

Many of the fire-scar chronologies developed for the Montane Cordillera and in the northwestern USA were collected in low- to mid-elevation coniferous forests with mixed-severity fire regimes (e.g., Hessburg et al. 2007, 2016; Perry et al. 2011; Heyerdahl et al. 2012;

Marcoux et al. 2013; Chavardès and Daniels 2016; Harvey and Smith 2017). Mixed-severity fire regimes are represented by fires that burn across space and time with a broad range of severities, from low-severity surface fires to high-severity crown fires (Perry et al. 2011; Daniels et al. 2017). The range of fire severities is reflected by the spatial and temporal variation in mortality effects on vegetation, and consequently forest stands across the landscape are compositionally and structurally diverse (Halofsky et al. 2011; Daniels et al. 2017). Although climate is a well-documented top-down driver of fires in this region (e.g., Heyerdahl et al. 2008b; Harvey and Smith 2017; Chavardès et al. 2018), understanding the more nuanced influences of climatic variation on the range of fire severities remains poorly understood.

In this research, I tested the hypothesis that spatio-temporal variation in climate was an important driver of fire synchrony within and among regions but that extreme droughts that facilitated synchronous fires across sites were rare. Specifically, I address the following two questions: 1) How frequently did historical fires burn synchronously among sites within the Montane Cordillera? 2) What climate conditions were associated with various levels of fire synchrony at regional and subregional scales? To answer these questions, I used fire-scar records previously sampled at 17 sites across the Montane Cordillera in western Canada and quantified the occurrence and frequency with which fires synchronously burned at multiple sites and regions in a given year (i.e., fire synchrony). I reconstructed regional climatic proxies for summer temperature, annual precipitation, and summer drought and tested for associations between climate and years of fire synchrony at regional and subregional scales. I also applied a spatial model to networks of climate reconstructions to characterize fire-climate associations at a subregional scale. My findings reveal that fire synchrony driven by droughts was common but that widespread-fire synchrony was rare and driven by pronounced droughts.

4.2 Methods

4.2.1 Study area

This research was conducted in the central and southern parts of the Montane Cordillera of Canada covering approximately 310,000 km^2 and extending from the eastern slopes of the Coast and Cascade Mountains in British Columbia to the foothills of the Rocky Mountain in Alberta, and from the northern conterminous USA border to the northern extent of the Cariboo Mountains (Figure 4.1). Climate in the region is continental, with some maritime influences in the south modulated by rain-shadow effects of the Coast Mountains in the west, and the Columbia and Rocky Mountains in the east (Scudder and Smith 2011). Topographic influences on climate contribute to diverse forest ecosystems dominated by coniferous tree species (Scudder and Smith 2011). In the warmest and driest areas at low- to mid-elevations in the interior plateau and in the valleys within and between the eastern mountains, forests are predominantly composed of interior Douglas-fir (*Pseudotsuga menziesii* var *glauca* (Beissn.) Franco) and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), with western larch (*Larix occidentalis* Nutt.) present in the valleys within and between the eastern mountains (Demarchi 2011). In mid-elevation forests of the eastern mountains and Rocky Mountain foothills, climate is cooler and wetter than in the interior plateau or low- to mid-elevation valleys in the eastern mountains (Environment Canada 2019). Coniferous species also present within these forests include western red cedar (*Thuja plicata* Donn *ex* D.Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) in the Columbia Mountains, and lodgepole pine (*P. contorta* var. *latifolia* Douglas) and white spruce (*Picea Glauca* (Moench) Voss) in the Rocky Mountains and its foothills (Scudder and Smith 2011).

4.2.2 Historical fire records

I acquired the crossdated fire-scar records from fire-history reconstructions conducted in the Montane Cordillera and composited fire-scar chronologies into 17 site-level fire records (Appendix B). The site-level fire records combined multiple plot-level fire records sampled by different researchers reconstructing historical fire occurrence (Table 4.1). In total, fire records from the 17 sites comprised 1,886 crossdated fire-scar samples. The recording period for each site was defined by the years in which ≥2 living, fire-scarred trees were present and had the potential to form a scar in the advent of fire.

At the site level, the fire records were compiled in two different ways. (1) Fires recorded by ≥2 trees in a given year were considered a "fire year" (Heyerdahl et al. 2008a), and (2) fires recorded by ≥2 trees and ≥10% of recorder trees in a given year were a "widespread-fire year" (Trouet et al. 2010). For each year, the number of sites recording a fire year or widespread-fire year were summed, generating a regional fire record. Based on the number of sites recording a fire year, I designated each year in one of five categories of synchrony: 1) "no fire synchrony" for years with fire scars at one site only; 2) "low fire synchrony" for years with fire scars at two to three sites; 3) "moderate fire synchrony" for years with fire scars at four to five sites; 4) "high fire synchrony" for years with fire scars at six or more sites; and 5) "synchronous non-fire years" when no fires were recording at all 17 sites (adapted from Heyerdahl et al. 2008a).

4.2.3 Reconstructions of regional climate

To represent climate throughout the Montane Cordillera, I used tree-ring proxy reconstructions of maximum temperature anomalies, precipitation, and the Palmer Drought Severity Index (PDSI), a drought index which combines the effects of temperature and precipitation (Palmer 1965). I used the reconstruction of summer maximum temperature anomalies for Interior British Columbia (Wilson and Luckman 2003), reconstructions of annual precipitation (previous July to current June; Watson and Luckman 2004) for 11 locations that provided the longest periods of record (i.e., Banff, Big Creek, Cranbrook, Jasper, Lillooet, Lytton, North Thompson, Oliver, Summerland, Waterton, and Williams Lake), and reconstructions of summer PDSI for 20 grid points (Cook et al. 2004) that covered the study region (grid points: 22–25, 29–32, 40–43, 52–55, and 65–68) (Appendix B).

I developed and compared regional climate reconstructions over the period of analysis from 1746–1945. This period corresponds to the common period between the regional fire record and climate reconstructions, all of which start prior to or in 1746. The period ends in 1945 because of subsequent documented influences that can confound fire-climate associations including fire exclusion policies imposed at the turn of the 20^{th} Century, and the introduction of advanced and organized fire suppression after 1945 in western North America (Pyne 1982, 2007; Keane et al. 2002). A single regional climate reconstruction was needed for each of the three sets of climate reconstructions (i.e., summer maximum temperature anomalies, annual precipitation, and summer PDSI). The reconstruction of summer maximum temperature anomalies for Interior British Columbia was originally developed to represent the region and was used without modification. For the other two sets of climate reconstructions, I used Principle Components Analysis (PCA) (SAS Institute Incorporated 2017) to extract the first principle component (PC1) from the 11 reconstructions of annual precipitation ($PC1_{PPT}$), and PC1 from the 20 reconstructions of summer PDSI ($PC1_{PDSI}$). $PC1_{PPT}$ and $PC1_{PDSI}$ were considered representative of regional annual precipitation and summer PDSI, respectively. I tested for linear correlations among the three regional climate reconstructions using scatter plots and by calculating Pearson product moment correlations between the reconstruction of summer maximum temperature anomalies, $PC1_{PPT}$, and $PC1_{PDSI}$.

4.2.4 Regional fire-climate associations

Over the period of analysis, I used two approaches to test if increasing fire synchrony was associated with warm and dry regional climate. First, I compared values of each regional climate reconstruction across categories of synchrony using boxplots and analysis of variance of ranks followed by post-hoc Dunn's tests (Gorvine et al. 2018). Second, I conducted additional analyses on three subsets of years with moderate to high degree of synchrony (hereafter, collectively referred to as "synchronous events"): (1) moderate–high fire synchrony (i.e., ≥4 sites recorded fire), (2) moderate–high widespread-fire synchrony (i.e., ≥4 sites recorded widespread fire), and 3) synchronous non-fire years during the period of analysis. To test the associations between synchronous events and the regional climate reconstructions, I used Superposed Epoch Analysis (SEA) in the Fire History Analysis and Exploration System (Brewer et al. 2015). To meet the assumptions of SEA, I used Autoregressive Integrated Moving Average (ARIMA) procedures to test for and remove autocorrelation from the reconstruction of summer maximum temperature anomalies, $PC1_{PPT}$, and $PC1_{PDSI}$. ARIMA procedures showed that the reconstruction of summer maximum temperature anomalies did not have statistically significant temporal autocorrelation (white noise tests $p \geq 0.188$ up to 24 lags); however, $PC1_{PPT}$ and $PC1_{PDSI}$ were not white noise ($p \leq 0.016$ up to six lags). I applied AR(1) models to derive white noise residuals of $PC1_{PPT}$ and $PC1_{PDSI}$ ($p \geq 0.57$ up to 24 lags). For the reconstruction of summer maximum temperature anomalies, and $PC1_{PPT}$ and $PC1_{PDSI}$ residuals, I calculated mean values during the year coinciding with extreme synchronous events and the three preceding years and compared them to bootstrapped values derived from a Monte Carlo simulation of randomly selected years that provided 95%, 99%, and 99.9% confidence intervals (Sutherland et al. 2015).

