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USING COMPLEMENTARY DROUGHT PROXIES IMPROVES INTERPRETATIONS OF FIRE HISTORIES IN MONTANE FORESTS

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ABSTRACT

To investigate drought influences on mixed-severity fire regimes in montane forests of southeastern British Columbia, we developed a Douglas-fir latewood-width chronology and tested its associations with drought records across the fire season. Associations were strong between drought and latewood-widths particularly for June–August. Based on the chronology, we reconstructed the summer Drought Code, an index of moisture content in slow-drying deep compact organics in the soil and coarse woody fuels. Using the summer Drought Code and an existing reconstruction of the summer Palmer Drought Severity Index, representing moisture content in the quick-drying duff layer, we tested fire–drought associations using fire-scar records. Subtle differences in fire–drought associations reflect distinct drying rates and overwintering capacity among forest fuels represented by each summer drought reconstruction. Variable moisture conditions across fuels influence fire occurrence; in particular when the summer Drought Code exceeds 344 and the summer Palmer Drought Severity Index is below 0.08, fire occurrence is more likely. The application of these thresholds with climate change scenarios may provide insights on how mixed-severity fire regimes could be impacted in montane forests of southeastern British Columbia.

Keywords: montane forests, Drought Code, PDSI, fire history, fire–drought associations, mixed-severity fire regimes, fuel moisture, British Columbia.

INTRODUCTION

Drought-driven fire risk is expected to increase over the 21st Century across many forests of western North America as a result of climate change (Stephens *et al.* 2013; Moritz *et al.* 2014). Drought intensified by warmer temperatures and lower precipitation (Diffenbaugh *et al.* 2015) causes forest fuels to 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). Interactions among drought, fuels and fire intensity are critical for characterizing mixed-severity fire regimes; however, these remain insufficiently understood in montane forests of western North America (Halofsky *et al.* 2011).

Mixed-severity fire regimes are comparatively more complex than low- and high-severity fire regimes (Agee 1998; Schoennagel *et al.* 2004; Halofsky *et al.* 2011). Low-severity fire regimes are dominated by frequent surface fires, which cause minimal tree mortality but reduce surface fuels, whereas high-severity fire regimes are dominated by infrequent crown fires with high tree mortality, which 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 compositionally and structurally diverse forest stands (Hessburg *et al.* 2016, 2019; 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, which

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influence fuels (Turner 2010; Gedalof 2011; Perry *et al.* 2011). An improved understanding of the interactions between drought, fuels and fires by investigating fire–drought associations 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.* 2010). Yet, this period includes advances in fire suppression technologies (Morgan *et al.* 2008; Flannigan *et al.* 2009), which can impact interpretations of 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.* 2004). Such reconstructions are based on climate–growth analyses, which 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) 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 moisture availability, which is consistent with findings from the northwestern USA (Littell *et al.* 2008; Crawford *et al.* 2015). Seasonally, low moisture availability in June and July during the growing season when the ring is formed significantly decreased latewood widths (Watson and Luckman 2002; Crawford *et al.* 2015). Low moisture availability also favors 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 monthly 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). Monthly PDSI, which indicates the moisture content of the forest floor, duff layer and upper mineral soil horizon (Hu and Willson 2000; Miyanishi 2001), is calculated from a temperature-driven evapotranspiration algorithm and a precipitation-driven water balance method (Thornthwaite 1948; Palmer 1965). Based on monthly PDSI records and moisture sensitive tree-ring chronologies, including Douglas-fir chronologies from western Canada (Watson and Luckman 2004), Cook *et al.* (2004) developed multi-century 2.5° x 2.5° gridded reconstructions of summer (June–August) PDSI over North America. 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.* 2008a), even though monthly PDSI was originally developed as an agricultural index (Palmer 1965) rather than a fire-weather index.

The Drought Code (DC) is a daily fire-weather index used in the Canadian Forest Fire Behavior Prediction System to indicate the moisture content in slow-drying deep compact organics in the soil and coarse woody fuels (Girardin and Wotton 2009; Podur and Wotton 2010; Chavardès *et al.* 2019). Over the fire season, DC is calculated by adding the effects of total daily precipitation followed by daily potential evapotranspiration (Van Wagner 1987). Following prolonged droughts, DC values are high and indicate that deep and coarse fuels have low moisture content and are more likely to combust (de Groot *et al.* 2009). A unique feature of the 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). Over-winter 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). To represent the onset, duration, and degree of drought during 20th Century fire seasons, Chavardès *et al.* (2019) developed a predictive model of the monthly mean Drought Code (hereafter, "monthly DC"). Monthly DC exhibited strong and significant fire–drought associations in surrounding montane forests. Given the unique characteristics of the monthly DC and its direct link to fire weather, we propose the use of a drought-sensitive Douglas-fir latewood-width chronology to develop a proxy record of summer DC that pre-dates instrumental records.

Compared to monthly DC, monthly PDSI and its summer reconstructions indicate moisture content in the fast-drying forest floor, duff layer and upper mineral soil horizon (Hu and Willson 2000; Miyanishi 2001). During hot and dry weather, the duff layer dries quickly and is highly susceptible to ignition and combustion (Wotton *et al.* 2005); therefore, monthly and summer PDSI are often used to test fire–drought associations in North America (Littell *et al.* 2016). Because the duff layer dries more quickly than deeper and coarser fuels (Van Wagner 1987), fire–drought associations with monthly and summer PDSI will likely be more common than those for monthly and summer DC. It remains unclear, however, whether monthly and summer PDSI can differentiate changes in moisture content caused by a relatively short drought from a longer-term drought. Given the difference in fuels represented by monthly and summer DC compared to monthly and summer PDSI, we hypothesized fire–drought associations with summer DC will help identify the prolonged droughts. Thus, by using summer DC and PDSI in combination, we expected to enhance our understanding of drought as a driver of mixed-severity fire regimes.

We conducted this research in the montane forests of southeastern British Columbia, where the frequency and severity of historical fires represents a mixed-severity fire regime (Marcoux *et al.* 2013, 2015). In this research, we constructed a moisture-sensitive Douglas-fir latewood-width chronology from which we developed a new proxy of drought during the fire season, the summer DC. We addressed three inter-related questions. (1) How do climate–growth relations between the Douglas-fir latewood chronology and monthly DC compare with relations using monthly PDSI? (2) How does the summer DC reconstruction compare with the nearest gridded reconstruction of summer PDSI? (3) How do fire–drought associations differ between summer DC and summer PDSI reconstructions? The comparison of fire–drought associations using our new reconstruction of summer DC against the extensively-used gridded reconstruction of summer PDSI (Stahle *et al.* 2000; Cook *et al.* 2010) allowed us to test the hypothesis that using two proxy reconstructions of drought, summer DC and PDSI, provides contrasting information about the climatic conditions in which fires burned. Parsing out the subset of fires significantly associated with summer DC allowed a better identification of fire years that coincided with prolonged droughts. Combined, summer DC and PDSI provide a more nuanced understanding of the type and degree of droughts associated with historical mixed-severity fire regimes in montane forests of southeastern British Columbia.

