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The authors advise of an error to Fig. 2 of the above paper. Some values in the final two columns of the figure were incorrectly noted. The corrected figure is provided below.

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

Fig. 2. Categories and thresholds for annual precipitation and summer Palmer Drought Severity Index (PDSI; Palmer 1965).

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Regional drought synchronised historical fires in dry forests of the Montane Cordillera Ecozone, Canada

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Abstract. Understanding climate as a driver of low- to moderate-severity fires in the Montane Cordillera Ecozone of Canada is a priority given predicted and observed increases in frequency and severity of large fires due to climate change. We characterised historical fire-climate associations using 14 crossdated fire-scar records and tree-ring proxy reconstructions of summer drought and annual precipitation from the region. We compared fire-climate associations among years when fires burned in multiple study areas. From 1746 to 1945, there were 32 years with moderate fire synchrony in which four to six study areas recorded fire. During four high fire synchrony years, 7 to 10 study areas recorded fire. Below-average annual precipitation and summer drought synchronised fires, whereas infrequent years of high fire synchrony were preceded by a wet summer. After 1945, decreased fire occurrence and synchrony reflects fire exclusion, suppression and climatic variation. Global climate change manifests as blocking high-pressure ridges that superimpose on longer fire-seasons and increased droughts. Combined, they make dry forests increasingly susceptible to synchronous fires, which are difficult to suppress as observed during the record-breaking 2017, 2018 and 2021 fire seasons in British Columbia.

Keywords: fire history, mixed-severity fire regime, dendrochronology, climate, annual precipitation, proxy-climate reconstructions, Palmer Drought Severity Index.

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Introduction

Anthropogenic climate change is leading to prolonged drought conducive to fire occurrence with high-severity impacts in forests of western North America (Westerling 2016; Wotton *et al.* 2017; Hanes *et al.* 2019). Ultimately, this will result in more frequent fires placing human communities at risk (Moritz *et al.* 2014; Sankey 2019). For example, within the Montane Cordillera Ecozone of Canada, many large (>200 ha) forest fires, including mega-fires (>10 000 ha; Stephens *et al.* 2014), overwhelmed the deployment and control capabilities of fire suppression organisations during the 2017, 2018 and 2021 fire seasons (Natural Resources Canada 2021). Across the region, these fire seasons coincided with record-breaking persistent warm and dry weather conditions driven by anthropogenic climate change (Kirchmeier-Young *et al.* 2019). Such conditions over the fire season lower forest fuel moisture content, and facilitate the ignition, combustion and spread of fires (Gedalof 2011; Macias Fauria *et al.* 2011). Determining whether there is historical precedence for similar fire synchrony across the region is an important question that needs to be addressed to support fire managers in anticipating potential climate change impacts on fire regimes.

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

Many of the fire-scar chronologies developed for the Montane Cordillera Ecozone and in the north-western USA were collected in low- to mid-elevation coniferous forests with mixed-severity fire regimes (Perry *et al.* 2011; Heyerdahl *et al.* 2012; Marcoux *et al.* 2013; Harvey and Smith 2017; Hessburg *et al.* 2019). Mixed-severity fire regimes are represented by fires that burn across space and time with a broad range of severities, from low-severity surface fires to high-severity crown fires (Perry *et al.* 2011; Daniels *et al.* 2017). The range of fire severities is reflected by the spatial and temporal variation in mortality effects on vegetation, and consequently forest stands across the landscape are compositionally and structurally diverse (Halofsky *et al.* 2011; Daniels *et al.* 2017). Although climate is a well-documented top-down driver of fires in this region (Heyerdahl *et al.* 2008*b*; Harvey and Smith 2017; Chavardès *et al.* 2018), understanding the more nuanced influences of climatic variation on the range of fire severities remains poorly understood.

In this research, we tested the hypothesis that spatio-temporal variation in climate was an important driver of fire synchrony within the Montane Cordillera Ecozone but that extreme droughts facilitating synchronous fires across study areas were relatively rare. Specifically, we address the following two questions: (1) How frequently did historical fires burn synchronously among study areas in the Montane Cordillera Ecozone? (2) What climate conditions were associated with various levels of fire synchrony? To answer these questions, we conducted a meta-analysis of fire-scar records previously sampled in 14 study areas across the Montane Cordillera Ecozone and quantified the occurrence and frequency with which fires synchronously burned in multiple study areas in a given year (i.e. fire synchrony). We used regional climatic proxies for annual precipitation and summer drought, and tested for associations between climate and years of fire synchrony. We also applied spatial interpolation with networks of climate reconstructions to characterise fire-climate associations.