4.2.5 Subregional fire-climate associations

Over the period of analysis, I used two approaches to visually explore climate conditions during years with high fire synchrony and synchronous events. For the first approach, to represent precipitation anomalies across space, I calculated z-scores (Salkind 2007) for each of the 11 reconstructions of annual precipitation. Using the multiple point reconstructions of annual precipitation z-scores (n = 11) and summer PDSI (n = 20) across the study area, I applied Inverse Distance Weighted (IDW) interpolation (Bivand et al. 2008) to develop continuous maps depicting climate conditions during each year with high fire synchrony. For the second approach, I calculated means for each of the 11 reconstructions of annual precipitation z-scores and 20 reconstructions of summer PDSI during synchronous events. I applied IDW interpolation to develop continuous maps depicting average climate conditions during synchronous events. For both approaches, to describe climate conditions and to colour-code the maps, annual precipitation z-scores, and summer PDSI values were assigned to one of 11 classes ranging from 'extremely wet' to 'extreme drought' (see Table 11 in Palmer 1965; Appendix C).

4.3 Results

4.3.1 Historical fire records

The 17 site-level fire records revealed abundant fire activity between 1735 and 2000 (Figure 4.2; Table 4.1). From 1746–1945, fires scarred trees in 186 years; 90 of these showed widespread scarring at one or more sites. Of the 186 fire years, 48 were recorded at one site only.

Low, moderate, and high fire synchrony were recorded in 88, 39, and 11 years, respectively. Only 14 years had no fire scars at any of the sites.

4.3.2 Reconstructions of regional climate

Based on PCA, variances explained for $PC1_{PPT}$ (33%) and $PC1_{PDSI}$ (73%) indicated the reconstructions of annual precipitation exhibited more spatial variability across the 11 locations than the reconstructions of summer PDSI across the 20 grid points. Diagnostic plots and Pearson product moment correlations revealed the strongest linear correlation was negative between the reconstruction of summer maximum temperature anomalies and $PC1_{PDSI}$ (r^2 = -0.74, p <0.001) (Figure 4.3). In contrast, $PC1_{PPT}$ had a moderately strong positive linear correlation with $PC1_{PDSI}$ (r^2 = 0.62, p <0.001), and a moderately weak negative linear correlation with the reconstruction of summer maximum temperature anomalies (r^2 = -0.35, p <0.001).

4.3.3 Regional fire-climate associations

Years when fires burned synchronously at multiple sites were generally associated with warmer summer maximum temperature anomalies and significantly associated with lower annual precipitation and summer PDSI, indicating relatively dry conditions (Figure 4.4). During the 50 years with moderate–high fire synchrony (fire interval mean and range: 4 yrs, 1–15 yrs), climate conditions were significantly drier and warmer in the year coinciding with fire (p <0.001) and/or previous year (p <0.05) (Figure 4.5a–c). Conditions were drier and warmer, on average, during the six years with moderate–high widespread-fire synchrony (fire interval mean and range: 26 yrs, 10–63 yrs); however, the associations were only statistically significant during the year coinciding with fire (p <0.01) (Figure 4.5d–f). In contrast to years with moderate–high fire synchrony and widespread-fire synchrony, conditions during the 14 non-fire years were significantly wetter than average ($p < 0.01$), and cooler and wetter in the preceding year ($p < 0.05$) (Figure 4.5g–i).

4.3.4 Subregional fire-climate associations

The 11 years with high fire synchrony coincided with a wide range of climatic conditions across the region. Annual precipitation z-scores spanned the full range of climatic conditions, from ‘extremely wet’ to ‘extreme drought’ (Figure 4.6). Compared to annual precipitation z-scores, summer PDSI spanned a narrower range of climatic conditions, from ‘slightly wet’ to ‘extreme drought’ (Figure 4.7).

Distinct climatic patterns coincided with the three categories of synchronous events. During the 50 years with moderate–high fire synchrony, mean annual precipitation z-scores showed ‘mild drought’ at eastern sites and most northern sites, whereas ‘incipient drought’ to ‘near normal’ conditions were found at most western sites (Figure 4.8a; Appendix D). Mean summer PDSI values showed ‘near normal’ conditions at the northern sites along the continental divide and increased from ‘incipient drought’ to ‘moderate drought’ with decreasing latitude (Figure 4.8b).

During the six years with moderate–high widespread-fire synchrony, mean annual precipitation z-scores corresponded to ‘severe drought’ and ‘extreme drought’ at eastern and northern sites, and ‘near normal’ to ‘moderate drought’ conditions at southwestern sites (Figure 4.8c). Mean summer PDSI values showed ‘incipient drought’ to ‘extreme drought’ conditions from the northwest to southeast (Figure 4.8d).

The 14 non-fire years mean annual precipitation z-scores and summer PDSI values showed mostly 'incipient wet' to 'moderately wet' conditions across the region with wetter conditions in the south and east (Figure 4.8e and 4.8f).

4.4 Discussion

4.4.1 Fire synchrony mostly coincided with drought

In the Montane Cordillera of Canada, synchronous fires that scarred trees at ≥4 study sites (i.e., years of moderate-high fire synchrony) during the same year were common historically and generally facilitated by regionally warm and dry climate during the fire season and preceding year. My findings corroborate those found in several regions of western North America showing greater fire synchrony during droughts (e.g., Heyerdahl et al. 2008a, 2008b; Trouet et al. 2010; Margolis and Swetnam 2013); however, I also found that regional drought was not a necessary condition for fire synchrony. Several years with moderate–high fire synchrony occurred during regionally wetter-than-normal conditions (e.g., 1827, 1828, 1866, and 1915). As explained by Gedalof et al. (2005) and Macias Fauria et al. (2011), warm, dry, or windy weather for periods of only two to three weeks during the fire season can lower the moisture content of some forest fuels sufficiently to enable ignition and spread. Following short periods that dry fuels, low-intensity fires that scar but do not kill trees could have occurred in low- and mid-elevation forests in the region. These fires may have been constrained spatially due to adjacent forest fuels that maintained high moisture content and temporally due to the return of weather conditions less favourable for burning, such as precipitation, lower temperature, higher relative humidity, and lack of wind (Flannigan and Harrington 1988; Meyn et al. 2007). A likely consequence of these spatial and temporal constraints would be fewer widespread fires, which is consistent with the fire-scars formed in 1827, 1828, 1866, and 1915.

On average, moderate–high fire synchrony coincided with significantly drier-than-average climate, particularly in the Columbia and Rocky Mountains that are located in the eastern part of the region. Specifically, most years with high fire synchrony revealed that fires in the Columbia and Rocky Mountains were more likely to burn during summer droughts that followed low antecedent annual precipitation. Such conditions occurred during 8 of the 11 years with high fire synchrony (1831, 1847, 1863, 1864, 1869, 1883, 1889, and 1896). My findings likely reflect the presence of mid-tropospheric anomalies, and possibly documented phases of Pacific oceanic-atmospheric teleconnections such as the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) that were conducive to fire synchrony. Mid-tropospheric anomalies in the form of upper-atmosphere blocking ridges were related to lower moisture, fuel drying, and increased fire activity over western Canada (Skinner et al. 1999), including the Canadian Rocky Mountains (Johnson and Wowchuck 1993). Over the Pacific Northwest, including some of the sites from the Interior Plateau of British Columbia, Kitzberger et al. (2007) and Heyerdahl et al. (2008b) found fire synchrony coincided with dry climate related to warm phases of ENSO and PDO. However, the findings from these studies contrasted the results of Macias Fauria and Johnson (2006, 2008) who reported cool phases of ENSO and PDO coincided with increased fire activity over most of the Montane Cordillera, and the findings of Harvey and Smith (2017) and Chavardès et al. (2018) who documented no significant relationships. Lack of congruence among these studies may be due to a strong expression of rain shadow effects on the Interior Plateau (Harvey and Smith 2017), and a climatic transition zone along the Columbia and Rocky Mountains (Macias Fauria and Johnson 2008). As a post-hoc analysis I used published reconstructions of Pacific oceanic-atmospheric teleconnections including ENSO (Stahle et al. 1998, D'Arrigo et al. 2005; Braganza et al. 2009; Wilson et al. 2010), the Pacific North American circulation pattern (Trouet and Taylor 2010; Liu et al. 2017), PDO (Biondi et al. 2001; D'Arrigo et al. 2001; Gedalof and Smith 2001; D'Arrigo and Wilson 2006; MacDonald and Case 2005), and Pacific Decadal Variability (Black et al. 2016) that overlapped with the period of analysis, to test whether opposing phases were associated with categories of synchrony. I found none of the 11 reconstructions revealed significant associations between phases and categories of synchrony based on analysis of variance on ranks ($p \geq 0.381$). A possible explanation for the lack of association with historical fire synchrony in the region is that these teleconnections had distinct subregional influences (Watson and Luckman 2005), that were temporally unstable (e.g., Knapp et al. 2002; Black et al. 2016).

4.4.2 Uncommon, synchronous widespread-fires were driven by pronounced drought

Although widespread fires were common at the site level, synchronous widespread-fires that scarred trees at ≥4 sites were uncommon and exclusively coincided with pronounced drought at regional and subregional scales. In 1831, 1847, 1869, and 1889, pronounced drought during the summer preceded by low annual precipitation particularly in the eastern parts of the region coincided with widespread fires at sites in both the Interior Plateau and Rocky Mountains. Similarly, drought conditions were found to facilitate historical widespread fires in forests of the northwestern USA (Hessl et al. 2004; Gedalof et al. 2005; Heyerdahl et al. 2008a, 2008b). However, I found many individual years with regional drought conditions between 1746 and 1945 that lacked evidence of synchronous fires at our study sites. This finding indicates that regional drought does not guarantee fire occurrence and synchrony (Gedalof 2011). There are several potential explanations for the lack of evidence of fire synchrony during these years. Despite drought pre-conditioning forest fuels for fire spread, there may have been few ignitions from lightning or people during those particular years. Fires burned but their intensity was insufficient to scar trees (Swetnam et al. 1999) or intense fires killed rather than scarred trees. Fires were recorded at only a few sites as a result of spatial variation in the degree of drought. Alternately, fires burned and scarred trees but the evidence was subsequently eliminated by successive fires, wood decomposition, and mechanical damage (Parson et al. 2007; Swetnam et al. 2011).