METHODS

Study Area

This research focused on montane forests (1000–1550 m above sea level (a.s.l.)) of southeastern British Columbia, Canada (Figure 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 (*Pinus ponderosa* Douglas ex Lawson). 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-severity 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 a.s.l.) 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%) during April–October, and 113 mm as

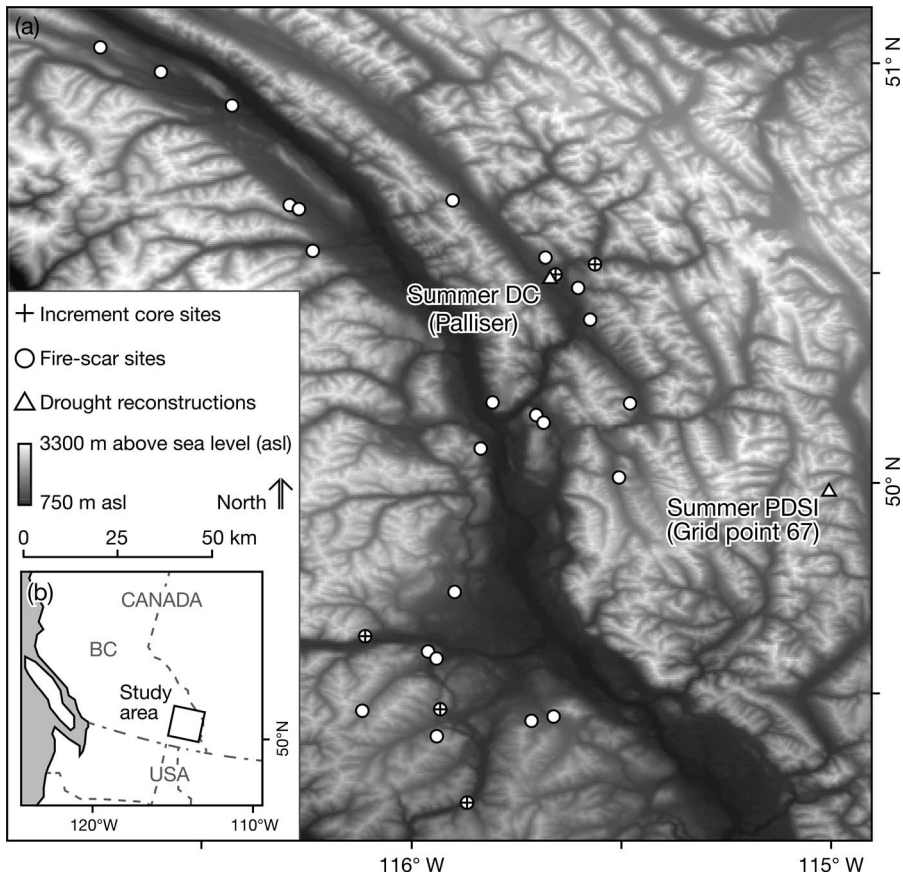

Figure 1. (a) Douglas-fir increment core sampling sites (n = 5) (Daniels *et al.* 2007), and fire-scar record sampling sites (n = 28) (Cochrane 2007; Daniels *et al.* 2011), (inset b) in montane forests of southeastern British Columbia (BC), Canada. Also shown are the locations for the summer Drought Code (DC) reconstruction at Palliser fire-weather station, and the summer Palmer Drought Severity Index (PDSI) reconstruction (Cook *et al.* 2004) at grid point 67.

snow during November–March (Chavardès *et al.* 2019). Despite most of the precipitation falling during April–October, peak activity of lightning-ignited forest fires was common during July–August (Natural Resources Canada 2019).

Monthly Drought Indices

To assess drought variability for each fire season (April–October) from 1901–2004, we calculated monthly DC and monthly PDSI for the Palliser fire-weather station. We compiled monthly maximum and average temperatures (°C) and total monthly precipitation (mm; as water equivalent) from daily weather records and monthly climate data (after Chavardès *et al.* 2019). Monthly DC was computed from monthly precipitation and maximum temperature data, while accounting for over-winter drying (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). We 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.* 2010). 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.

Table 1. Location and elevation (meters above sea level) of the five sampling sites for Douglas-fir increment cores (n = 29) (Daniels *et al.* 2007) used to develop the latewood-width chronology.

Site	Latitude (N)	Longitude (W)	Elevation (m a.s.l.)	No. Cores
1	50°31′20″	115°33′53″	1219	11
2	50°29′49″	115°39′32″	1042	2
3	49°38′15″	116°06′38″	1248	9
4	49°27′50″	115°55′57″	1245	4
5	49°14′35″	115°52′08″	1032	3

Douglas-fir Latewood-Width Chronology

To develop a multi-century drought proxy, we analyzed latewood widths of 110 Douglas-fir increment cores collected from five sites located in montane forests of southeastern British Columbia (Table 1; 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, we crossdated latewood widths using the programs CDendro (Larsson 2011) and COFECHA (Holmes 1983). To avoid the potentially confounding influences of fire and other stand-level disturbances on tree growth, we used conservative criteria when selecting series to include in the chronology. Using the default settings in COFECHA, the cross-correlation matrix of 50-year segments overlapping by 25 years was used to select series with correlations ≥ 0.54 over the full lifespan of the tree and no flags (*i.e.* no segments with low correlations indicating possible dating errors). The resulting 29 series were combined into the latewood-width chronology to represent average latewood-width growth in the study area. To describe the latewood-width chronology we calculated statistics including the mean series intercorrelation (r), mean sensitivity (MS), and first order autocorrelation (AC1) (Cook and Kairiukstis 1990).

We applied signal-free detrending (Melvin and Briffa 2008, 2014) 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 remove temporal autocorrelation (Fritts 1976).

Climate–Growth Analyses

To quantify the strength of the climate–growth relationships between the detrended residual chronology and the monthly drought indices from 1901–2004, we conducted correlation function analyses (Fritts 1976) with the "treeclim" R package (Zang and Biondi 2015). We conducted these analyses over the 7-month window corresponding to the fire season (current year April–October). We calculated Pearson's product moment correlation coefficients between the detrended residual chronology and each monthly drought index using 95% confidence intervals derived from 1000 random bootstrapped samples (Zang and Biondi 2015).

Reconstructions of Summer Drought

We assessed multi-century drought variability using two reconstructions of summer drought: a new reconstruction of summer (June–August) DC, which we developed in this study, and a published reconstruction of summer (June–August) PDSI for the grid point nearest to the Palliser fire-weather station (GP 67, 50°N, 115°W; Cook *et al.* 2004). To model summer DC as a function of the detrended residual chronology, we applied a linear model using the "lm" function in R (R Core Team 2018). We verified model assumptions were met with regards to normality, homoscedasticity, and serially independent data using Shapiro-Wilk, Breusch-Pagan, and Durbin-Watson tests, respectively, in addition to quantile-quantile and residual plots. 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 $\ln(\varepsilon^2) = \ln(\mathbf{X})$. To assess model fit over 1901–2004, we calculated R^2, reduction of error (RE) (Fritts 1976; Macias-Fauria *et al.* 2012), and root mean squared error (RMSE). To validate model consistency over time, we used the following split-sample periods: 1901–1952, 1953–2004, odd years, and even years (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). Finally,

we calculated the Pearson product moment correlation between the reconstructions of summer DC and summer PDSI over their common period (hereafter, "period of analysis").