Methods

Study area

We analysed the crossdated fire-scar records previously collected from 14 study areas located in the relatively dry forests of the Montane Cordillera Ecozone (Fig. 1, Table 1). This ecozone covers ~30 million hectares (ha) extending from the crest of the Coast Mountains in southern British Columbia eastward across the Rocky Mountains to the foothills in Alberta, Canada. Climate across the Montane Cordillera Ecozone is continental, with maritime influences from the westerly flow of air masses from the Pacific Ocean that are modulated by orographic uplift and rain-shadow effects of the Coastal, Caribou, Columbia and Rocky Mountain ranges (Fig. 1*a*; Ecological Stratification Working Group 1995). The study areas were distributed in about 3 million ha of forests in very dry and dry climatic subzones, according to the biogeoclimatic classification (Pojar and Meidinger 1991). Study areas 1–6 were within 20–215 km of each other on the Central Interior Plateau but were 300–600 km from study areas 8–14. Study areas 8–14 were within 20–190 km of each other in the Columbia and Rocky Mountains. Study area 7 was in an intermediate location, ~200 km south of areas 5–6 and 200 km west of areas 8–9.

Locally, topographic influences on climate contribute to complex environmental gradients and diverse ecosystems dominated by coniferous tree species, as follows (Fig. 1*b*; Pojar and Meidinger 1991). The warmest and driest study areas were

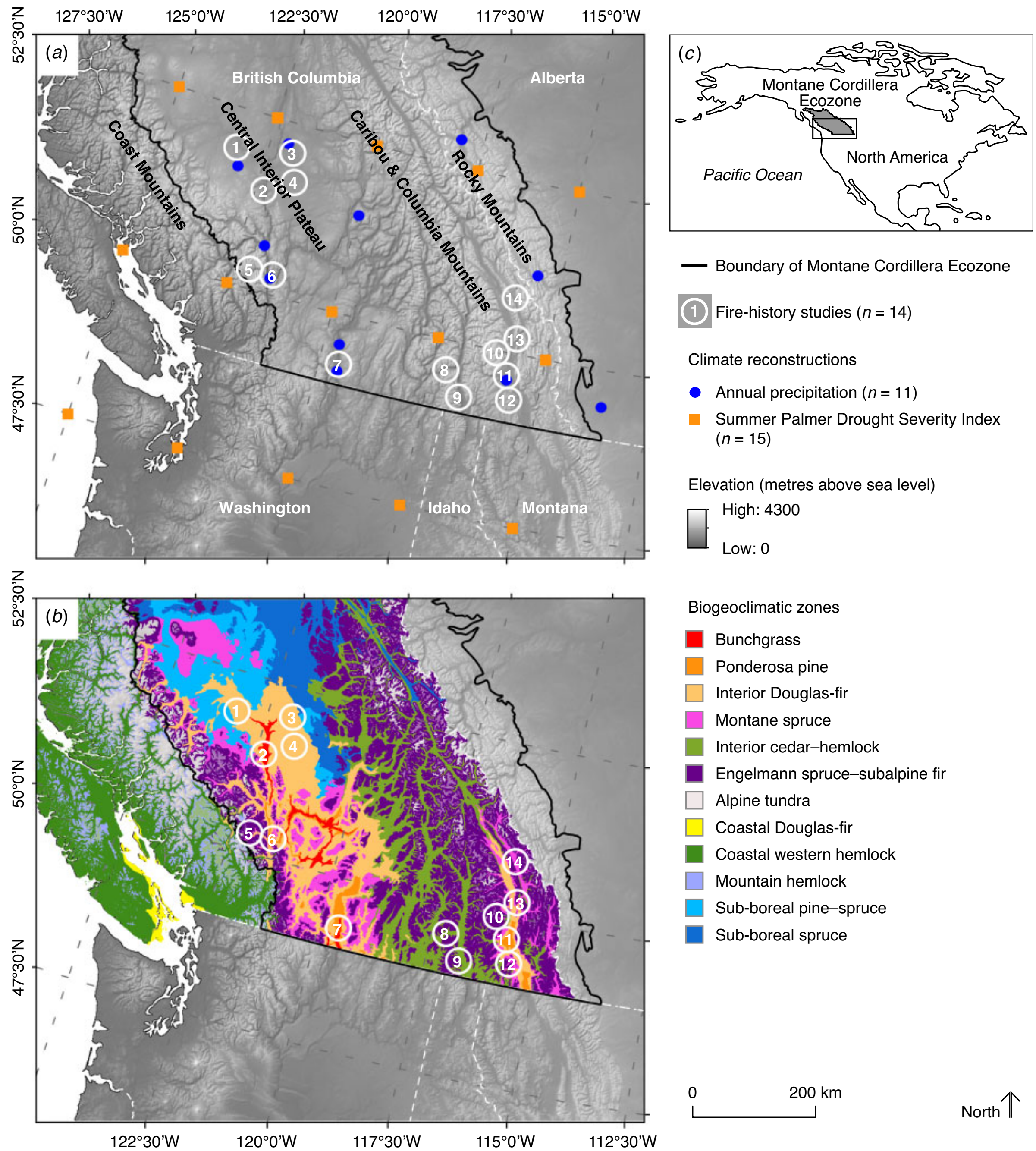

Fig. 1. (*a*) Centroid locations for the fire-history studies and locations of the climate reconstructions along with major geographic features and (*b*) biogeoclimatic zones (Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2021) in the (*c*) Montane Cordillera Ecozone, Canada.