The high number of fire-scars formed during years with multiple widespread fires highlights the historic importance of surface fires even during regionally pronounced droughts affecting low- and mid-elevation coniferous forests of the Montane Cordillera. I surmise the historical extensiveness of surface fires may have been promoted by different factors. For example, in 1831 and 1847, pronounced summer drought conditions covered most of the region except in parts of the Interior Plateau that had near normal to incipient drought conditions. However, even under these fairly low drought conditions, sites in the Interior Plateau had abundant evidence of surface fires. In the low- to mid-elevation dry mixed-conifer forests of the Interior Plateau, fuels are more likely sufficiently desiccated by the regular periods of warm, dry weather therefore climate is less of a fire regime control than in more mesic forests (Heyerdahl et al. 2007, 2012; Harvey et al. 2017). As a result of surface fires capable of burning even under low drought conditions, fires can be fairly frequent, which is corroborated by the fire-scar records from sites in the Interior Plateau. Fairly frequent surface fires suggest that surface fuels and potential ladder fuels were more likely consumed thus further facilitating surface fires relative to crown fires (Agee 1993; Bond and Keeley 2005). Another possible factor is that some of the surface fires may have burned over periods that did not coincide with peak fire season, such as during the early or late months of the fire season when drought conditions were less pronounced. Fires occurring during months with milder drought conditions likely consumed fewer fuels due to higher fuel moisture contents and as a result fires were more likely of lower severity (e.g., Chavardès et al. 2019).

4.4.3 Changes during the 20th century

Decreased surface fire evidence across the Montane Cordillera after 1945 reflects findings from western North American forests, which relate the decrease to a period combining the imposition of fire exclusion policies at the turn of the 20th century, the modernization of fire suppression organizations (Keane et al. 2002; Donovan and Brown 2007; Pyne 1982, 2007), and less fire-conducive climate over several decades in the Northern Rocky Mountains of the USA (Higuera et al. 2015), and across the province of British Columbia (Meyn et al. 2010a). As a result of decreased fire activity, changes in fuel structure and availability were identified, including persistence of ladder fuels and increased canopy closure in some western USA forests (e.g., Taylor and Skinner 2003; Brown et al. 2004; Schoennagel et al. 2004; Higuera et al. 2015) and forests of the Montane Cordillera (e.g., Daniels et al. 2011; Marcoux et al. 2015; Chavardès and Daniels 2016; Harvey et al. 2017). My findings suggest that the resilience associated with frequent surface fires is eroding with the evidence of these fires from our records across the Montane Cordillera starting in the mid-20th century.

As the climate of western North America became more conducive to fire after the mid-1980s via increased temperatures and prolonged fire seasons, fire activity also increased in western US forests (Westerling et al. 2006; Higuera et al. 2015; Westerling 2016). In Canada, increased fire activity in forests of the Montane Cordillera was not detected until the early 21st Century (Filmon et al. 2003; Tzembelicos et al. 2018; Kirchmeier-Young et al. 2019). A possible explanation for the lagged response may stem from strong fire suppression policies maintained until the early 21st Century. For example, these policies were maintained until 2012 in British Columbia and it is only afterwards that more flexible management approaches were implemented such as permitting some fires to burn when these do not threaten communities and infrastructure (Government of British Columbia 2012). An added explanation is that lower temperatures at higher latitudes mitigated increases in lightning ignitions (Price and Rind 1994) and fire activity (Wang et al. 2014). However, as temperatures further increased into the 21st Century, and landscapes were subject to fewer surface fires, conditions likely shifted towards supporting large fires with high-severity effects that pose risks to human communities (Sankey 2019). Such fires in the region are likely to occur again given the availability of forest fuels, expansion of human communities, and climate-change predictions including longer fire seasons, increased cumulative fire severity ratings (Flannigan et al. 2013), and increased lightning ignitions (Price and Rind 1994; Krawchuk et al. 2009).

4.5 Conclusion

I conclude that until 1945 years when fires scarred trees at ≥4 sites (i.e., moderate–high fire synchrony) were common within the Montane Cordillera, but that years when widespread fires scarred trees at ≥4 sites (i.e., moderate–high widespread-fire synchrony) and when none of the study sites included fire scars were fairly rare. Warm and dry climate particularly during the summer at regional and subregional scales facilitated moderate–high fire synchrony; although, these conditions needed to be more pronounced for moderate–high widespread-fire synchrony.

Decreased fire synchrony after 1945 coincided with advances in fire suppression and less fire conducive climate during several decades. The drop in fire synchrony across the region is consistent with increased ladder fuels and canopy cover found in many forests, suggesting that seasonal climate is becoming a less important driver of fire than fuel abundance and short term variations in weather. Regional predictions including longer fire-seasons, and increased fire-severity ratings suggest that these forests may include more frequent, high-severity fires that can synchronize as observed during the 2017 and 2018 fire seasons in the Montane Cordillera.

Table 4.1 Characteristics of the 17 site-level fire records arranged from north to south in the Montane Cordillera of Canada.

Site	Location		No. of fire-scar samples	Complete fire record (years)	Period of analysis (1746–1945)			
					First fire year	Last fire year	No. of fire years	No. of widespread fire years
1	53°50'N	117°47'W	62	1640–2009	1756	1934	9	5
2	53°03'N	118°05'W	102	1604–2011	1772	1915	12	5
3	52°54'N	118°04'W	170	1735–1974	1846	1944	41	4
4	52°04'N	121°54'W	65	1558–2015	1747	1943	12	7
5	51°55'N	123°13'W	139	1513–2013	1747	1945	73	5
6	51°40'N	121°40'W	139	1491–1995	1756	1938	32	7
7	51°26'N	122°18'W	92	1520–2012	1748	1943	56	11
8	50°48'N	115°58'W	83	1693–2009	1848	1926	11	4
9	50°18'N	121°58'W	155	1511–1999	1754	1937	62	17
10	50°16'N	121°39'W	162	1608–1996	1749	1941	57	19
11	50°10'N	115°47'W	149	1431–2006	1757	1938	25	5
12	50°01'N	116°05'W	108	1353–2005	1748	1937	34	8
13	49°34'N	117°10'W	45	1665–2009	1834	1927	10	6
14	49°34'N	115°46'W	43	1522–2003	1751	1891	20	10
15	49°25'N	115°40'W	96	1510–2007	1751	1923	17	6
16	49°17'N	119°33'W	149	1611–2013	1759	1945	31	17
17	49°13'N	116°45'W	127	1407–2009	1768	1926	18	9

Sources for each site-level fire record: 1: Amoroso et al. 2011; 2: Chavardès et al. 2018; 3: Dinh 2014; 4: Brookes 2019; 5: Harvey and Smith 2017; 6: Daniels and Watson 2003; 7: Harvey et al. 2017; 8: Kubian 2013; 9: Heyerdahl et al. 2008, 2012; 10: Heyerdahl et al. 2007; 11: Cochrane 2007; 12: Daniels et al. 2006, Gray and Daniels 2007; 13: Nesbitt 2010; 14: Nesbitt and Daniels 2009; 15: Marcoux et al. 2013, Villemaire-Côté 2014; 16: Pogue 2017; 17: Greene and Daniels 2017.