Fire–Drought Associations

Crossdated fire-scars collected from 28 montane forest sites in southeastern British Columbia represented the historical fire record (Cochrane 2007; Daniels *et al.* 2011). We 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.

Three approaches were used to explore fire–drought associations during the period of analysis. The superposed epoch analysis (SEA) module of the Fire History Analysis and Exploration System (Brewer *et al.* 2015) was applied to determine whether fire years or non-fire years occurred after and during significantly drier or wetter than average summer conditions (Swetnam 1993; Sutherland *et al.* 2017). To meet the assumptions of SEA, we used autoregressive integrated moving average (ARIMA) procedures to test for autocorrelation in the summer DC and summer PDSI reconstructions (after Heyerdahl *et al.* 2008a). ARIMA procedures showed that the reconstruction of summer PDSI was not white noise ($p < 0.001$ up to six lags), so we applied an AR(1) model to derive white noise residuals of the reconstruction of summer PDSI ($p \geq 0.547$ up to 24 lags). To differentiate wetter from drier conditions, we standardized the reconstruction of summer DC to z-scores, and we 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, we 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.* 2017).

To test the effects of weather extremes on historical fire occurrence, we applied bivariate event analysis (BEA) using the K1D software (Gavin 2010). Compared to SEA, BEA focuses on extreme rather than average conditions, which avoids problems caused by serial autocorrelation because it does not rely on continuous drought records (Gartner *et al.* 2012). Weather extremes were identified as years that exceeded ±1 standard deviation, based on z-scores calculated for the summer DC and summer PDSI reconstructions. To determine whether fire/non-fire years were concurrent with or lagged extremely dry/wet summer conditions (*e.g.* Harvey and Smith 2017), we conducted BEA over the period of analysis with forward selection so that weather extremes preceded fire years. We tested if the two sets of events were temporally synchronous (*versus* independent *versus* asynchronous) by generating 95% confidence intervals based on 1000 randomized Monte Carlo simulations (after Harvey and Smith 2017).

In a third analysis, 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 receiver operating characteristic (ROC) curve minimized the sum of false positives and false negatives (Toms and Villard 2015).

RESULTS

Reconstruction of Summer Drought from Douglas-fir Latewood Widths

The Douglas-fir latewood-width chronology used to reconstruct summer drought 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.

Drought during the fire season was correlated with narrow latewood in Douglas-fir (Figure 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

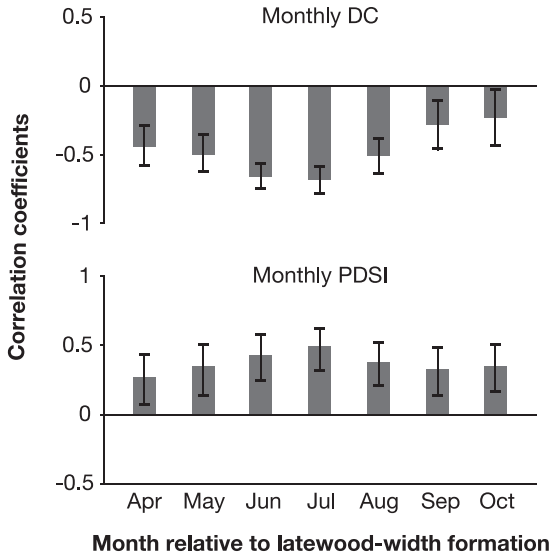

Figure 2. Bootstrapped correlation coefficients of the detrended residual latewood-width chronology against the monthly Drought Code (monthly DC; dimensionless), and monthly Palmer Drought Severity Index (monthly PDSI; dimensionless) at Palliser weather station. All correlation coefficients shown as 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.

monthly PDSI. Correlations with monthly DC were stronger for April–August, but weaker in September and October relative to monthly PDSI.

The model used to reconstruct summer DC from Douglas-fir latewood widths 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 2). Validation statistics revealed similar values of R^2 ranging from 0.41 to 0.49, and of RE ranging from 0.37 to 0.45. Over the common period of analysis spanning 1686–2004, the summer DC reconstruction revealed a moderate negative Pearson product moment correlation with the summer PDSI reconstruction ($r = -0.50$; $p < 0.001$) (Figure 3).

Fire–Drought Associations

From 1686 to 2004, the outcomes from SEA indicated the 68 fire years occurred during significantly dry summers according to both drought reconstructions ($p < 0.001$) (Figure 4). The year preceding fire years was also dry according to summer PDSI only ($p < 0.05$). Conversely, the 251 non-fire years were associated with significantly wetter conditions according to summer DC ($p < 0.05$) and summer PDSI ($p < 0.01$).

Similarly, BEA indicated fire years were synchronous with summer weather extremes corresponding to drought, with lagged effects that were more pronounced than those detected by SEA (Figure 5). Fires burned when summer DC was high the year of and one year prior to fire ($p < 0.05$) and summer PDSI was low the year of and up to three years prior to fire ($p < 0.05$). Conversely, 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 occurred independently ($p \geq 0.05$) of extremely dry and wet summers.

Historically, fire years were most likely to occur when summer DC was ≥344 and summer PDSI was ≤0.08 (Figure 6). Over the 319 years of 1686–2004, both summer DC and summer PDSI exceeded these thresholds in 100 years (*e.g.* upper left quadrant of Figure 6), 41 of which were classified as fire years based on the fire-scar record. Under these prolonged drought conditions, fire scars

Table 2. Reconstruction of the summer Drought Code (DC) at the Palliser fire-weather station. Pearson product moment correlation and model coefficients (top); the model was validated using two time periods and odd versus even years (bottom).

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	Odd years	0.49	Even years		0.38
RMSE = 59.04	Even years	0.41	Odd years		0.45