located on the Central Interior Plateau (study areas 1–4) or in dry valley bottoms (study areas 5–7, 11) where bunchgrass (BG; elevation = 150–600 m above sea level (masl)), ponderosa pine (PP; 250–900 masl) and Interior Douglas-fir (IDF; 350–1450 masl) biogeoclimatic zones include open- and closed-canopy forests composed of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), Interior Douglas-fir (*Pseudotsuga menziesii var. glauca* (Beissn.) Franco) and western larch (*Larix occidentalis* Nutt.). In mountainous terrain, climate becomes cooler and more mesic along the elevational gradient from valley bottoms to subalpine forests. On the relatively dry, leeward side of the Caribou and Columbia Mountains and in the Rocky Mountains (study areas 10, 12–14), forests of the Montane spruce (MS; 1250–1700 masl) zone are dominated by ponderosa pine, Douglas-fir, western larch, lodgepole pine (*P. contorta var. latifolia* Douglas) and hybrid spruce (*Picea engelmannii* Parry ex

Table 1. Summary of biophysical, research design and fire-history attributes for 14 study areas in the Montane Cordillera Ecozone, Canada

Study area: 1, Harvey and Smith (2017); 2, Harvey *et al.* (2017); 3, Brookes *et al.* (2021); 4, Daniels and Watson (2003); 5, Heyerdahl *et al.* (2012); 6, Heyerdahl *et al.* (2007); 7, Pogue (2017); 8, Nesbitt (2010); 9, Greene and Daniels (2017); 10, Daniels *et al.* (2007), Daniels and Gray (2007); 11, Nesbitt and Daniels (2009); 12, Marcoux *et al.* (2013), Villemaire-Côté (2014); 13, Cochrane (2007); 14, Kubian (2013). ICH, Interior cedar – hemlock; IDF, Interior Douglas-fir; ESSF, Engelmann spruce – subalpine fir; MS, Montane spruce; PP, ponderosa pine

Study area	Location of study area centroid		Elevation (masl)	Biogeoclimatic zone	Plots		Sample sizes			Composite fire record (calendar yrs)	Fire years (*n*)	Plot-level mean (range) fire intervals (yrs)	Study-area annual probability of fire (%)	Last fire (calendar yr)
					Number (*n*)	Area (ha)	Trees (*n*)	Scars (*n*)	Dormant season (%)					
1	51°55′N	123°13′W	790–1125	IDF	8	30–40	139	535	96	1513–2013	95	28 (1–138)	3.57	1990
2	51°40′N	121°40′W	865–1290	IDF	27	1	92	437	73	1520–2012	80	23 (1–104)	4.35	1991
3	52°04′N	121°54′W	760–880	IDF	35	1	65	224	–	1558–2015	20	35 (9–113)	2.86	1943
4	51°26′N	122°18′W	900–1285	IDF	9	1	136	280	35	1491–1995	39	24 (2–104)	4.17	1938
5	50°18′N	121°58′W	260–610	IDF	43	2	155	997	45	1511–1999	86	21 (2–60)	4.76	1937
6	50°16′N	121°39′W	235–575	PP, IDF	37	1.5	162	748	55	1608–1996	69	24 (1–117)	4.17	1947
7	49°17′N	119°33′W	325–675	PP	43	1	149	439	59	1611–2013	34	31 (3–145)	3.23	1970
8	49°34′N	117°10′W	600–1725	ICH, ESSF	18	1	45	67	–	1665–2009	14	52 (14–149)	1.92	1927
9	49°13′N	116°45′W	595–1690	ICH, ESSF	45	1	127	340	95	1407–2009	23	33 (3–128)	3.03	1926
10	50°01′N	116°05′W	930–1600	MS	10	20–100	108	294	82	1353–2005	46	37 (2–202)	2.70	1937
11	49°34′N	115°46′W	940–1000	IDF	2	20	43	165	–	1522–2003	30	21 (3–236)	4.76	1891
12	49°25′N	115°40′W	1080–1980	IDF, MS, ESSF	22	1	96	221	–	1510–2007	34	35 (4–148)	2.86	1957
13	51°55′N	115°47′W	1100–1555	MS	20	1	149	272	44	1431–2006	40	57 (4–232)	1.75	2003
14	51°26′N	115°58′W	1100–1330	MS	43	1.4	83	123	92	1693–2009	11	26 (5–57)	3.85	1926

Engelm × *Picea glauca* (Moench) Voss). On the relatively wet, windward side of the Columbia Mountains (study areas 8–9), the diverse forests of the Interior cedar hemlock (ICH; 400–1500 masl) zone include all tree species from the MS zone, as well as western red cedar (*Thuja plicata* Donn ex D.Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) on mesic sites. Engelmann spruce and subalpine fir (*Abies lasiocarpa* Hook (Nutt.)) dominate at the highest elevations (ESSF zone; 1500–2300 masl), above the MS and ICH zones (study areas 8–9, 12).