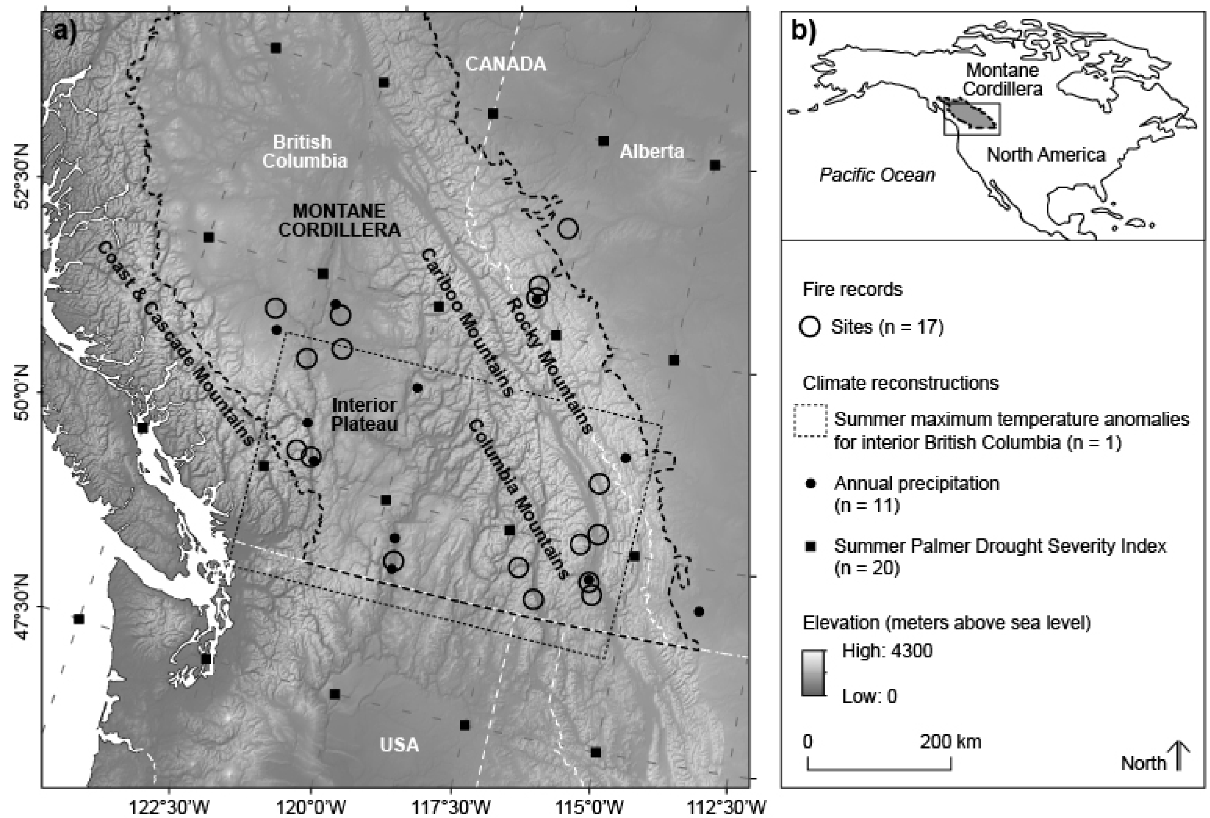

Figure 4.1 (A) Centroid locations for the sites with fire records and locations of the climate reconstructions across the Montane Cordillera of Canada in (B) western North America.

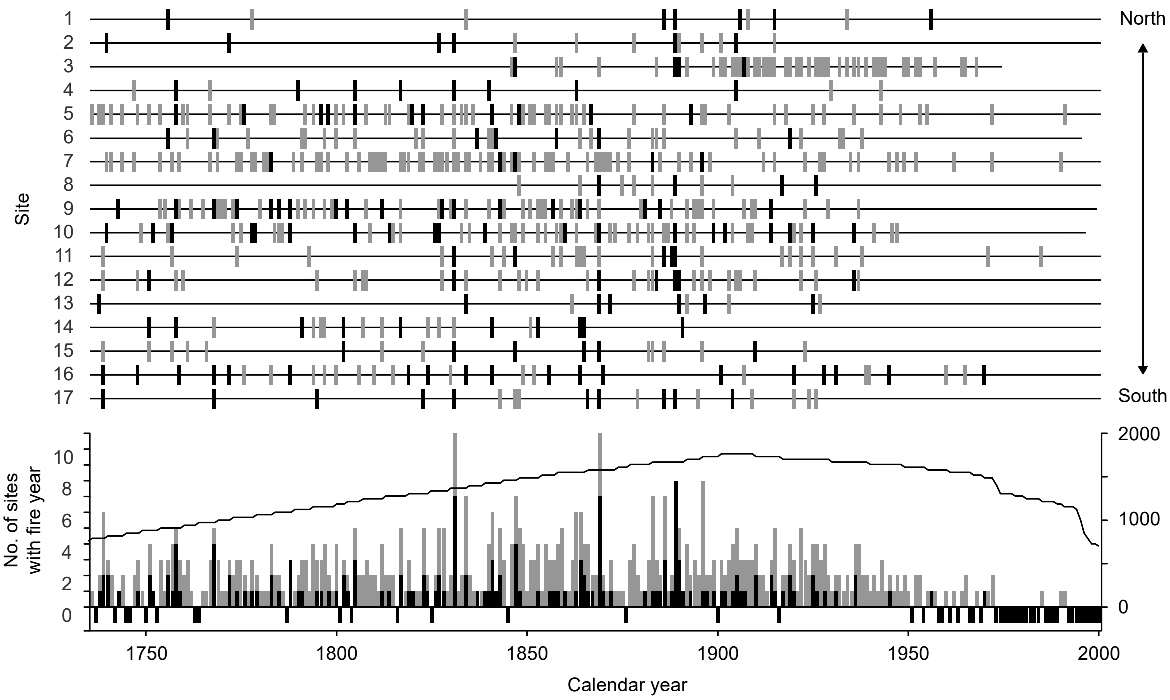

Figure 4.2 Fire records from 1735–2000 for the 17 sites within the Montane Cordillera. The top panel shows the fire record for each site organized by latitude from northernmost to southernmost locations, the temporal extent of each fire record from the starting year among fire records as a horizontal line, each fire year as a gray tick, and each widespread-fire year as a black tick. The bottom panel shows the number of sites with a given fire year as gray columns, and widespread-fire year as black columns. Years in which no sites recorded fire are synchronous non-fire years and shown as black columns extending downward for emphasis. The curve indicates the number of crossdated fire-scar samples over time.

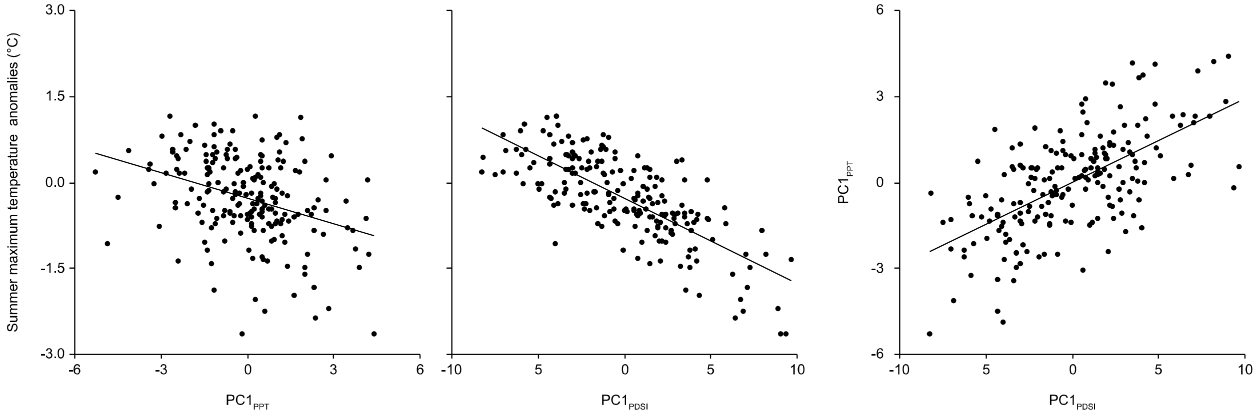

Figure 4.3 Scatter plots for the reconstructions of regional climate for the Montane Cordillera. Reconstructions of regional climate corresponds to the reconstruction of summer maximum temperature anomalies (C°), the first principle component of the 11 reconstructions of annual precipitation ($PC1_{PPT}$), and the first principle component of the 20 reconstructions of summer Palmer Drought Severity Index ($PC1_{PDSI}$). Drier (wetter) conditions according to $PC1_{PPT}$ and $PC1_{PDSI}$ lie below (above) zero.

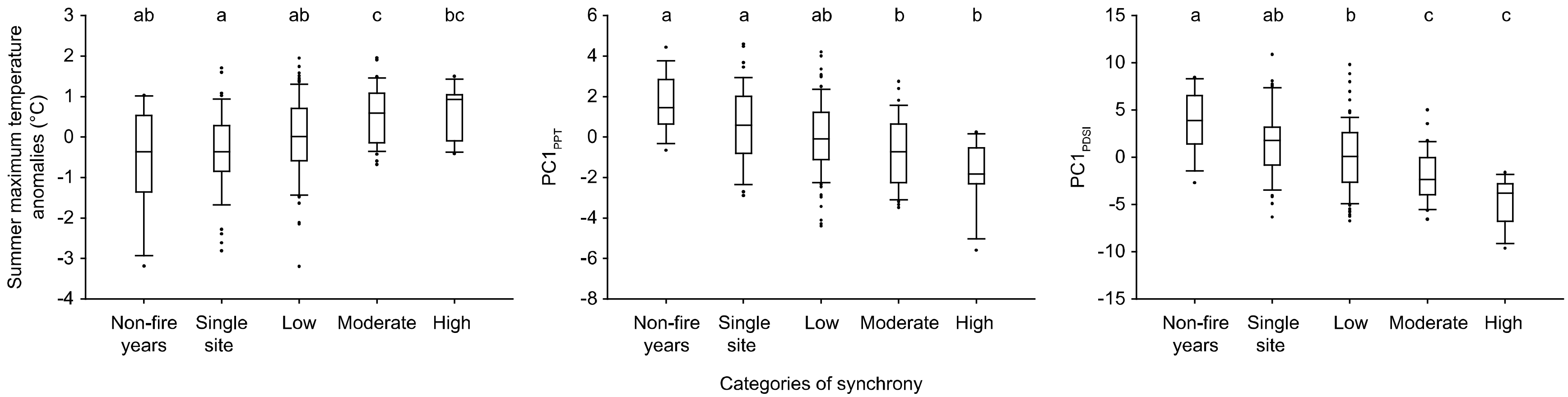

Figure 4.4 Reconstructions of regional climate according to categories of synchrony in the Montane Cordillera. Reconstructions of regional climate correspond to the reconstruction of summer maximum temperature anomalies (C°), the first principle component of the 11 reconstructions of annual precipitation ($PC1_{PPT}$), and the first principle component of the 20 reconstructions of summer Palmer Drought Severity Index ($PC1_{PDSI}$). Drier (wetter) conditions according to $PC1_{PPT}$ and $PC1_{PDSI}$ lie below (above) zero. Categories of synchrony correspond to: non-fire years = no fire years recorded at all 17 sites (n = 14); single site = fire year recorded at one site only (n = 48); low = fire year recorded at two to three sites (n = 88); moderate = fire year recorded at four to five sites (n = 39); and high = fire year recorded at six or more sites (n = 11) (adapted from Heyerdahl et al. 2008a). In each box plot, the black horizontal line represents the median, box boundaries are the 25th and 75th percentiles, and bars are the 10th and 90th percentiles. Different letters denote significant differences among median reconstructed regional climate values ($\alpha = 0.05$).

