

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

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Abstract. We compared three monthly adaptations of the daily Drought Code (DC) of Canada's Fire Weather Index System and applied them to interpret drought conditions associated with historical fires in montane forests of south-eastern British Columbia. 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 cross-dated fire-scar record from 20 sites in montane forests surrounding the Palliser station, we found significant fire–drought associations from June to August with all adaptations, and significant associations in April and May with the two new adaptations. Of the 17 fire years from 1901 to 2013, 6 years had low initial drought conditions that increased late in the fire season, and 5 years had high drought conditions throughout the fire season. We conclude that variable drought within and among fire seasons influenced fire severity. Our findings provide a connection between modern drought indices used to rank fire danger and drought effects on the historical mixed-severity fire regime in montane forests of south-eastern British Columbia.

Additional keywords: drought variability, fire behaviour, fire history, fire-weather records, Monthly Drought Code.

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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 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 and Daniels 2016; Rogeau *et al.* 2016). Some montane forests in

south-eastern 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 the 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 characterise 20th century droughts during the fire season (1 May–31 October) 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 to 2002, Girardin and Wotton (2009) assumed overwintering effects were low and set initial values of DC and MDC to 15 on 30 April of each year (i.e. 1 day before the start of the fire season on 1 May). This approach resulted in mean July MDC values from 46 to 300 across Canada (Girardin and Wotton 2009). In contrast, DC calculated using daily fire-weather station records from south-eastern 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 (2001–13) stations yielded July means of 338, 464 and 499 and August means of 472, 602 and 642 respectively (BC Wildfire Management Branch, unpubl. data). We have sought to understand why the MDC values underestimated DC_m during peak fire season in this region.

We hypothesise 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 south-eastern British Columbia (British Columbia Wildfire Management Branch, unpubl. 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 $\geq 12^\circ\text{C}$ in regions where snow cover is not consistent (Lawson and Armitage 2008). Typically, 1 May has been the start date when calculating MDC (Girardin and Wotton 2009; Girardin *et al.* 2009; Girardin *et al.* 2013; Mori and Johnson 2013). However, the median start date of actual fire-weather records from 1981 to 2010 for the Canadian Southern Cordillera was 12 April (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 2016; Wotton *et al.* 2017). Therefore, initiating calculations of MDC on 1 April 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 = $0.83 \times (\text{daily total precipitation} > 2.8 \text{ mm}) - 1.27 \text{ mm}$ (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 south-eastern British Columbia.

In the present study, our goal was to interpret drought conditions associated with historical fires in montane forests of south-eastern British Columbia. Using fire-weather data from the Palliser station located in the montane forest, we 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, we computed three monthly adaptations of the drought code (MDC, adjusted MDC and predicted DC_m) from 1901 to 2013 and tested their associations with a cross-dated 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.

Methods

Study area

The study area encompasses the Palliser fire-weather station ($50^\circ29'40''\text{N}$, $115^\circ39'59''\text{W}$; 1100 m asl) and 20 fire-history research sites distributed along a 250-km north–south transect representing 255 400 ha of mid-elevation montane forests (1100–1550 m asl) in south-eastern British Columbia, Canada (Fig. 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 rain shadow 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 to October, and 113 mm as snow from November to March. Lightning-ignited forest fires are most common from July to August (Natural Resources Canada 2019).