All study areas are located in the Southern Cordillera homogeneous fire regime zone delineated by Boulanger *et al.* (2014). Using documented fire records (1959–1999), the authors estimated 0.06% of the area burned from an average of 4.3 fires per 100 000 km^2 annually. Ignitions are strongly influenced by lightning, particularly in July and August (Boulanger *et al.* 2014). Historically, mixed-severity fire regimes dominated as indicated by abundant trees with multiple fire scars across elevations and forest types (Table 1; Marcoux *et al.* 2013; Hessburg *et al.* 2019). Surface fires were frequent at low- and mid-elevations transitioning to infrequent crown fires in subalpine elevations (Marcoux *et al.* 2013; Hessburg *et al.* 2019). Fire-scar records consistently show the near elimination of surface fires starting in the late-19th to mid-20th centuries. Effective fire suppression was preceded by extensive agriculture and livestock grazing in valley bottoms, while colonisation by Euro-Canadians ended cultural fire stewardship by Indigenous people, whose oral histories convey prevalent fire use (Lewis *et al.* 2018; Lake and Christianson 2019).

Historical fire records

We compiled crossdated fire-scar records representing historical fire occurrence in 14 study areas in the Montane Cordillera Ecozone (Fig. 1, Table 1). Individual studies included 2–45 (median = 25) plots, 43–162 (median = 118) fire-scar samples and 67–997 (median = 296) crossdated fire scars (Table 1). To allow direct comparison across all study areas, we defined the start of the recording period as the year in which ≥2 living fire-scarred trees were present and had the potential to re-scar in the advent of subsequent fires. Fires recorded by ≥2 trees during a given year were considered a 'fire year' (after Heyerdahl *et al.* 2008*a*). Within each study area, we calculated plot-level means and ranges of scar-to-scar fire intervals from the start of the recording period to the last scar. The probability of burning in each year was calculated as the inverse of study-area overall mean fire interval, multiplied by 100 to be expressed as a percentage. Fire years were composited into study-area level fire records. For each year, the number of study areas recording a fire year were summed, generating an ecozone-level composite fire record. Based on the number of study areas recording a fire in each calendar year, we designated four categories of synchrony using criteria from Heyerdahl *et al.* (2008*a*): (1) 'low fire synchrony' for years with fire scars in one to three study areas, (2) 'moderate fire synchrony' for years with fire scars in four to six study areas, (3) 'high fire synchrony' for years with fire scars in more than six study areas, and (4) 'synchronous non-fire years' when no fires were recorded in any of the 14 study areas. The seasonality of fires was interpreted for most, but not all, of the fire-history studies. Most scars were dormant season scars, which would have been caused by fires in mid to late summer

(Heyerdahl *et al.* 2012; Harvey *et al.* 2017; Pogue 2017) or late summer to fall (Daniels and Watson 2003; Cochrane 2007; Daniels *et al.* 2007; Nesbitt and Daniels 2009), if caused by lightning. Dormant-season fire scars can also be caused by Indigenous fire stewardship commonly practised in fall or early spring (Lake and Christianson 2019).

Reconstructions of regional climate

To represent climate throughout the Montane Cordillera Ecozone, we applied Principal Components Analysis (PCA) (SAS Institute Inc. 2017) to derive regional-scale tree-ring proxy reconstructions of precipitation and the Palmer Drought Severity Index (PDSI), a drought index that combines the effects of temperature and precipitation (Palmer 1965). We used 11 long site-level reconstructions of annual precipitation (previous July to current June) within the ecozone (Banff, Jasper and Waterton Lakes, Alberta, and Big Creek, Cranbrook, Lillooet, Lytton, North Thompson, Oliver, Summerland and Williams Lake, British Columbia) (Watson and Luckman 2004) and reconstructions of summer PDSI for 15 grid points encompassing the study areas (grid points 23–25, 30–32, 41–43, 53–55 and 66–68; Cook *et al.* 2004) (Fig. 1). To derive regional proxy reconstructions for annual precipitation and summer drought, we extracted the first principal component (PC1) from the 11 reconstructions of annual precipitation ($PC1_{PPT}$) and the 15 reconstructions of summer PDSI ($PC1_{PDSI}$). We tested for linear correlation between $PC1_{PPT}$ and $PC1_{PDSI}$ using a scatter plot and by calculating the Pearson product moment correlation between them.

Regional fire-climate associations

The common period between the ecozone-level composite fire record and the two regional climate reconstructions, 1746–1945, defined the period of analyses for fire-climate associations. The period ends in 1945 to avoid the confounding influences of fire exclusion policies imposed at the turn of the 20th century that were reinforced by the introduction of organised and mechanised fire suppression after 1945 in western North America (Pyne 1982, 2007; Keane *et al.* 2002; Donovan and Brown 2007).