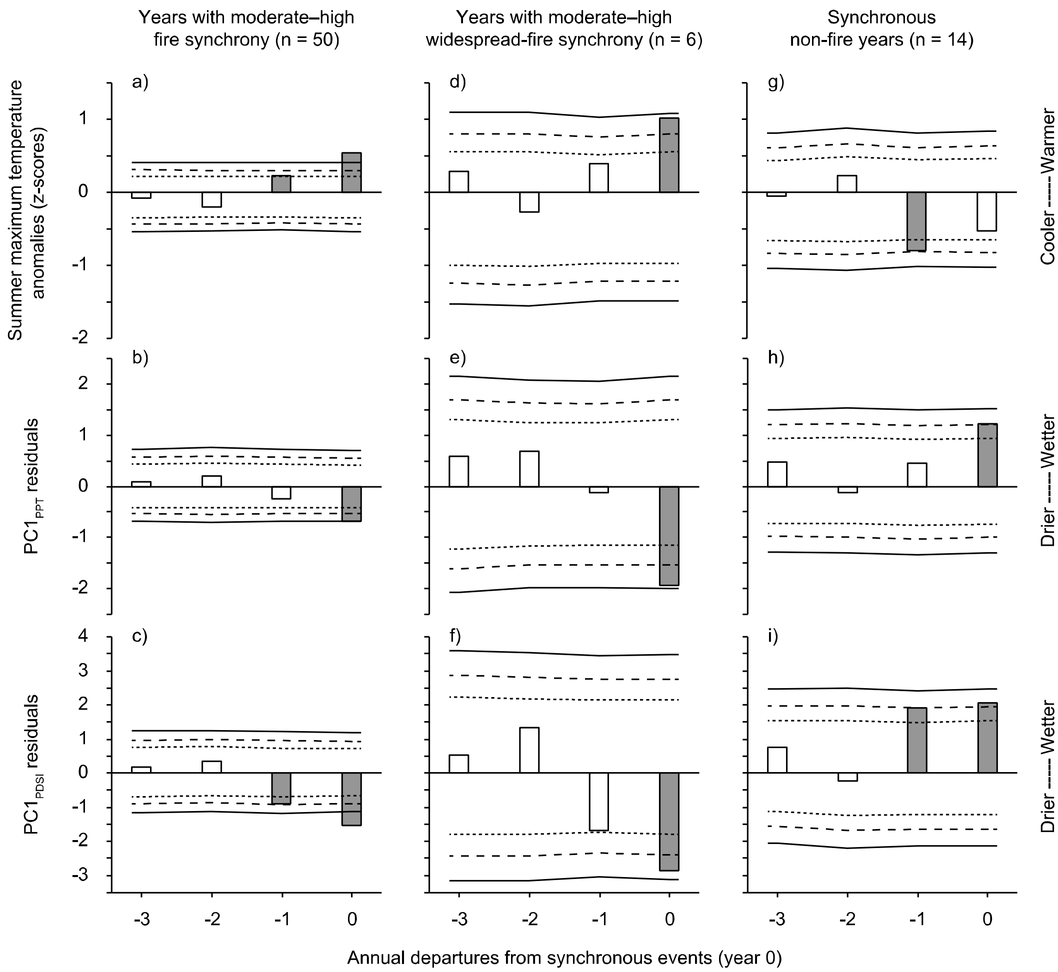

Figure 4.5 Superposed epoch analyses showing associations between reconstructions of regional climate during synchronous events (moderate–high fire synchrony or widespread-fire synchrony, or synchronous non-fire years) from 1746–1945. Reconstructions of regional climate correspond to z-scores of the reconstruction of summer maximum temperature anomalies, white noise residuals of the first principle component for the 11 reconstructions of annual precipitation ($PC1_{PPT}$ residuals), and white noise residuals of the first principle component for the 20 reconstructions of summer Palmer Drought Severity Index ($PC1_{PDSI}$ residuals). Solid, long- and short-dashed lines represent confidence intervals of 99.9%, 99%, and 95%, respectively. Gray bars indicate statistically significant departures from the mean ($p < 0.05$).

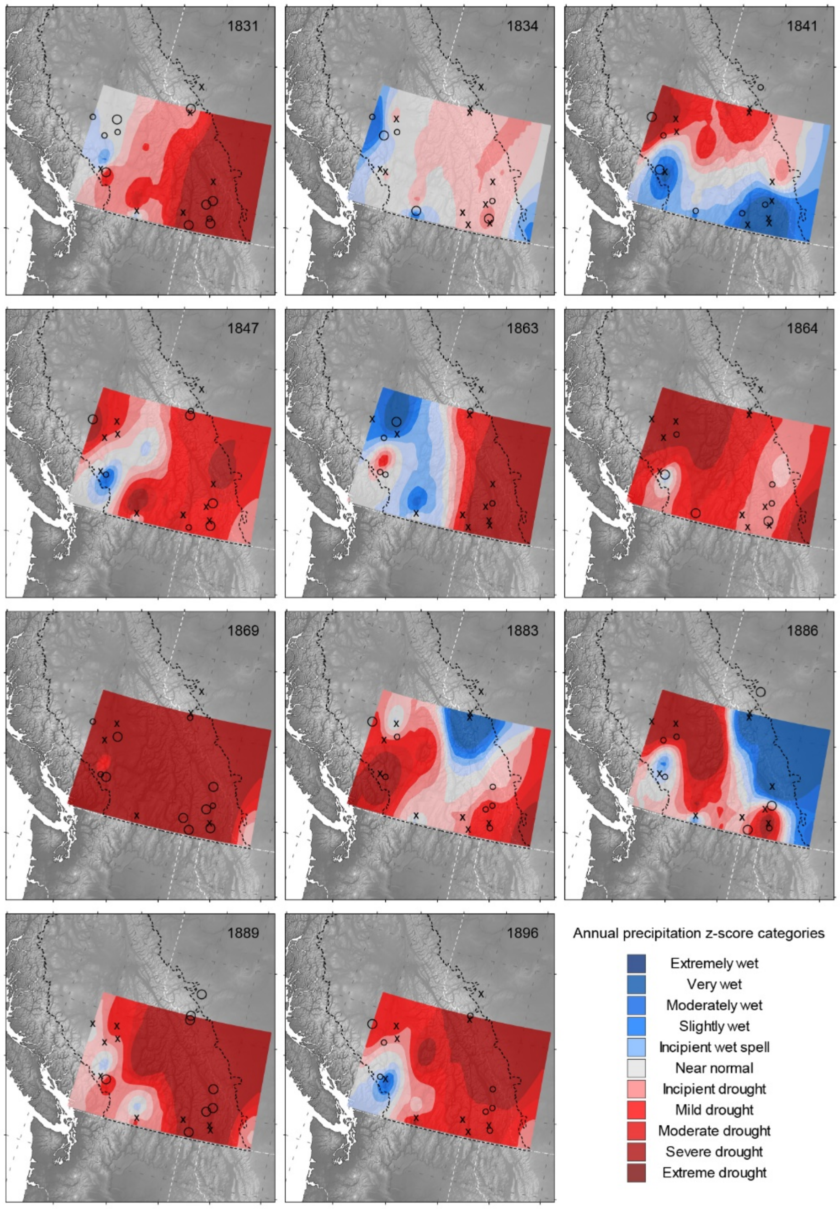

Figure 4.6 Reconstructions of mean annual precipitation z-scores interpolated across the Montane Cordillera during the 11 years with high fire synchrony. Darker reds (blues) indicate drier (wetter) conditions, whereas grey indicates near normal conditions (see Appendix D for more details). Small and large open circles indicate a fire and widespread fire was found at the site during the given year, respectively, whereas an ‘x’ indicates no fire scars were found at the site during the given year.