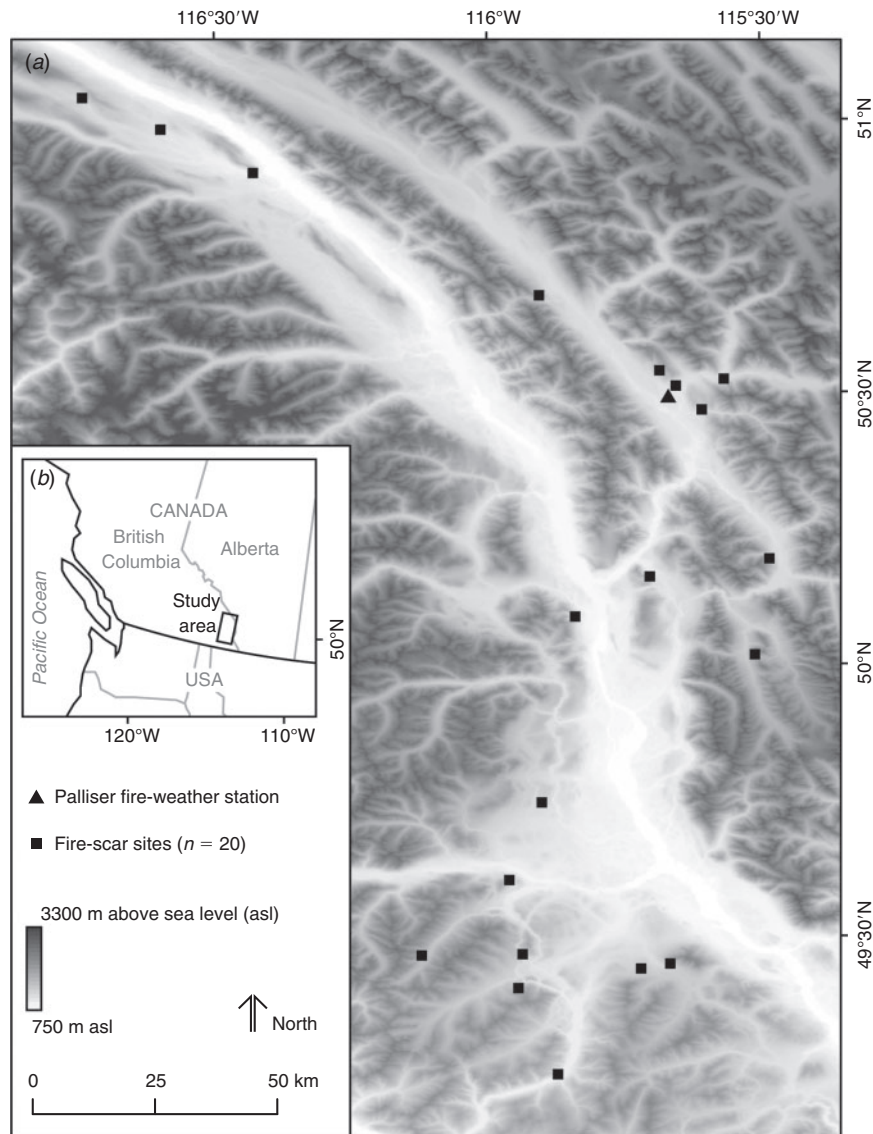


Fig. 1. (a) Palliser fire-weather station and fire-scar sites within montane forests of (b) south-eastern British Columbia, Canada.

Daily and monthly fire-weather data

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

Acquiring monthly fire-weather data required multiple steps. We 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 (1 April to 31 October) 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 DC calculations at the beginning of each fire season. We identified missing monthly maximum temperature and precipitation values, and monthly mean DC (DC_m) values using the criteria for the Adjusted and Homogenised Canadian Climate Data (Mekis and Vincent 2011; Vincent *et al.* 2012). From 1989 to 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 for November–May, mostly during the months between fire seasons. To estimate missing values, we generated records of monthly maximum temperature for April–October, and monthly precipitation for January–December for 1989–2013 using *ClimateNA* (Wang *et al.* 2016). We used the *ClimateNA*-generated records to impute the monthly maximum temperature and precipitation values that were missing from the 1989–2013 Palliser monthly records.

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

We computed two monthly adaptations of DC over each fire season from 1989 to 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 30 April in each year (S1, available as Supplementary material to this paper). Adjusted MDC (adjMDC) accounted for overwintering and an earlier start to the fire season. From an initial DC value of 195.7 measured on 31 May 1989, adjMDC was calculated for June–October of 1989. From 1990 to 2013, adjMDC was calculated for April–October with the April starting value accounting for overwinter drying between each fire season adapted to the monthly scale (Supplementary material S1).