Over the period of analysis, we used two approaches to test if increasing fire synchrony was associated with warm and dry regional climate. First, we compared values of each regional climate reconstruction across categories of synchrony using box plots and analysis of variance of ranks followed by post-hoc Dunn's tests (Gorvine *et al.* 2018). Second, we conducted additional analyses on three subsets of years based on degrees of synchrony (hereafter, collectively referred to as 'synchronous events'): (1) moderate–high fire synchrony were years when ≥4 study areas included scars (i.e. moderate and high fire synchrony classes combined), (2) high fire synchrony, and (3) synchronous non-fire years. To test the associations between synchronous events and the regional climate reconstructions, we used Superposed Epoch Analysis (SEA) from the Fire History Analysis and Exploration System developed by Brewer *et al.* (2015). To meet the assumptions of SEA, we used Autoregressive Integrated Moving Average (ARIMA) procedures to test for autocorrelation with up to six lags then remove it from $PC1_{PPT}$ and $PC1_{PDSI}$ (SAS Institute Inc. 2017). ARIMA procedures showed that $PC1_{PPT}$ and $PC1_{PDSI}$ had temporal autocorrelation ($P < 0.001$ and $P = 0.016$, respectively), so we fitted first order autoregressive process models and used the white noise residuals of $PC1_{PPT}$ and $PC1_{PDSI}$ (white noise tests $P = 0.881$ and $P = 0.595$, respectively) in SEA. For $PC1_{PPT}$ and $PC1_{PDSI}$ residuals, we calculated mean values during the year coinciding with synchronous events and the three preceding years and compared them to bootstrapped values derived from a Monte Carlo simulation of randomly selected years that provided 95%, 99% and 99.9% confidence intervals.

We visually depicted mean climate conditions for the three sets of synchronous events: (1) years with moderate–high fire synchrony, (2) years with high fire synchrony, and (3) non-fire years, as well as climate conditions during four individual years with high fire synchrony. To represent climate anomalies, we calculated *z*-scores (Salkind 2007) for each of the 11 site-level reconstructions of annual precipitation and used the summer PDSI values for each of the 15 grid-point reconstructions. We applied Inverse Distance Weighted (IDW) interpolation (Bivand *et al.* 2008) to develop continuous maps depicting mean climate conditions during each type of synchronous event and climate conditions during the four years with high fire synchrony. To select a suitable combination of parameters that optimised IDW interpolation, we conducted a sensitivity analysis. The parameters included a search neighbourhood of 3°35′ with a range of three to eight neighbours, a cell size of 0°15′ and a power of two (Environmental Systems Research Institute 2018). To describe climate conditions and to colour-code the maps, annual precipitation *z*-scores and summer PDSI values were assigned to 1 of 11 classes ranging from 'extremely wet' to 'extreme drought' (Fig. 2).

Results

Historical fire records

The fire-scar records from the 14 study areas revealed abundant fire activity (Fig. 3). In individual study areas, mean fire intervals ranged from 21 to 57 years, with corresponding annual probabilities of fire from 4.76% to 1.75%, respectively (Table 1). Between 1746 and 1945, 179 fire years (89.5% of 200-year period) were identified at the ecozone scale, with low, moderate and high fire synchrony recorded in 143, 32 and 4 years,

Category	Colour	Annual precipitation *z*-scores	Summer PDSI values
Extremely wet		≥0.90	≥4.00
Very wet		0.89–0.70	3.00–3.99
Moderately wet		0.69–0.50	2.00–2.99
Slightly wet		0.49–0.30	1.00–1.99
Incipient wet spell		0.29–0.10	0.50–0.99
Near normal		−0.09–0.09	−0.49–0.49
Incipient drought		−0.29–0.10	−0.50–0.99
Mild drought		−0.49–0.30	−1.00–1.99
Moderate drought		−0.69–0.50	−2.00–2.99
Severe drought		−0.89–0.70	−3.00–3.99
Extreme drought		≤−0.90	≤−4.00

Fig. 2. Categories and thresholds for annual precipitation and summer Palmer Drought Severity Index (PDSI; Palmer 1965).