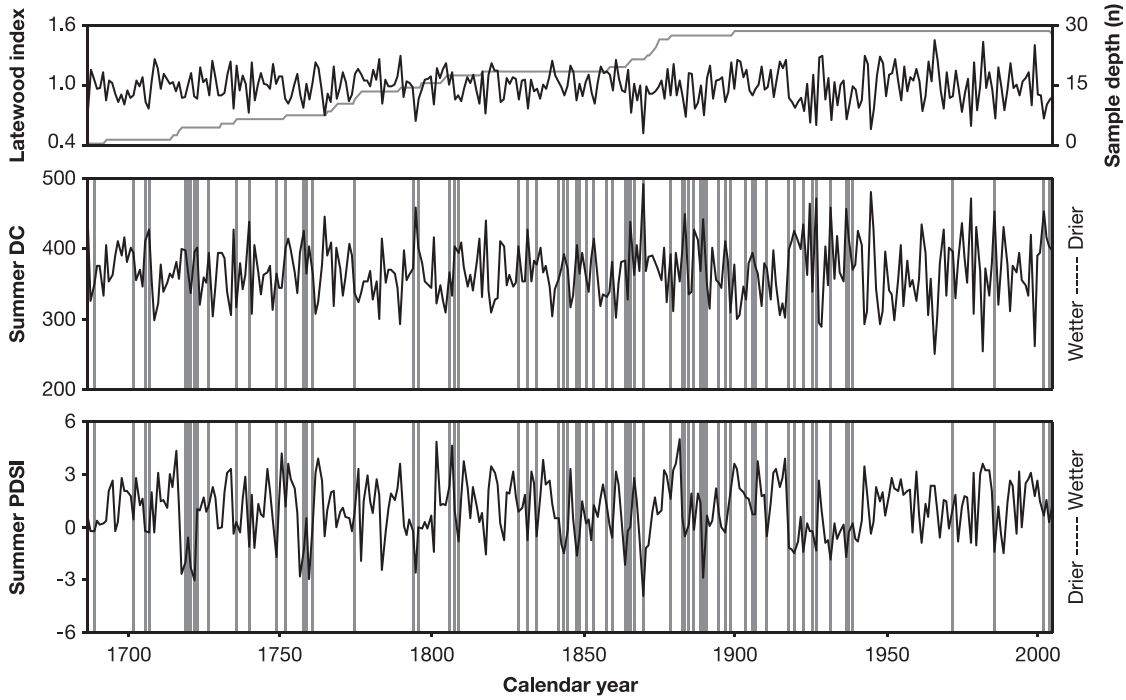

Figure 3. Indices for the detrended residual latewood-width chronology (black line) along with the sample depth (grey line; top panel), and reconstructions of the summer Drought Code (DC) and summer Palmer Drought Severity Index (PDSI) from 1686–2004 (middle and bottom panels, respectively). The 68 fire years are shown as vertical grey bars in the middle and bottom panels.

formed at multiple sites in 28 years, with up to nine of the 28 sites recording fire in a single year. Summer PDSI was ≤0.08 and summer DC was <344 in 55 years (*e.g.* lower left quadrant of Figure 6), 16 of which were fire years recorded at a maximum of four sites. Of the 55 years that coincided with summer DC ≥344 and summer PDSI >0.08 (*e.g.* upper right quadrant of Figure 6), only 6 were fire years recorded at a maximum of four sites. Of the 109 years when summer DC was <344 and summer PDSI was >0.08 (*e.g.* lower right quadrant of Figure 6), only 5 were fire years and scars were recorded at a maximum of three sites.

DISCUSSION

Monthly DC and PDSI Reveal Subtle Differences in Drought in Montane Forests

Using the two drought indices in concert provides key insights on the temporal characteristics of historical droughts within fire seasons in montane forests of southeastern British Columbia. 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 fire occurrence. Latewood widths were more strongly correlated with monthly DC in the early months of the fire season, compared with monthly PDSI. Monthly DC, developed as a fire-weather index, accounts for soil moisture depletion over the winter between fire seasons, in addition to cumulative drought during the fire season (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 for April–August monthly DC than monthly PDSI. In contrast to monthly DC, monthly PDSI poorly accounts for snowfall (Riley *et al.* 2013), snowmelt,

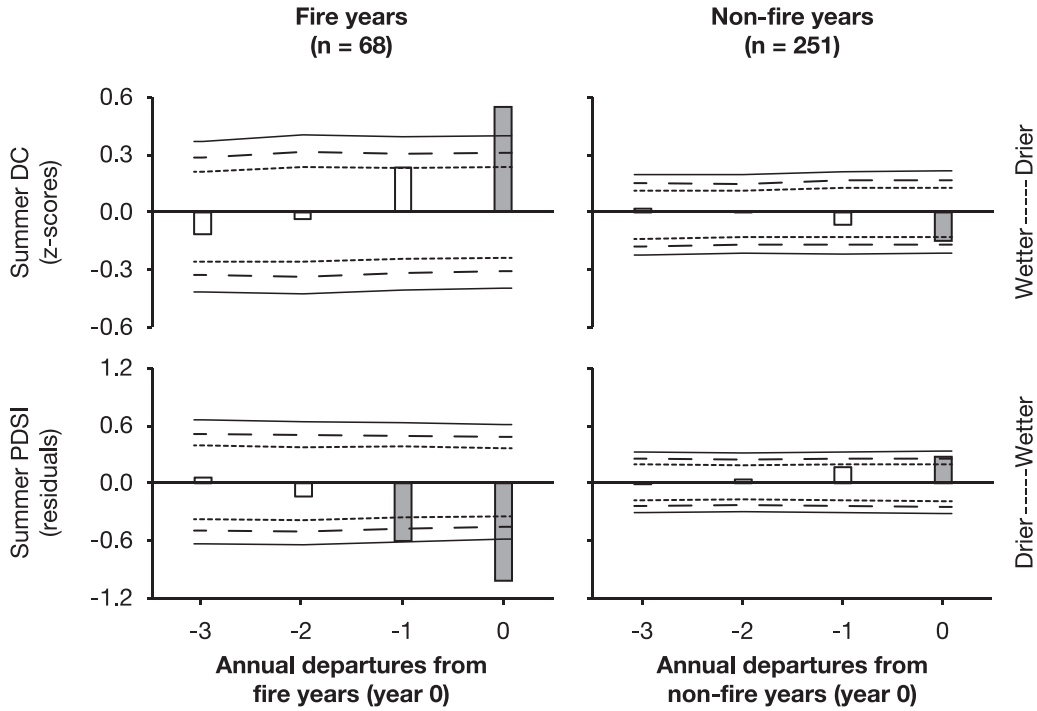

Figure 4. Superposed epoch analyses (SEA) showing associations for the reconstructions of the summer Drought Code (DC) and the summer Palmer Drought severity Index (PDSI) during fire years and non-fire years. To differentiate wetter from drier conditions, the reconstruction of summer DC was standardized to z-scores. White noise residuals of the reconstruction of summer PDSI were derived to meet the assumptions of SEA. Solid, long- and short-dashed lines represent confidence intervals of 99.9%, 99%, and 95%, respectively. Grey bars indicate statistically significant departures from the mean ($p < 0.05$).

or frozen ground, which can be problematic when using PDSI at high-latitudes and mountainous areas (Alley 1984). Instead, monthly PDSI displayed stronger climate–growth correlations than monthly DC during September and October, which was consistent with strong correlations between monthly PDSI and soil moisture during late summer and autumn in the western USA (Dai *et al.* 2004). Combined, our findings provide support for the application of monthly DC along with monthly PDSI to improve interpretations of the effects of drought during different parts of the fire season in montane forests of southeastern British Columbia.

Fire–Drought Associations Highlight Differences in Moisture Content over Time

Fire–drought associations for summer DC and PDSI reflected the distinct capacities of these two drought indicators to integrate moisture content over time. Both indices revealed fire years were strongly associated with summer droughts corroborating the many findings on fire–climate associations in western North America (*e.g.* Gedalof *et al.* 2005; Trouet *et al.* 2006, 2010; Heyerdahl *et al.* 2008a, 2008b; Littell *et al.* 2009). We also found strong associations between fires and dry conditions during the previous year based on summer PDSI, which was documented in the Pacific Northwest (*e.g.* Westerling *et al.* 2003; Hessl *et al.* 2004). However, summer PDSI does not explicitly account for multi-year droughts that can lead to low fuel moisture conditions in the early months of the fire season (*i.e.* in April and May). Our findings suggest that summer PDSI is an excellent indicator of droughts encompassing the middle of the fire season (*i.e.* June–August), although research shows low winter and spring PDSI values indicating dry conditions were also associated with fire years in western North America (*e.g.* Trouet *et al.* 2006).