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

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

$$Y_i = X_i\beta + Z_i b_i + \varepsilon_i$$

where i = month (April, May, ..., October) or group of months (early fire season: April–May, mid–late fire season: June–October), Y_i is a column vector of length n_i of DC_m observations for each group i , X_i and Z_i are design matrices of dimension $n_i \times 2$ containing adjMDC values as predictor variables, β and b_i are vectors of fixed- and random-effect coefficients respectively, and ε_i is a column vector of length n_i of random, normally distributed errors for observations in i with covariance matrix $\sigma_{\varepsilon_i}^2$. During model development, we tested whether it was justified to include (i) random effects (intercepts and slopes) for each month vs a random effect for each group of months; and (ii) autoregressive (AR) model of order 1 correlation to account for autocorrelation. Model selection was based on minimising Akaike's information criterion (AIC), likelihood ratio tests and model simplicity (Bolker *et al.* 2009). To assess the fit of our model, we calculated for each month, and group of months, average bias (B) and root-mean-squared error (RMSE) using leave-one-out cross-validation.

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

To assess the accuracy of MDC, adjMDC or predicted DC_m (pred DC_m) relative to DC_m from 1989 to 2013, we used boxplots with Mann–Whitney rank sum tests and calculated Pearson product moment correlations (Systat Software 2014). To evaluate discrepancies among these DCs, we 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). We 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.

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

We used the *ClimateNA*-generated monthly data to calculate MDC from May to October 1901–2013, using an initial value of 15 on 30 April of each year (Girardin and Wotton 2009). We calculated adjMDC continuously from April 1901 to October 2013 from an initial value of 15 on 31 March 1901 (Canadian Forestry Service 1984). We applied the linear mixed-effects model coefficients to predict DC_m over the same period as adjMDC.

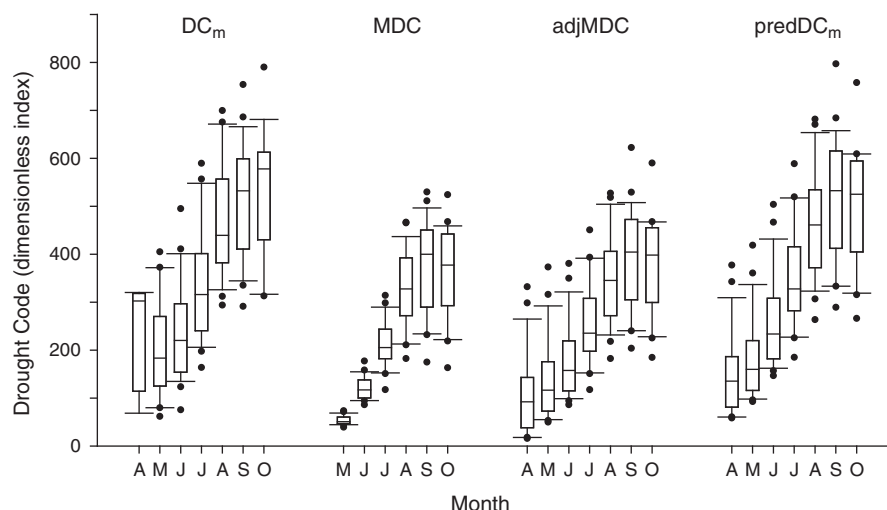
To compare MDC, adjMDC and pred DC_m from 1901 to 2013, we categorised their values as low (<200), intermediate (≥ 200 and <400) or high (≥ 400) according to thresholds corresponding to relative moisture content in compact organics and coarse woody fuels (after Bergeron *et al.* 2010). When DCs are low, fuels are quite wet and least likely to combust, whereas high values indicate dry, combustible fuels, which is supported by the findings of de Groot *et al.* (2009) that more forest floor fuels are consumed by fire as DCs increase. To assess the onset of drought during each fire season, we compared the first month in each year when values were ≥ 200 for each code. To assess the magnitude of fire season droughts, we compared the proportion of months categorised as low, intermediate and high during all fire seasons from 1901 to 2013. For each pair of monthly adaptations of DC, we derived two-way contingency tables of observed values from which we calculated expected values and assessed differences using chi-square goodness-of-fit tests (Systat Software 2014).

Fire–drought associations, 1901–2013

We combined cross-dated fire-scar records from 20 montane forest sites in our study area (Cochrane 2007; Daniels *et al.* 2011) and identified 17 years from 1901 to 2013 in which ≥ 2 trees were scarred (hereafter, 'fire years'). We tested fire–drought associations in two ways. First, we 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 pred DC_m . We 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 pred DC_m represented the magnitude of droughts during fire years similarly, we compared the proportion of months categorised as low, intermediate and high during the 17 fire years. For each pair of monthly adaptations, we derived two-way contingency tables of observed values from which we calculated expected values and assessed differences using chi-square goodness-of-fit tests (Systat Software 2014).