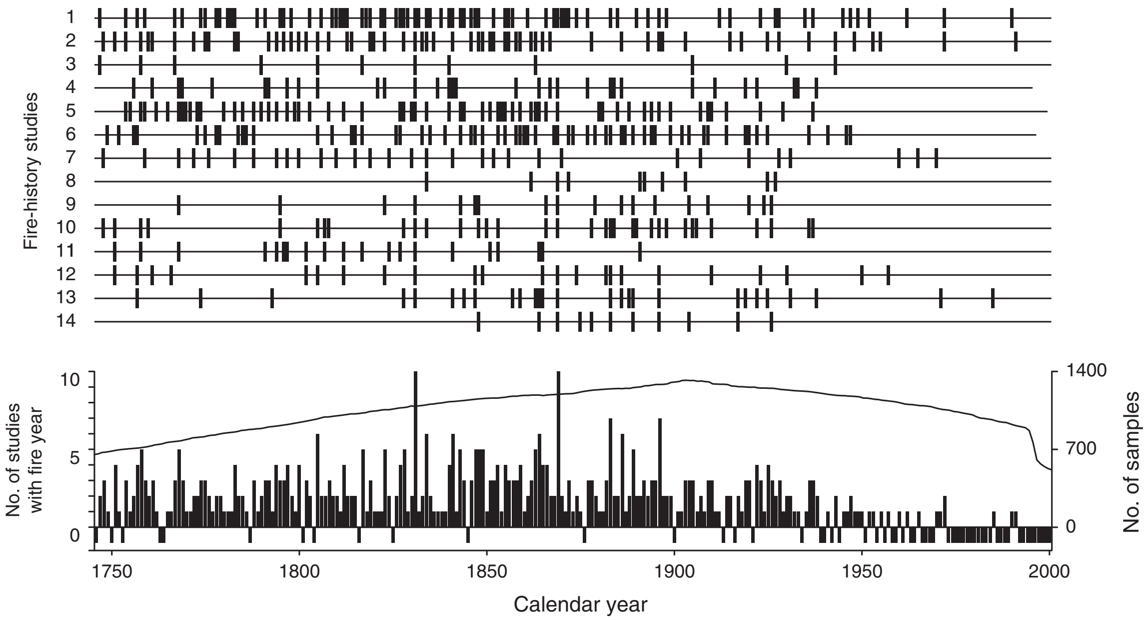

Fig. 3. Fire records from 1746–2000 for the 14 fire-history studies within the Montane Cordillera Ecozone. The top panel shows the fire record for each study, the temporal extent of each fire record from 1746 as a horizontal line, and each fire year as a black tick. The bottom panel shows the number of studies with a given fire year as black columns. Years in which no sites recorded fire are synchronous non-fire years and are shown as black columns extending downward for emphasis. The curve indicates the number of crossdated fire-scar samples over time.

respectively. During those 200 years, only 21 years (10.5%) were synchronous non-fire years. After 1945, 37 years (67.3%) were synchronous non-fire years, while 16 and 2 years were fire years in only one and two study areas, respectively.

Reconstructions of regional climate

Based on PCA, variances explained for $PC1_{PPT}$ (33%) and $PC1_{PDSI}$ (77%) indicated the reconstructions of annual precipitation exhibited more spatial variability across the 11 sites than the reconstructions of summer PDSI across the 15 grid points. The diagnostic plot and Pearson product moment correlation revealed a moderately strong positive linear correlation between $PC1_{PPT}$ and $PC1_{PDSI}$ ($r^2 = 0.66$, $P < 0.001$) (Fig. 4).

Regional fire-climate associations

Synchronous fire events were associated with distinct regional droughts, indicated by low annual precipitation and negative summer PDSI (Fig. 5). Temporally, the 36 years with moderate–high fire synchrony occurred at intervals of 1 to 26 years, averaging five years between them. On average, annual precipitation was significantly drier in the year coinciding with fire ($P < 0.001$) (Fig. 6*a*), and summer PDSI was significantly drier both the year of fire ($P < 0.001$) and the previous year ($P < 0.05$) (Fig. 6*b*). These climate associations were amplified during the four years with high fire synchrony during the 1800s. Fire was recorded in 10 study areas in 1831 and 1869 and in seven areas in 1883 and 1896, recurring at intervals of 13 to 38 years, averaging 22 years. Annual and summer climate were significantly drier than average in the year coinciding with fire ($P < 0.01$ and $P < 0.05$, respectively), and summers were significantly wetter than average three years before fire years

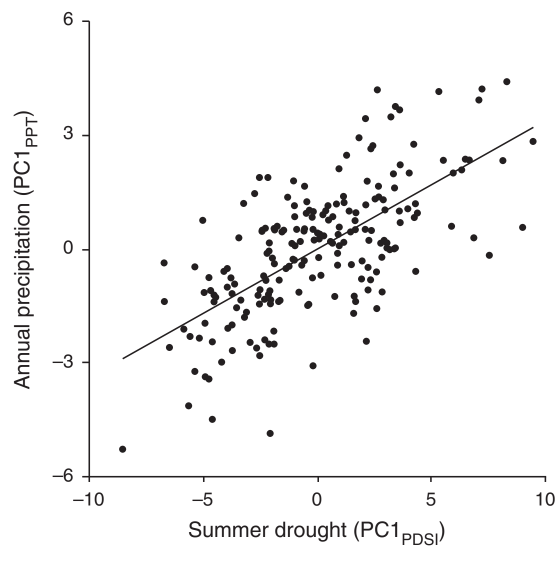

Fig. 4. Scatter plot of regional climate reconstructions for the Montane Cordillera Ecozone. Reconstructions correspond to the first principal component of the 11 reconstructions of annual precipitation ($PC1_{PPT}$), and the first principal component of the 15 reconstructions of summer Palmer Drought Severity Index ($PC1_{PDSI}$). Drier conditions according to $PC1_{PPT}$ and $PC1_{PDSI}$ lie below zero.

($P < 0.05$) (Fig. 6*c*, *d*). In contrast, regional climate conditions were significantly wetter than average during the 21 synchronous non-fire years before 1945 ($P < 0.01$) (Fig. 6*e*, *f*).