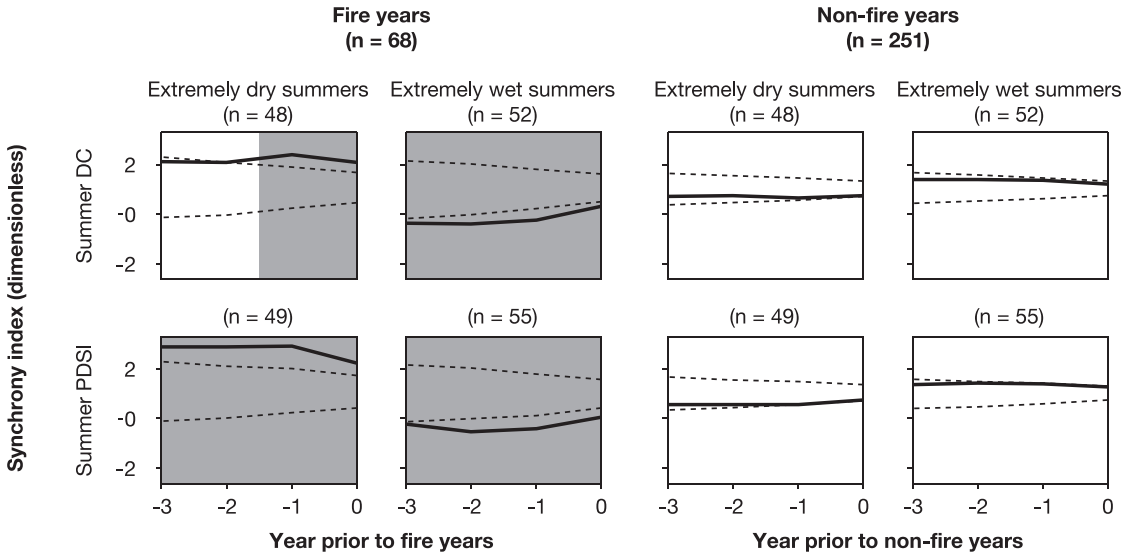

Figure 5. Bivariate event analyses showing associations for fire years and non-fire years during coinciding and preceding extremely dry or wet summers (±1SD) according to the reconstructions of the summer Drought Code (DC) and summer Palmer Drought severity Index (PDSI). Solid black lines represent reconstruction 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 falling between envelopes are not statistically significant 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 ($p < 0.05$).

Compared with summer PDSI, summer DC explicitly accounts for overwintering conditions that dry fuels and can occur from the end of the previous fire season (*i.e.* between October and November) to the start of the current fire season. Such conditions can lead to dry deep organics and coarse woody fuels at the start of and throughout the fire season. Thus, summer DC explicitly provides information on droughts that can last for multiple fire seasons. Given that climate change is expected to extend droughts into the early months of the fire season in western North America (Wotton and Flannigan 1993; Westerling *et al.* 2006; Westerling 2016), we suggest the application of summer DC and PDSI to provide insights into how mixed-severity fire regimes could be impacted in montane forests of southeastern British Columbia. For our research, we can apply both drought indicators to provide insights into how long- and short-term droughts may have influenced the mixed-severity fire regime in our study area.

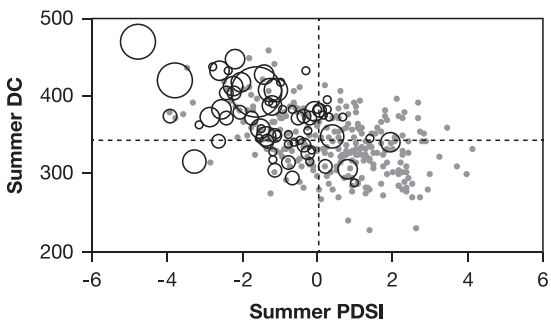

Figure 6. Scatterplot for the reconstruction of the summer Drought Code (DC) versus reconstruction of summer Palmer Drought Severity Index (PDSI) during fire years (black circles) and non-fire years (grey points). The number of sites recording each fire year is represented by the size of each circle. The optimal pair of threshold values for summer DC and PDSI to predict the probability of a fire year was 344 and 0.08, respectively (dashed lines).

Drought as an Indicator of Fire Severity in Montane Forests

Combinations of long- and short-term droughts influenced the historical fire regime as indicated by the variation in the number of fire years and number of sites recording fire in

the four quadrants shown in Figure 6. The upper left quadrant represents the drought conditions that were most conducive to fire. The prolonged droughts required for summer DC to exceed the critical threshold of 344, drying deep organics and coarse woody fuels making them more likely to burn (Girardin and Wotton 2009), also yielded average to very low summer PDSI values (<0.08). Under these climatic conditions, fires were most frequent and commonly occurred at multiple sites, with a tendency for more sites to record fire during more extreme droughts. We would expect fires that coincided with high summer DC and low summer PDSI burned at higher intensities and resulted in more severe effects, given that most fuels had low moisture content (Keeley 2009). Although fire severity cannot be interpreted from fire scars alone (Daniels *et al.* 2017), the presence of fire-scars indicates tree survival, even in extreme drought years when fires burned at several locations within the study area. It is possible that individual fires had a range of effects within their perimeters and the fire-scarred trees sampled were survivors in island remnants or along the edges of predominantly high-severity fires. Alternatively, spatial variation in moisture gradients and the amount of combustible fuels likely influenced fire severity within and among sites, as found in other montane forests with mixed-severity fire regimes in western North America (Halofsky *et al.* 2011; Daniels *et al.* 2017). Finally, despite mostly dry fuels, the variation in the number of sites that recorded fires during prolonged droughts also highlights the limiting effect of ignitions (Gedalof 2011).

Fires coinciding with short-term droughts in the study area highlight the importance of a dry duff layer to sustain fire ignition and combustion that is sufficiently intense to scar trees. Fire occurrence was likely when summer PDSI was low, even in years when summer DC was below the threshold of 344, as shown in the lower left quadrant of Figure 6. Such conditions develop during relatively mesic summers, when short-term droughts dry the duff layer, but not the deep organics and coarse woody fuels. In comparison, fire years were less common when summer PDSI exceeded the threshold of 0.08, indicating relatively mesic to wet conditions in which the duff layer was least susceptible to sustain ignitions (Falk *et al.* 2007; Abatzoglou *et al.* 2016). In general, high summer PDSI coincided with low summer DC, indicating high moisture content across fuels and the conditions least conducive to burning (*e.g.* lower right quadrant of Figure 6). Less frequently, high summer PDSI coincided with low moisture content in deep organics and coarse woody fuels (*e.g.* upper right quadrant of Figure 6). Our interpretations agreed with findings that a dry duff layer can sustain fire ignition and combustion (Wotton *et al.* 2005). We also interpreted that fires occurring during short-term droughts in the montane forests of our study area were more likely of low to moderate severity. Similar findings were documented in other montane forests of western North America with evidence of low- to moderate-severity fires during less pronounced and persistent droughts (Perry *et al.* 2011; Hessburg *et al.* 2016).