Table 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

**Fig. 2.** Boxplots of the monthly mean Drought Code (DC_m), Monthly Drought Code (MDC), adjusted MDC (adjMDC) and predicted DC_m (pred DC_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.

Results

Model predicting DC_m

The graph of DC_m vs adjMDC revealed distinct slopes for two groups of months (group 1: April–May and group 2: June–October) (see Fig. S1). 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 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 to July ($-15 \leq B \leq 7$). 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 to September ($36 \leq \text{RMSE} \leq 42$), greatest from April to June ($51 \leq \text{RMSE} \leq 52$) and intermediate over October (RMSE = 46).

Improved predictions of DC_m

Of the monthly adaptations of DC, adjMDC was more accurate than MDC, and pred DC_m was the most accurate representation

of DC_m (Fig. 2). 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 to September. When comparing adjMDC with DC_m , medians were similar early in the fire season ($P = 0.841$ and 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. Both pred DC_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 pred DC_m with DC_m were strong and significant ($r^2 \geq 0.87$, $P \leq 0.027$) for all months.

At the Palliser fire-weather station, monthly precipitation was greatest in June, increased from April to June and decreased from June to October (Table 2). Precipitation was >2.8 mm, which was sufficient to wet deep organic fuels and coarse wood and reduce their combustibility, thus altering daily DC on 9–25% of days per month. Monthly effective precipitation averaged from 19 to 64 mm, whereas it averaged from 9 to 47 mm when calculated from daily effective precipitation

Table 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 (<i>n</i>)	Daily precipitation (% of days)			Effective precipitation (mm)		Overestimate (%)
		0 mm	>0 and ≤2.8 mm	>2.8 mm	(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