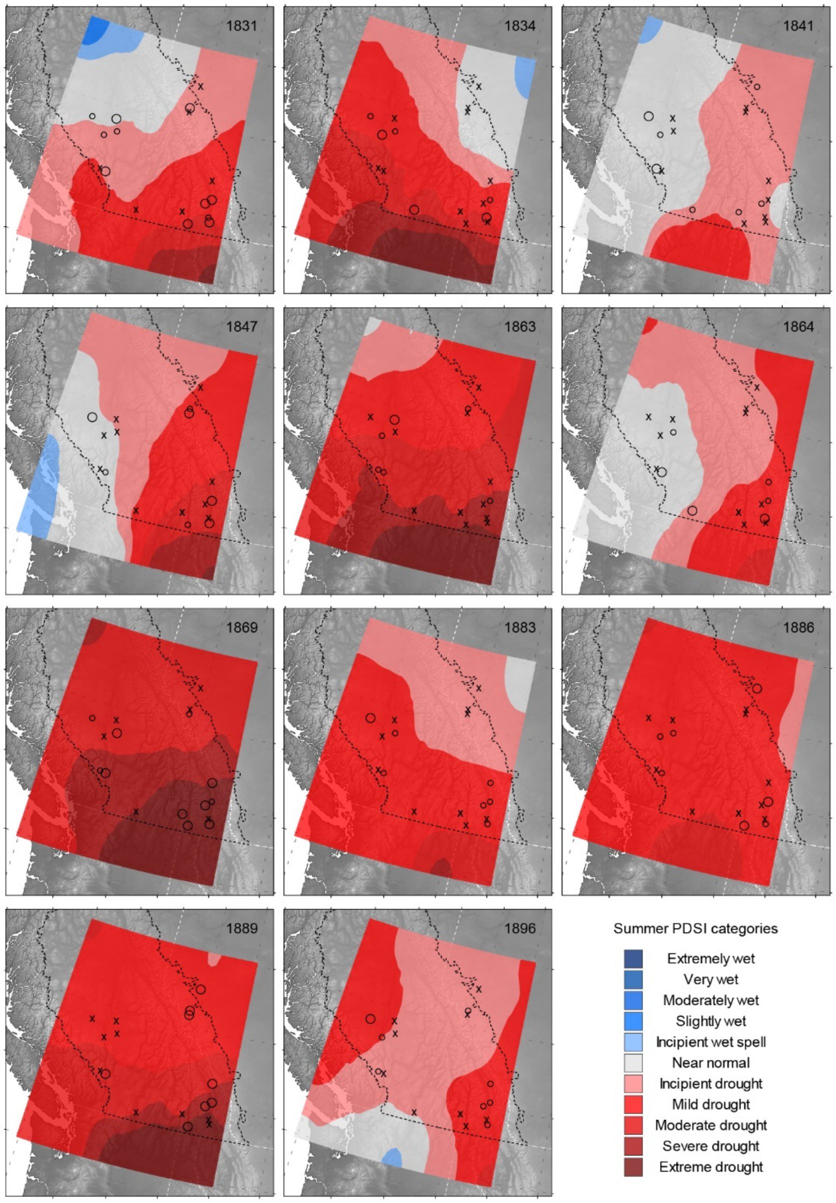

Figure 4.7 Reconstructions of mean summer Palmer Drought Severity Index (PDSI) values interpolated across the Montane Cordillera during the 11 years with high fire synchrony. Darker reds (blues) indicate drier (wetter) conditions, whereas grey indicates near normal conditions (see Appendix D for more details). Small and large open circles indicate a fire and widespread fire was found at the site during the given year, respectively, whereas an 'x' indicates no fire scars were found at the site during the given year.

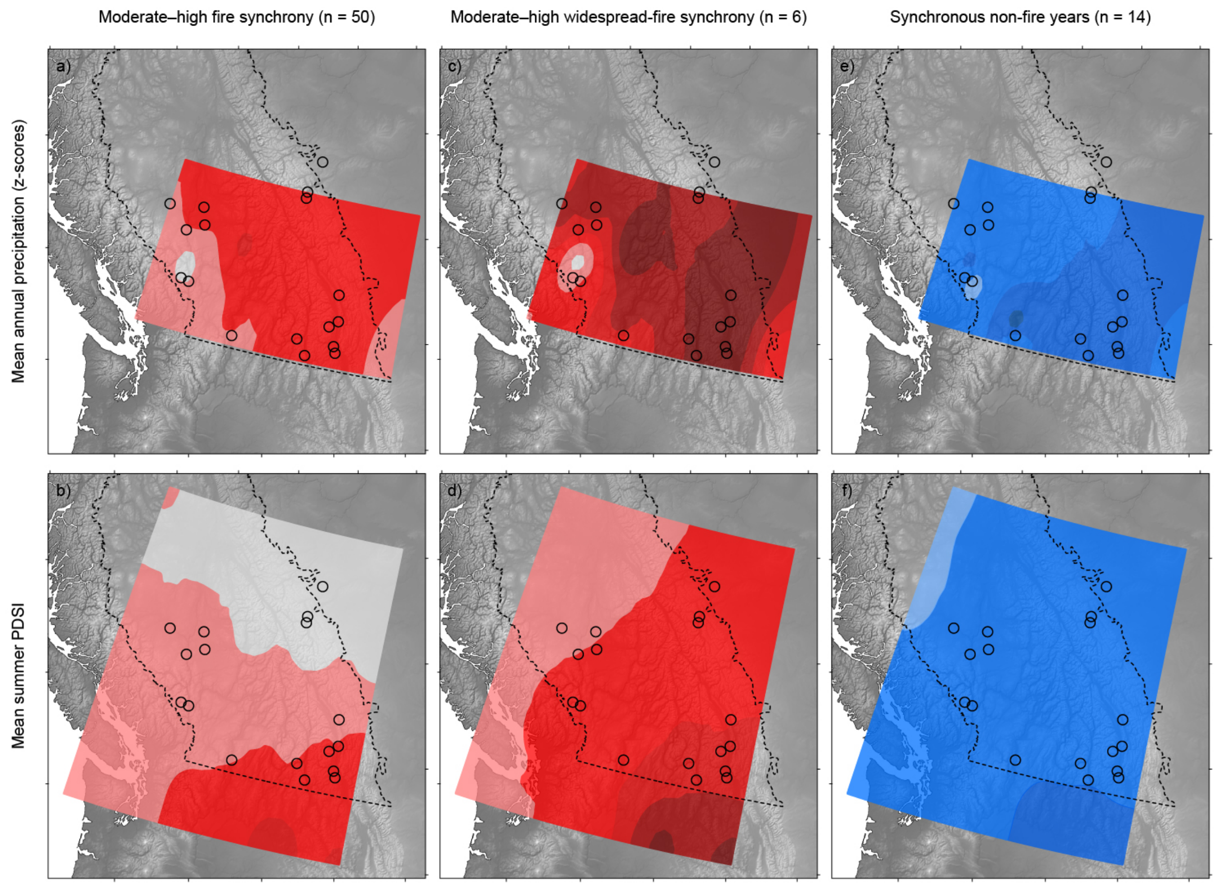

Figure 4.8 Reconstructions of mean annual precipitation z-scores, and mean summer Palmer Drought Severity Index (PDSI) values interpolated across the Montane Cordillera from 1746–1945 during years with synchronous events (moderate–high fire synchrony or widespread-fire synchrony, or synchronous non-fire years). Darker reds (blues) indicate drier (wetter) conditions, whereas grey indicates near normal conditions (see Appendix D for more details). Open circles indicate the 17 sites.

Chapter 5: Conclusion

5.1 Thesis Contribution and Summary

Understanding drought as a driver of mixed-severity fire regimes across temporal and spatial scales in the Montane Cordillera is important because some of the fire regimes in this region are expected to include increased frequency of large fires with a greater proportion of high-severity impacts (Daniels et al. 2011; 2017). In western North America, including the Montane Cordillera, warming temperatures were associated with longer fire seasons comprising more frequent and large fires (Westerling et al. 2006; Dennison et al. 2014; Kirchmeier-Young et al. 2019). When combined with 20th century increases in ladder fuels and canopy cover documented in some forests with mixed-severity fire regimes (e.g., Daniels et al. 2011; Marcoux et al. 2015; Chavardès and Daniels 2016; Harvey et al. 2017), the changes to the fire season can favour higher-severity fires in these forests. Moreover, further warming over the 21st Century is expected to increase fire-severity ratings (Flannigan et al. 2013) and the number of lightning ignitions (Price and Rind 1994; Krawchuk et al. 2009).

The findings from this thesis contribute to the understanding of how drought influences mixed-severity fire regimes across temporal and spatial scales in the Montane Cordillera of Canada as follows. In Chapter 2, three monthly adaptations of the daily Drought Code (DC) of Canada's Fire Weather Index System were compared and applied to interpret drought conditions associated with historical fires in montane forests of southeastern British Columbia within the Montane Cordillera. The three adaptations were compared with the monthly mean DC calculated from daily values for the Palliser fire-weather station. Two adaptations improved on the existing Monthly DC calculated from monthly climate data by (1) accounting for overwinter drying and an early start to the fire season, and (2) improving estimates of effective precipitation. Using a crossdated fire-scar record from 20 sites in montane forests surrounding the Palliser station, revealed significant fire-drought associations from June–August with all adaptations, and significant associations in April and May with the two new adaptations. Of the 17 fire years from 1901–2013, six years had low initial drought conditions that increased late in the fire season, and five years had high drought conditions throughout the fire season. The findings from Chapter 2 highlight that variable drought conditions within and among fire seasons influenced fire severity.