CONCLUSIONS

Using the reconstructions of summer DC and PDSI in concert provided nuanced insights on the range of drought conditions driving historical mixed-severity fire regimes in montane forests of southeastern British Columbia. The development of a summer DC reconstruction provided a practical connection between historical fires and a modern fire-weather index derived from empirical research on fire behavior. 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 have subtle effects on fire–drought associations. Specifically, fire–drought associations were less common with summer DC than summer PDSI, suggesting that summer DC is a better indicator of long-term droughts across successive fire seasons than summer PDSI in montane forests of southeastern British Columbia. Fire years coincided with variable fuel moisture conditions, suggesting that fires ignited and burned with a range of severities. We conclude that when summer DC exceeds 344 and summer PDSI is below 0.08, landscape managers of montane forests in southeastern British Columbia can expect greater chances of fire occurrence. We propose the application of these thresholds on future climate scenarios to provide insights

into how fire occurrence may change within these forests.

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REFERENCES CITED

Abatzoglou, J. T., C. A. Kolden, J. K. Balch, and B. A. Bradley, 2016. Controls on interannual variability in lightning-caused fire activity in the western US. *Environmental Research Letters* 11(4):1–12. doi:10.1088/1748-9326/11/4/045005.

Agee, J. K., 1993. *Fire Ecology of Pacific Northwest Forests*. Island Press, Washington, DC, USA; 493 pp.

Agee, J. K., 1998. The landscape ecology of western forest fire regimes. *Northwest Science* 72:24–34.

Alley, W. M., 1984. The Palmer Drought Severity Index: Limitations and assumptions. *Journal of Climate and Applied Meteorology* 23:1100–1109.

Brewer, P. W., M. E. Velásquez, E. K. Sutherland, and D. A. Falk, 2015. Fire History Analysis and Exploration System (FHAES) version 2.0, https://www.frames/fhaes/home. doi:10.5281/zenodo.593323.

Carnwath, G. C., D. W. Peterson, and C. R. Nelson, 2012. Effect of crown class and habitat type on climate-growth relationships of ponderosa pine and Douglas-fir. *Forest Ecology and Management* 285:44–52.

Chavardès, R. D., L. D. Daniels, B. N. I. Eskelson, and P. D. Pickell, 2019. Monthly adaptations of the Drought Code reveal nuanced fire-drought associations in montane forests with a mixed-severity fire regime. *International Journal of Wildland Fire* 28(6):445–455.

Chen, P. Y., C. Welsh, and A. Hamann, 2010. Geographic variation in growth response of Douglas-fir to interannual climate variability and projected climate change. *Global Change Biology* 16(12):3374–3385.

Cochrane, J. D., 2007. *Characteristics of Historical Forest Fires in Complex Mixed-Conifer Forests of Southeastern British Columbia*. M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, Canada; 101 pp.

Cook, E. R., and L. A. Kairiukstis, 1990. *Methods of Dendrochronology: Applications in the Environmental Sciences*. Kluwer Academic Publishers, Dordrecht, Netherlands; 394 pp. doi:10.1007/978-94-015-7879-0.

Cook, E. R., and K. Peters, 1981. The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin* 41:45–53.

Cook, E. R., R. Seager, R. R. Heim, R. S. Vose, C. Herweijer, and C. A. Woodhouse, 2010. Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term paleoclimate context. *Journal of Quaternary Science* 25(1):48–61.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle, 2004. Long-term aridity changes in the western United States. *Science* 306(5698):1015–1018.

Crawford, C. J., D. Griffin, and K. F. Kipfmueller, 2015. Capturing season-specific precipitation signals in the northern Rocky Mountains, USA, using earlywood and latewood tree rings. *Journal of Geophysical Research: Biogeosciences* 120(3):428–440.

Dai, A., K. E. Trenberth, and T. Qian, 2004. A global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology* 5(6):1117–1130.

Daniels, L. D., J. Cochrane, and R. W. Gray, 2007. *Mixed-Severity Fire Regimes: Regional Analysis of the Impacts of Climate on Fire Frequency in the Rocky Mountain Forest District*. Report to Tembec Inc., Canadian Forest Products Ltd., and the Forest Investment Account of British Columbia; 36 pp.

Daniels, L. D., T. B. Maertens, A. B. Stan, S. P. J. McCloskey, J. D. Cochrane, and R. W. Gray, 2011. Direct and indirect impacts of climate change on forests: Three case studies from British Columbia. *Canadian Journal of Plant Pathology* 33(2):108–116.

Daniels, L. D., L. L. Yocom Kent, R. L. Sherriff, and E. K. Heyerdahl, 2017. Deciphering the complexity of historical fire regimes: Diversity among forests of Western North America. In *Dendroecology: Tree-Ring Analyses Applied to Ecological Studies*, edited by Amoroso, M. M., L. D. Daniels, J. J. Baker, and J. J. Camarero, pp. 185–210. Springer International Publishing, Cham, Switzerland.

de Groot, W. J., J. Pritchard, and T. J. Lynham, 2009. Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. *Canadian Journal of Forest Research* 39(2):367–382.

Diffenbaugh, N. S., D. L. Swain, and D. Touma, 2015. Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences of the United States of America* 112(13):3931–3936.

Falk, D. A., C. Miller, D. McKenzie, and A. E. Black, 2007. Cross-scale analysis of fire regimes. *Ecosystems* 10(5):809–823.

Flannigan, M. D., A. S. Cantin, W. J. de Groot, M. B. Wotton, A. Newbery, and L. M. Gowman, 2013. Global wildland fire season severity in the 21st century. *Forest Ecology and Management* 294:54–61.

Flannigan, M. D., M. A. Krawchuk, W. J. de Groot, M. B. Wotton, and L. M. Gowman, 2009. Implications of changing climate for global wildland fire. *International Journal of Wildland Fire* 18(5):483–507.

Flannigan, M. D., B. M. Wotton, G. A., Marshall, W. J. de Groot, J. Johnston, N. Jurko, and A. S. Cantin, 2016. Fuel moisture sensitivity to temperature and precipitation: Climate change implications. *Climatic Change* 134(1–2):59–71.

Fox, J., and S. Weisberg, 2019. *An R Companion to Applied Regression*. Sage Publishing, Inc., Thousand Oaks, California, USA; 571 pp.

Fritts, H. C., 1976. *Tree Rings and Climate*. Academic Press, New York, New York, USA; 567 pp.

Gartner, M. H., T. T. Veblen, R. L. Sherriff, and T. L. Schoennagel, 2012. Proximity to grasslands influences fire frequency and sensitivity to climate variability in ponderosa pine forests of the Colorado Front Range. *International Journal of Wildland Fire* 21(5):562–571.