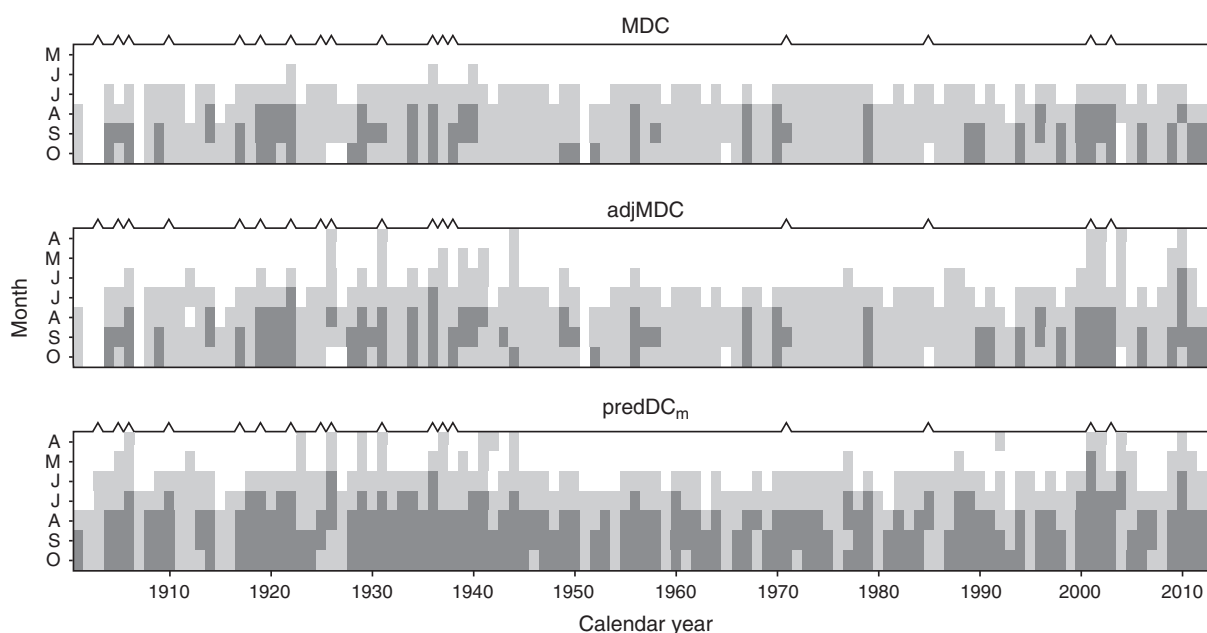


Fig. 3. Months during each fire season with low (<200; white areas), intermediate (≥200 and <400; light grey areas), and high (≥400; dark grey areas) values of the Monthly Drought Code (MDC), adjusted MDC (adjMDC) and predicted monthly mean Drought Code (predDC_m) from 1901 to 2013 for the Palliser fire-weather station. Peaks at the top of each graphic represent the 17 fire years indicated by fire scars.

summed over the month. Overestimation of effective precipitation during a given month ranged from 36 to 117% and was greatest in October and least in June.

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 (Fig. 3). MDC indicated the least amount of drought conducive to fire. Over 113 years from 1901 to 2013, MDC was ≥200 in 4 ± 1 months per year (mean $\pm$ 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 with 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)

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 = ≥200 and <400 = ≥400 =

Fig. 4. 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.

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 to 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 categorised as low, intermediate and high from 1901 to 2013 ($\chi^2 = 0.7$, $P = 0.703$).

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 (Fig. S2). 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 to 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 (Fig. 4).

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 with 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 with 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 ($\chi^2 = 16.4$, $P < 0.001$ and $\chi^2 = 14.7$, $P < 0.001$ respectively). MDC and adjMDC did not differ significantly across the proportion of months categorised as low, intermediate and high during fire years ($\chi^2 = 0.2$, $P = 0.898$).

Discussion

adjMDC improved drought estimation in montane forests of south-eastern British Columbia

In the Canadian Fire Weather Index System, the daily 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). We aimed to determine whether the mean monthly DC (DC_m) was well represented by the 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 fire-weather station in montane forests of south-eastern British Columbia, we found lower MDC values during April–May and lower MDC and adjMDC values during June–September relative to DC_m . We found that MDC underestimated the degree of drought throughout the fire season in dry montane forests of south-eastern British Columbia. Therefore, we 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 to September, when fires commonly burn in montane forests of British Columbia (Natural Resources Canada 2019).

Our 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 to 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 to 53%. These inaccuracies are cumulative; consequently, differences between MDC and adjMDC relative to DC_m increased through the fire season.

Implications of improved drought predictions for montane forests of south-eastern 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 pred DC_m more accurately represented DC_m than MDC or adjMDC and improved our understanding of the onset and duration of droughts during fire years from 1901 to 2013. The shift from low to intermediate drought codes provides critical information about increasing fire danger and risk of a

sustained ignition. The pred DC_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 2016; Wotton *et al.* 2017) with the trend expected to continue over the 21st century (Flannigan *et al.* 2013), our novel 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 south-eastern British Columbia. In turn, these historical drought conditions can be compared with 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 pred DC_m values at Palliser were common and of adequate magnitude and duration to sustain fire, had an ignition occurred. Specifically, pred DC_m values for July and August from 1901 to 2013 averaged 345 and 452 respectively. These values are greater than mean July MDC values ≤ 300 reported across Canada from 1901 to 2002 (Girardin and Wotton 2009) and mean August MDC values < 200 reported for the Montane Cordillera from 1901 to 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, our pred DC_m calculated at a finer spatial scale in south-eastern 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.

Drought variability influenced the historical mixed-severity fire regime

Using cross-dated 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 our 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 cross-dated 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 our 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. We found both adjMDC and predDC_m values were predominantly low during the early-fire season, indicating wet and 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 to 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 our interpretations, montane forests of our 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). Our findings provide an opportunity for future research that uses adjMDC and predDC_m alongside fire-scar seasonality to test the hypothesis that early- vs late-season fires differed in severity, depending on the onset and duration of fire-season drought.

Conclusion

Monthly adaptations of DC provided a nuanced understanding of the variability in drought within and among fire seasons in montane forests of south-eastern 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 to 2013. We 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 our 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, we recommend continued investigation of these new DCs. 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 generalised and where they are not applicable.

We 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. We 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.

Conflicts of interest

The authors declare no conflicts of interest.

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