In Chapter 3, drought influences on mixed-severity fire regimes in montane forests of southeastern British Columbia were further investigated. Initially, a Douglas-fir latewood-width chronology was developed and tested for associations with monthly drought records across the fire season. Associations were strong between records and latewood-widths, particularly from June–August. Based on the chronology, a summer Drought Code was reconstructed, and compared to a reconstruction of the Palmer Drought Severity Index. Comparing reconstructions provided a nuanced understanding of moisture content among forest fuels, namely in deep compact organics in the soil and coarse woody fuels versus the duff layer. Fire-drought associations were tested using the reconstructions and fire-scar records from montane forests of southeastern British Columbia. These tests revealed fire years were associated with previous and current year summer droughts; but limited by previous and current summer wet conditions. The findings from Chapter 3, highlight that variable fuel moisture conditions across fuels during fire years according to the reconstructions likely led to fires igniting and burning with a range of severities.

Chapter 4 provided information on fires that occurred at multiple sites during historical fire seasons in the Montane Cordillera, and the climate conditions under which these fires burned. Local fire-scar chronologies were composited into 17 site-level records comprising

1,886 fire-scar samples. The composite fire record was tested against regional climate reconstructions to examine historical fire-climate associations for years with synchronous events, namely years when fires and widespread fires scarred trees at ≥4 sites and non-fire years, when none of the study sites included fire scars. Findings revealed that years with fires at ≥4 sites (i.e., moderate–high fire synchrony) occurred during 50 distinct years from 1746–1945. Years with widespread-fires at ≥4 sites (i.e., moderate–high widespread-fire synchrony) and no fires recorded at all sites were less common, occurring during 6 and 14 years, respectively. At regional and subregional scales, years with moderate–high fire synchrony coincided with warm and dry climate, with pronounced drought conditions occurring during years with moderate–high widespread-fire synchrony. From 1945 to 2000, decreased fire synchrony partly reflects improvements in fire suppression technology. Given anticipated longer fire-seasons and increased fire-severity ratings, more frequent, widespread, and potentially high-severity fires will have a greater chance of burning.

5.2 Management Implications

The 2017 and 2018 fire seasons in the Montane Cordillera of western Canada challenged fire managers to accept that extreme back-to-back summer droughts with multiple large synchronous fires can overwhelm fire suppression capacities (Sankey 2019). To adapt to this new reality of climate change impacts on fire regimes within the region, fire managers should use novel information that can support them strategically. The drought indices and methods developed and applied in my research provide practical information on drought variability and fire-drought associations across temporal and spatial scales in the Montane Cordillera. Apart from gaining a historical perspective on the drought conditions during which fires burned at, fire managers can compare this information to current drought conditions coinciding with fires and droughts anticipated due to climate change. Specifically, understanding how climate change could affect seasonal droughts can reveal critical information on the frequency of fire seasons with suitable and safe conditions for prescribed burns (Parks Canada and the Canadian Parks Council 2008; British Columbia Wildfire Service 2010). Likewise, detailed information about differences among drought indicators provides fire managers with long-term perspectives on fire behaviour such as the likelihood of sustained ignitions and fires burning across a range of severities. Such knowledge can ultimately guide sustainable fire management strategies that account for the historic range of variability in these forests (Keane et al. 2009). Finally, given the historical evidence that fires burned at multiple locations across the region during extreme droughts and climate change predictions indicating increased fire-severity ratings (Flannigan et al. 2013) and lightning ignitions (Price and Rind 1994), I suggest that fire managers should plan for future scenarios with higher frequency of fire seasons with extreme droughts and multiple large fires across the Montane Cordillera.

5.3 Directions for Future Research

5.3.1 Comparing the strength of fire-drought associations among fire regimes

To test the hypothesis that the strength of fire-drought associations varies among fire regimes (Agee 1993; Schoennagel et al. 2004), I suggest calculating monthly DCs and testing their associations with historical and modern fire records at different locations across western Canada including similar montane forests, drier low-elevation forests, and cooler and more mesic subalpine forests and boreal forests. Compared to drier low-elevation forests, I expect stronger fire-drought associations in more mesic forests because they require prolonged periods of drought that facilitate ignition and combustion (Macias Fauria et al. 2011). However, I also expect to find fewer fire years in these forests relative to drier forests. Fewer fire years will widen the confidence limits in statistical approaches such as superposed epoch analysis. To address this problem, a combined approach that also uses more flexible statistical models (e.g., generalized linear mixed models) may be more appropriate to test fire-drought associations. Ultimately, such research consolidates understanding of fire-drought associations across ecoclimatic regimes in western Canada.

5.3.2 Anticipating drought influences on future fire activity in montane forests of southeastern British Columbia

The summer DC and Palmer Drought Severity Index (PDSI) thresholds can be applied to meteorological data and climate predictions to assess how climate change could impact fire activity for montane forests with mixed-severity fire regimes in southeastern British Columbia. Specifically, when summer DC $\geq$344 and summer PDSI $\leq$0.08, fire managers can expect high probability of fire at one to multiple sites in these forests. Past these thresholds, my findings suggest that the duff layer is dry and facilitates ignitions, and that fires are more likely to burn dry deep organics in the soil and coarse woody fuels. To assess the impacts of climate change on the mixed-severity fire regime in these montane forests, I suggest to compare drought conditions during historical and future years according to summer DC and PDSI and their respective thresholds.

5.3.3 Assessing changes in fire severity for forests of the Montane Cordillera

The historical fire records including 1886 fire-scar samples from 17 sites provide evidence that low-severity surface fires were common in some low- and mid-elevation forests of the Montane Cordillera. By comparison, the many large fires in 2017 and 2018 included extensive high tree mortality indicting high-severity effects (Natural Resources Canada, unpublished data). I suggest to resurvey the sites from which the fire-scar records were collected to assess whether some of the 2017 and 2018 fires may have burned at high severity at these sites. If this is the case, then I may find some of the fire-scarred trees may have been consumed by these latter fires. Such a finding would provide evidence that some sites historically burned by fairly frequent low-severity surface fires are including more high-severity fires.

5.3.4 Interregional fire-climate associations focusing on teleconnections

Although other research has detected influences of Pacific oceanic-atmospheric teleconnections on fires in western North America (Kitzberger et al. 2007; Trouet et al. 2010), including the Pacific Northwest (Hoffman et al. 2016), and Southern Interior British Columbia (Heyerdahl et al. 2008b), I did not find associations between such teleconnection reconstructions and the regional fire records from forests of the Montane Cordillera. Two potential limitations are that the teleconnections were unstable over time (e.g., Knapp et al. 2002; Black et al. 2016) and their reconstructions reproduce the instability (e.g., Kipfmueller et al. 2012), or the teleconnections had distinct interregional influences. I propose to test the latter hypothesis with fire-scar records from sites located in sufficiently distant study areas such that differences in fire-climate associations can be detected.

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Appendices

Appendix A

A.1 Daily Drought Code

The daily Drought Code (DC) is a dimensionless index which tracks, on a daily basis over the fire season, changes in moisture within the deep layer (~18 cm) of compact (~25 kg m^{-2} dry weight) organics in the soil (Van Wagner 1987) and large diameter woody fuels (Wotton 2009). The DC has a slow drying rate with a lagtime of 51 days (Field et al. 2015) where the lag represents the time required to lose roughly two-thirds of the free moisture content over 24 hours at 21.1 °C and relative humidity of 45 % (Van Wagner 1987). By default, the DC is given a value of 15 at the start of the fire season which is either the third day after snow has melted in regions normally covered by snow during the winter, or the third day that noon temperatures of 12 °C or higher have been recorded in regions where snow cover is not a significant feature (Lawson and Armitage 2008). The DC on any subsequent day of the fire season is calculated as:

$\mathrm{DC} = 400 \times \ln(800/\mathrm{Q})$, if Q >800 then Q = 800

where Q is the daily moisture equivalent (dimensionless) with maximum value 800 corresponding to saturation, and minimum value 0 corresponding to the driest condition (Van Wagner 1987). On each successive day of the fire season, DC is calculated by adding the effects of total daily precipitation (mm, as water equivalent) (Lawson and Armitage 2008) followed by daily potential evapotranspiration. The effect of total daily precipitation ppt is added to the previous day's value of the DC (DC_{d-1}) and the moisture equivalent after precipitation Q_{ppt} is calculated as:

$\mathrm{Q_{ppt}} = 800 \times e^{[-\mathrm{DC_{d-1}}/400]} + 3.937 \times \mathrm{PPT_{EFF}}$, if ppt >2.8 mm

or

$Q_{ppt} = 800 \times e^{[-DC_{d-1}/400]}$, if ppt $\leq$2.8 mm

where $PPT_{EFF} = 0.833 \times ppt - 1.27$ is the effective precipitation (mm) after canopy and surface fuel interception (Girardin and Wotton 2009). The effect of potential evapotranspiration E (dimensionless) over a given day d of the fire season (E_d) is calculated as:

$E_d = 0.36(TMX_d) + L_f$, if $E_d < 0$ then $E_d = 0$, if $TMX_d < 0$ °C then $TMX_d = 0$ °C

where TMX_d is the daily maximum temperature (°C), and L_f is a standard day length adjustment factor which varies by month (April = 0.9, May = 3.8, June = 5.8, July = 6.4, August = 5.0, September = 2.4, October = 0.4, and November–March = -1.6) (Girardin and Wotton 2009). The present day's value of the DC (DC_d) is calculated as:

$DC_d = 400 \times \ln(800/Q_{ppt}) + 0.5 \times E_d$

By default, DC calculations are continued until snow covers the ground or noon temperatures drop below 12 °C for three consecutive days (Lawson and Armitage 2008).