Climatic conditions mapped across the Montane Cordillera Ecozone also differed among the three sets of synchronous

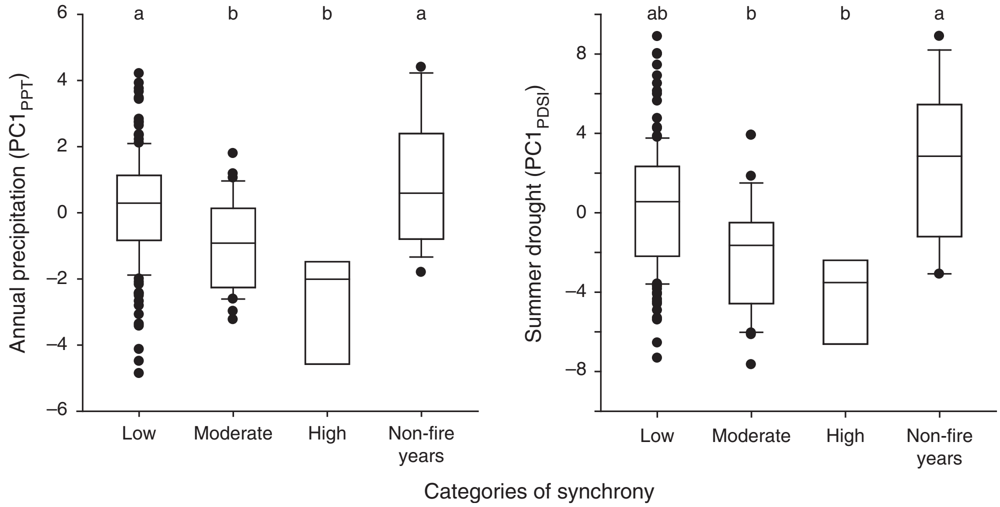

Fig. 5. Reconstructions of regional climate according to categories of synchrony in the Montane Cordillera Ecozone. Reconstructions of regional climate correspond to the first principal component of the 11 reconstructions of annual precipitation ($PC1_{PPT}$), and the first principal component of the 15 reconstructions of summer Palmer Drought Severity Index ($PC1_{PDSI}$). Drier conditions according to $PC1_{PPT}$ and $PC1_{PDSI}$ lie below zero. Categories of synchrony correspond to the following: low = fire year recorded in one to three study areas ($n = 143$); moderate = fire year recorded in four to six study areas ($n = 32$); high = fire year recorded in more than six study areas ($n = 4$); and non-fire years = no fire years recorded in all 14 study areas ($n = 21$) (from Heyerdahl *et al.* 2008*a*). In each box plot, the black horizontal line represents the median, box boundaries are the 25th and 75th percentiles, and bars are the 10th and 90th percentiles. Same letters and shared letters above box plots = no significant difference among median reconstructed regional climate values ($\alpha = 0.05$).

events (Fig. 7). On average, during the 36 years with moderate–high fire synchrony, annual precipitation indicated normal conditions to moderate drought (Fig. 7*a*) and summer PDSI indicated incipient to mild drought (Fig. 7*b*). During the four years with high fire synchrony, annual precipitation indicated incipient to extreme drought (Fig. 7*c*) and summer PDSI indicated mild to moderate drought (Fig. 7*d*). Spatially, drought conditions tended to be more pronounced in the mountain ranges to the east of the Central Interior Plateau during synchronous fire years. In contrast, during the 21 non-fire years both annual precipitation and summer PDSI indicated mostly slightly wet climate (Fig. 7*e*, *f*).

Drought varied spatially and temporally among the four individual years with high fire synchrony (Figs 8 and 9). Drought was most uniform in 1869, when annual precipitation indicated extreme drought and summer PDSI indicated moderate to extreme drought across the ecozone. In 1883, all fire-history study areas were affected by drought, although part of the ecozone had above-average precipitation. In 1831 and 1896, fires were recorded across the ecozone, although drought was more pronounced in the Columbia and Rocky Mountains than along the Central Interior Plateau.

Discussion

Historically, low- to moderate-severity fires that scarred trees were common and often burned synchronously in dry forests located across the Montane Cordillera Ecozone of Canada. The annual probabilities of fire ranged from 2% to 5% for individual study areas, producing fire return intervals from 20 to 60 years. Based on probability, had the fires been spatially and temporally independent, the chance of just two study areas burning synchronously is <0.2% or once in 440 years. In strong contrast, moderately synchronous fires burned in ≥4 of the 14 study areas 36 times during the 200 years before 1945, whereas highly synchronous fires burned ≥7 study areas four times during the 1800s, averaging only 22 years between events. Spatially, our study areas were separated and independent, with two minor exceptions. Study area 10 was a pilot study focused on forests with old-growth structures (Daniels *et al.* 2007; Daniels and Gray 2007), and study area 13 was a stratified-random sample of old forests across the landscape (Cochrane 2007), although no individual plots overlapped. Study areas 5 and 6 were adjacent to each other in the Stein River valley, separated by distance along and elevation above the river channel (Heyerdahl *et al.* 2007, 2012). Temporally, our ecozone-level fire record showed that 90% of years between 1746 and 1945 had low to high fire synchrony generally coinciding with droughts of various degrees, corroborating findings across several regions of western North America (Heyerdahl *et al.* 2008*a*, 2008*b*; Trouet *et al.* 2010; Margolis and Swetnam 2013). Evidently, fires were not temporally independent but were synchronised by fire season weather and climate.