Gavin, D. G., 2010. K1D: Multivariate Ripley's K-function for one dimensional data. Department of Geography, University of Oregon, Oregon, USA; 8 pp. http://geography.uoregon.edu/envchange/software/K1D_1.pdf

Gedalof, Z., 2011. Climate and spatial patterns of wildfire. In *The Landscape Ecology of Fire*, edited by McKenzie, D., C. Miller, and D. Falk, pp. 89–116. Springer, Dordrecht, Netherlands.

Gedalof, Z., D. L. Peterson, and N. J. Mantua, 2005. Atmospheric, climatic, and ecological controls of extreme wildfire years in the northwestern United States. *Ecological Applications* 15(1):154–174.

Girardin, M. P., J. Tardif, M. D. Flannigan, and Y. Bergeron, 2004. Multicentury reconstruction of the Canadian Drought Code from eastern Canada and its relationship with paleoclimatic indices. *Climate Dynamics* 23(2):99–115.

Girardin, M. P., and B. M. Wotton, 2009. Summer moisture and wildfire risks across Canada. *Journal of Applied Meteorology and Climatology* 48:517–533.

Griesbauer, H. P, and S. D. Green, 2010. Regional and ecological patterns in interior Douglas-fir climate–growth relationships in British Columbia, Canada. *Canadian Journal of Forest Research* 40(2):308–321.

Halofsky, J. E., D. C. Donato, D. E. Hibbs, J. L. Campbell, M. Donaghy Cannon, J. B. Fontaine, J. R. Thompson, R. G. Anthony, B. T. Bormann, L. J. Kayes, B. E. Law, D. L. Peterson, and T. A. Spies, 2011. Mixed-severity fire regimes: Lessons and hypotheses from the Klamath-Siskiyou Ecoregion. *Ecosphere* 2(4):1–19. doi:10.1890/ES10-001841.

Harvey, J. E., and D. J. Smith, 2017. Interannual climate variability drives regional fires in west central British Columbia, Canada. *Journal of Geophysical Research: Biogeosciences* 122(7):1759–1774.

Hessburg, P. F., C. L. Miller, S. A. Parks, N.A. Povak, A. H. Taylor, P. E. Higuera, S. J. Prichard, M. P. North, B. M. Collins, M. D. Hurteau, A. J. Larson, C. D. Allen, S. L. Stephens, H. Rivera-Huerta, C. S. Stevens-Rumann, L. D. Daniels, Z. Gedalof, R. W. Gray, V. R. Kane, D. J. Churchill, R. K. Hagmann, T. A. Spies, C. A. Cansler, R. T. Belote, T. T. Veblen, M. A. Battaglia, C. Hoffman, C. N. Skinner, H. D. Safford, and R. B. Salter, 2019. Climate, environment, and disturbance history govern resilience of western North American forests. *Frontiers in Ecology and Evolution* 7(239):1–27. doi:10.3389/fevo.2019.00239.

Hessburg, P. F., T. A. Spies, D. A. Perry, C. N. Skinner, A. H. Taylor, P. M. Brown, S. L. Stephens, A. J. Larson, D. J. Churchill, N. A. Povak, P. H. Singleton, B. McComb, W. J. Zielinski, B. M. Collins, R. B Salter, J. J. Keane, J. F. Franklin, and G. Riegel, 2016. Tamm review: Management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. *Forest Ecology and Management* 366:221–250.

Hessl, A. M., D. McKenzie, and R. Schellhaas, 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. *Ecological Applications* 14(2):425–442.

Heyerdahl, E. K., D. McKenzie, L. D. Daniels, A. E. Hessl, J. S. Littell, and N. J. Mantua, 2008a. Climate drivers of regionally synchronous fires in the inland Northwest (1651–1900). *International Journal of Wildland Fire* 17(1):40–49.

Heyerdahl, E. K., P. Morgan, and J. P. Rise II, 2008b. Multiseason climate synchronized historical fires in dry forests (1650–1900), Northern Rockies, USA. *Ecology* 89(3):705–716.

Holmes, R. L., 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin* 43:69–78.

Hu, Q. S., and G. D. Willson, 2000. Effects of temperature anomalies on the Palmer Drought Severity Index in the central United States. *International Journal of Climatology* 20:1899–1911. URL:https://digitalcommons.unl.edu/natrespapers/99/.

Keeley, J. E., 2009. Fire intensity, fire severity and burn severity: A brief review and suggested usage. *International Journal of Wildland Fire* 18(1):116–126.

Larsson, L., 2011. CDendro package version 7.4. Cybis Elektronik & Data AB. http://www.cybis.se.

Lawson, B. D., and O. B. Armitage, 2008. *Weather Guide for the Canadian Forest Fire Danger Rating System*. Northern Forestry Centre, Canadian Forest Service, Natural Resources Canada, Edmonton, Alberta, Canada; 87 pp. http://nofc.cfs.nrcan.gc.ca/bookstore_pdfs/29152.pdf.

Littell, J. S., D. McKenzie, D. L. Peterson, and A. L. Westerling, 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecological Applications* 19(4):1003–1021.

Littell, J. S., D. L. Peterson, K. L. Riley, Y. Liu, and C. H. Luce, 2016. A review of the relationships between drought and forest fire in the United States. *Global Change Biology* 22(7):1–17.

Littell, J. S., D. L. Peterson, and M. Tjoelker, 2008. Douglas-fir growth in mountain ecosystems: Water limits tree growth from stand to region. *Ecological Monographs* 78(3):349–368.

Macias-Fauria, M., A. Grinsted, S. Helama, and J. Holopainen, 2012. Persistence matters: Estimation of the statistical significance of paleoclimatic reconstruction statistics from autocorrelated time series. *Dendrochronologia* 30(2):179–187.

Marcoux, H. M., L. D. Daniels, S. E. Gergel, E. Da Silva, Z. Gedalof, and P. F. Hessburg, 2015. Differentiating mixed- and high-severity fire regimes in mixed-conifer forests of the Canadian Cordillera. *Forest Ecology and Management* 341:45–58.

Marcoux, H. M., S. G. Gergel, and L. D. Daniels, 2013. Mixed-severity fire regimes: How well are they represented by existing fire-regime classification systems? *Canadian Journal of Forest Research* 43(7):658−668.

Melvin, T. M., and K. R. Briffa, 2008. A "signal-free" approach to dendroclimatic standardisation. *Dendrochronologia* 26(2):71–86.

Melvin, T. M., and K. R. Briffa, 2014. CRUST: Software for the implementation of Regional Chronology Standardisation: Part 1. Signal-free RCS. *Dendrochronologia* 32(1):7–20.

Meyn, A., S. Schmidtlein, S. W. Taylor, M. P. Girardin, K. Thonicle, and W. Cramer, 2010. Spatial variation of trends in wildfire and summer drought in British Columbia, Canada, 1920–2000. *International Journal of Wildland Fire* 19(3): 272–283.

Miyanishi, K., 2001. Duff consumption. In *Forest Fires: Behavior and Ecological Effects*, edited by E. A. Johnson, and K. Miyanishi, pp. 437–475. Academic Press, San Diego, California, USA. doi:10.1016/B978-0-123-86660-8.X5000-4.