A.2 Overwintered Drought Code

In areas with moisture depletion in between fire seasons, the starting moisture equivalent value in the spring (Q_s; i.e., Q on the first day of the fire season) is calculated as:

$Q_s = a \times Q_f + b(3.94 \times ppt_w)$

where Q_f is the final moisture equivalent value in the fall (i.e., Q on the last day of the fire season), *a* is the carry-over fraction of prior fall moisture estimated as 0.5, 0.75 or 1.0, and *b* is the effectiveness of winter precipitation in recharging moisture reserves in spring estimated as 0.5, 0.75 or 0.9, and ppt_w is total winter precipitation (mm, as water equivalent) (Van Wagner 1987).

A.3 Monthly Drought Code

The Monthly Drought Code (MDC) is a dimensionless index which tracks monthly changes in moisture in deep compact organics in the soil and large-diameter woody fuels (Girardin and Wotton 2009). Typically, the MDC is assigned a value of 15 on April 30 (Girardin and Wotton 2009) or March 31 (Bergeron et al. 2010), the day preceding the start of the fire season. The MDC in any given month of the fire season is calculated as:

$\mathrm{MDC} = 400 \times \ln(800/\mathrm{Q_m})$, if $Q_m > 800$ then $Q_m = 800$

where Q_m is the moisture equivalent (dimensionless) during month m (Girardin and Wotton 2009). In their MDC calculations, Girardin and Wotton (2009) assumed that drying occurs in the first half of the month, total precipitation occurs in the middle of the month, and drying occurs again in the second half of the month. In a first step, potential evapotranspiration over a given month (E_m) of the fire season is calculated as:

$\mathrm{E_m} = \mathrm{N}[0.36(\mathrm{TMX_m}) + \mathrm{L_f}]$, if $E_m < 0$ then $E_m = 0$, if $TMX_m < 0$ °C then $TMX_m = 0$ °C

where TMX_m is the monthly mean of daily maximum temperatures (°C), L_f is the standard day length adjustment factor applied to each month as in the daily DC, and N is the number of days in the given month (Girardin and Wotton 2009). Following drying in the first half of the month, MDC is calculated as:

$\mathrm{MDC_{1st\ half}} = \mathrm{MDC_e} + 0.25 \times \mathrm{E_m}$

where MDC_e is the MDC value at the end of the previous month. The effect of total monthly precipitation (PPT_m; mm, as water equivalent) occurring mid-month affects the corresponding moisture equivalent (Q_{mr}) as follows:

$\mathrm{Q_{mr}} = 800 \times e^{[-(\mathrm{MDC_{1st\ half}})/400]} + 3.937 \times \mathrm{PPT_{EFF}}$

where $PPT_{EFF} = 0.833 \times PPT_m$ is the monthly effective precipitation (Girardin and Wotton 2009). Following drying over the second half of the month, the MDC value of at the end of the month, MDC is calculated as:

$$MDC_{2nd\ half} = 400 \times \ln(800/Q_{mr}) + 0.25 \times E_m$$

Averaging the MDC values at the end of the previous month and at the end of the given month yields the MDC value for the given month:

$$MDC_m = (MDC_e + MDC_{2nd\ half})/2$$

By default, MDC is calculations are discontinued at the end of each year on October 31 and does not account for potential overwinter drying of fuels (Girardin and Wotton 2009).

A.4 Adjusted Monthly Drought Code

The adjusted Monthly Drought Code (adjMDC) accounts for overwinter drying of fuels and starts on April 1. With adjMDC, moisture equivalents at the end of the fire season on October 31 (Q_{Oct}) and at the start of the fire season (Q_{Mar}) are calculated as:

$$Q_{Oct} = 800 \times e^{[-adjMDC_{Oct}/400]}$$

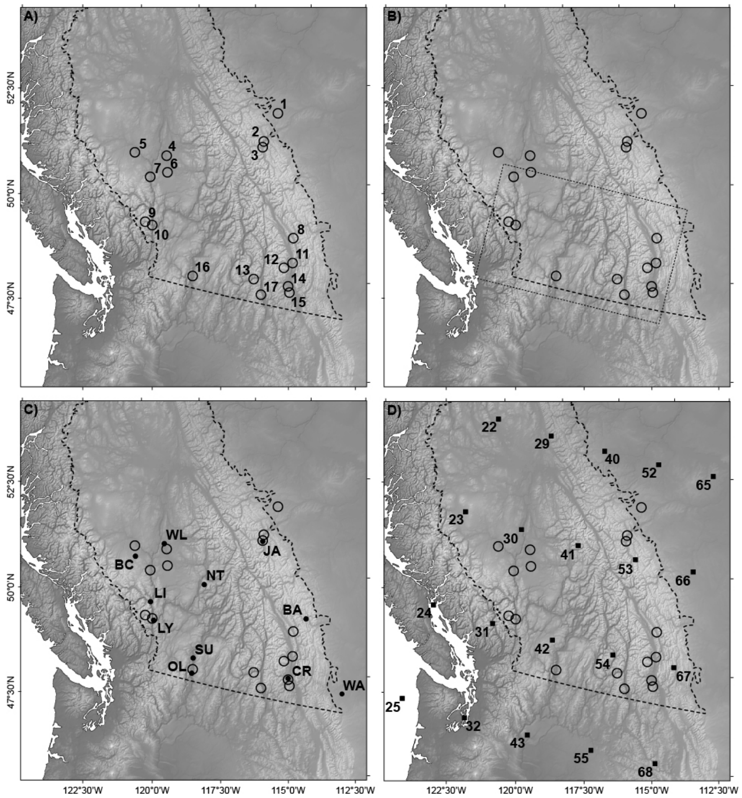
And,

$$Q_{Mar} = a \times Q_{Oct} + b(3.94 \times PPT_w),\ \text{if } Q_{Mar} > 800 \text{ then } Q_{Mar} = 800$$

where $adjMDC_{Oct}$ is the adjMDC value on October 31, *a* is the carry-over fraction of prior fall moisture estimated as 0.5, 0.75 or 1.0, *b* is the effectiveness of winter precipitation in recharging moisture reserves in spring estimated as 0.5, 0.75 or 0.9, and PPT_w is total winter precipitation (mm, as water equivalent) from November–March inclusive. I conducted a sensitivity analysis to select the most suitable combination *a* and *b* for our study area. I compared adjMDC, calculated with all possible combinations of *a* and *b*, against the overwintered DC_m values for April or May (depending on the start date for daily DC each year) from 1989–2013. Based on boxplots, Mann-Whitney rank sum tests, and Pearson product moment correlations adjMDC values were most suitable in April and May when *a* and *b* were both 0.75, corresponding to areas exposed to winter moisture depletion and sites that are moderately drained, respectively (Lawson and Armitage 2008). To begin each fire season, the adjMDC value on March 31 is calculated as:

$$\text{adjMDC}_{\text{Mar}} = 400 \times \ln(800/\text{Q}_{\text{Mar}})$$

Appendix B



B.1 (A) Centroids for site-level fire records: 1: Amoroso et al. 2011; 2: Chavardès et al. 2018; 3: Dinh 2014; 4: Brookes 2019; 5: Harvey and Smith 2017; 6: Daniels and Watson 2003; 7: Harvey et al. 2017; 8: Kubian 2013; 9: Heyerdahl et al. 2008b, 2012; 10: Heyerdahl et al. 2007; 11: Cochrane 2007; 12: Daniels et al. 2006, Gray and Daniels 2007; 13: Nesbitt 2010; 14: Nesbitt and Daniels 2009; 15: Marcoux et al. 2013, Villemaire-Côté 2014; 16: Pogue 2017; 17: Greene and Daniels 2017. (B) Approximate coverage of the reconstruction of maximum temperature anomalies for Interior British Columbia (dashed box). (C) Reconstructions of annual (previous July to current June) precipitation for Banff, Big Creek, Cranbrook, Jasper, Lillooet, Lytton, North Thompson, Oliver, Summerland, Waterton, and Williams Lake (Watson and Luckman 2004). (D) Reconstructions of summer Palmer Drought Severity Index (grid points: 22–25, 29–32, 40–43, 52–55, and 65–68) (Cook et al. 2004).

Appendix C

Annual precipitation (z-scores)		Summer PDSI	
Thresholds	Categories	Thresholds	Categories
≥0.90	Extremely wet	≥4.00	Extremely wet
0.89 to 0.70	Very wet	3.00 to 3.99	Very wet
0.69 to 0.50	Moderately wet	2.00 to 2.99	Moderately wet
0.49 to 0.30	Slightly wet	1.00 to 1.99	Slightly wet
0.29 to 0.10	Incipient wet spell	0.50 to 0.99	Incipient wet spell
-0.09 to 0.09	Near normal	-0.49 to 0.49	Near normal
-0.29 to -0.10	Incipient drought	-0.99 to -0.50	Incipient drought
-0.49 to -0.30	Mild drought	-1.99 to -1.00	Mild drought
-0.69 to -0.50	Moderate drought	-2.99 to -2.00	Moderate drought
-0.89 to -0.70	Severe drought	-3.99 to -3.00	Severe drought
≤-0.90	Extreme drought	≤-4.00	Extreme drought

C.1 Thresholds and categories for the reconstructions of annual precipitation z-scores, and summer Palmer Drought Severity Index (PDSI; see Table 11 in Palmer 1965) values.