Morgan, P., E. K. Heyerdahl, and C. E. Gibson, 2008. Multi-season climate synchronized forest fires throughout the 20th century, northern Rockies, USA. *Ecology* 89(3):717–728.

Moritz, M. A., E. Batllori, R. A. Bradstock, A. M. Gill, J. Handmer, P. F. Hessburg, J. Leonard, S. McCaffrey, D. C. Odion, T. Schoennagel, and A. D. Syphard, 2014. Learning to coexist with wildfire. *Nature* 515:58–66.

Natural Resources Canada, 2019. Canadian Wildland Fire Information System, CWFIS Datamart, National Fire Datadase fire point data. Government of Canada. http://cwfis.cfs.nrcan.gc.ca/datamart/metadata/nfdbpnt.

Palmer, W. C., 1965. *Meteorologic Drought*. Office of Climatology, United States Weather Bureau, Research Paper 45, Washington, DC, USA; 58 pp. https://www.ncdc.noaa.gov/temp-and-precip/drought/docs/palmer.pdf.

Perry, D. A., Hessburg, P. F., Skinner, C. N., Spies, T. A., Stephens, S. L., Taylor, A. H., Franklin, J. F., McComb, B., and G. Riegel, 2011. The ecology of mixed severity fire regimes in Washington, Oregon, and Northern California. *Forest Ecology and Management* 262(5): 703–717.

Podur, J., and M. Wotton, 2010. Will climate change overwhelm fire management capacity? *Ecological Modelling* 221(9):1301–1309.

Pojar, J., and D. V. Meidinger, 1991. British Columbia: The environmental setting. In *Ecosystems of British Columbia*, edited by D. V. Meidinger and J. Pojar, pp. 3.39–3.66. Research Branch, British Columbia Ministry of Forests, Victoria, British Columbia, Canada. https://www.for.gov.bc.ca/hfd/pubs/Docs/Srs/Srs06/chap3.pdf.

R Core Team, 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. https://www.R-project.org/.

Riley, K. L., J. T. Abatzoglou, I. C. Grenfell, A. E. Klene, and F. A. Heinsch, 2013. The relationship of large fire occurrence with drought and fire danger indices in the western USA, 1984–2008: The role of temporal scale. *International Journal of Wildland Fire* 22(7):894–909, doi:10.1071/WF12149.

Schoennagel, T., T. T. Veblen, and W. H. Romme, 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. *Bioscience* 54(7):661–676.

Stahle, D. W., E. R. Cook, M. K. Cleaveland, M. D. Therrell, D. M. Meko, H. D. Grissino-Mayer, E. Watson, and B. H. Luckman, 2000. Tree-ring data document 16th century megadrought over North America. *Eos Transactions, American Geophysical Union* 81(12):121–125.

Stephens, S. L., J. K. Agee, P. Z. Fulé, M. P. North, W. H. Romme, T. W. Swetnam, and M. G. Turner, 2013. Managing forests and fire in changing climates. *Science* 342(6154):41–42.

Sutherland, E. K., P. W. Brewer, D. A. Falk, and E. M. Velásquez, 2017. FHAES Fire History Analysis and Exploration System. Missoula Forestry Sciences Laboratory, Missoula, Montana, USA. https://help.fhaes.org/pdf/.

Swetnam, T. W., 1993. Fire history and climate change in giant sequoia groves. *Science* 262(5135):885–889.

Toms, J. D., and M. A. Villard, 2015. Threshold detection: Matching statistical methodology to ecological questions and conservation planning objectives. *Avian Conservation and Ecology* 10(1):1–8. doi:10.5751/ACE-00715-100102.

Trouet, V., A. H. Taylor, A. M. Carleton, and C. N. Skinner, 2006. Fire-climate interactions in forests of the American Pacific coast. *Geophysical Research Letters* 33(18):1–5. doi:10.1029/2006GL027502.

Trouet, V., A. H. Taylor, E. R. Wahl, C. N. Skinner, and S. L. Stephens, 2010. Fire-climate interactions in the American West since 1400 CE. *Geophysical Research Letters* 37(4):1–5. doi:10.1029/2009GL041695.

Turner, J. A., 1972. *The Drought Code Component of the Canadian Forest Fire Behaviour System*. Canadian Forest Service, Department of the Environment, Publication 1316, Ottawa, ON, Canada; 16 pp. http://www.cfs.nrcan.gc.ca/pubwarehouse/pdfs/28538.pdf.

Turner, M. G., 2010. Disturbance and landscape dynamics in a changing world. *Ecology* 91(10):2833–2849.

Van Wagner, C. E., 1987. *Development and Structure of the Canadian Forest Fire Weather Index System*. Canadian Forestry Service, Forestry Technical Report 35, Ottawa, Ontario, Canada; 48 pp. http://www.cfs.nrcan.gc.ca/pubwarehouse/pdfs/19927.pdf.

Watson, E., and B. H. Luckman, 2002. The dendroclimatic signal in Douglas-fir and ponderosa pine tree-ring chronologies from the southern Canadian Cordillera. *Canadian Journal of Forest Research* 32(10):1858–1874.

Watson, E., and B. H. Luckman, 2004. Tree-ring based reconstructions of precipitation for the southern Canadian Cordillera. *Climate Change* 65(1–2):209–241.

Wells, N., S. Goddard, and M. J. Hayes, 2004. A self-calibrating Palmer Drought Severity Index. *Journal of Climate* 17:2335–2351.

Westerling, A. L., 2016. Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society - Biological Sciences* 371(1696):1–10. doi:10.1098/rstb.2015.0178.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam, 2006. Warming and earlier Spring increase western U.S. forest wildfire activity. *Science* 313(5789):940–943.

Westerling, A. L., and T. W. Swetnam, 2003. Interannual to decadal drought and wildfire in the western United States. *EOS* 84(49):545–555.

Wigley, T. M. L., K. R. Briffa, and P. D. Jones, 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology* 23:201–213.

Williams, A. P., and J. T. Abatzoglou, 2016. Recent advances and remaining uncertainties in resolving past and future climate effects on global fire activity. *Current Climate Change Reports* 2(1):1–14. doi:10.1007/s40641-016-0031-0.

Wotton, B. M., 2009. Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications. *Environmental and Ecological Statistics* 16(2): 107–131.

Wotton, B. M., and M. D. Flannigan, 1993. Length of the fire season in a changing climate. *The Forestry Chronicle* 69(2):187–192.

Wotton, B. M., B. J. Stocks, and D. L. Martell, 2005. An index for tracking sheltered forest floor moisture within the Canadian Forest Fire Weather Index System. *International of Wildland Fire* 14(2):169–182.

Xiao, J. F., and Q. L. Zhuang, 2007. Drought effects on large fire activity in Canadian and Alaskan forests. *Environmental Research Letters* 2(4):1–7. doi:10.1088/1748-9326/2/4/044003.

Zang, C., and F. Biondi, 2015. Treeclim: An R package for the numerical calibration of proxy-climate relationships. *Ecography* 38(4):431–436.

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