Fires synchronised by drought

Synchronous low- to moderate-severity fires that scarred trees were facilitated by regionally dry climate. Tandem use of summer PDSI and annual precipitation reconstruction networks to test and characterise fire-climate associations in the Montane Cordillera Ecozone highlighted the temporal sequence and spatial patterns of climate conditions associated with high fire

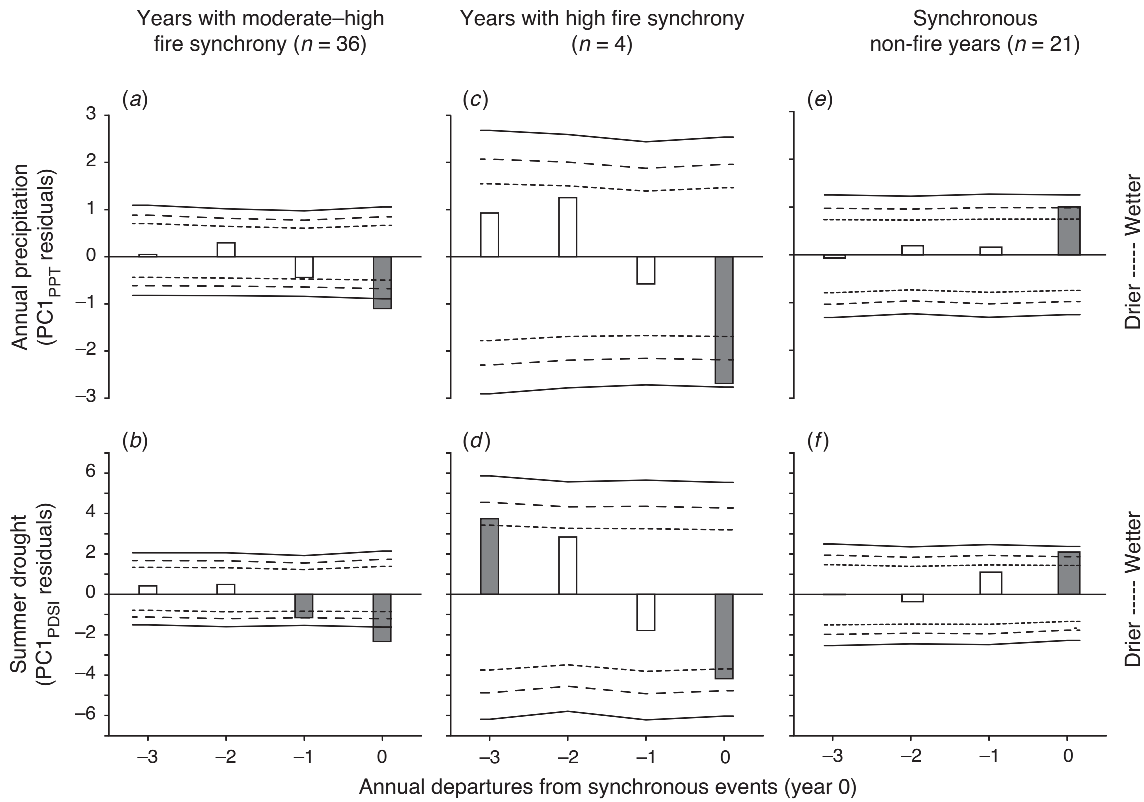

Fig. 6. Superposed epoch analyses showing associations between reconstructions of regional climate during synchronous events (moderate–high fire synchrony, high fire synchrony or synchronous non-fire years) from 1746–1945. Reconstructions of regional climate correspond to white noise residuals of the first principal component for the 11 reconstructions of annual precipitation ($PC1_{PPT}$ residuals), and white noise residuals of the first principal component for the 15 reconstructions of the summer Palmer Drought Severity Index ($PC1_{PDSI}$ residuals). 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 ($P < 0.05$).

synchrony. By applying two drought proxies, one for summer and one for the year leading to and including peak fire season, we found that high fire synchrony was associated with pronounced droughts that lowered the moisture content of a mixture of forest fuel types facilitating the ignition and combustion of fires at different locations in the ecozone.

The highly synchronous fires in 1831, 1869, 1883 and 1896, when 7 to 10 of the 14 study areas burned, coincided with pronounced drought during the summer preceded by low annual precipitation particularly in the eastern parts of the Montane Cordillera Ecozone. Low precipitation between fire seasons can lead to low fuel moisture conditions in deep compact organic matter in the soil and large-diameter woody fuels on the forest floor at the beginning of the fire season in many regions of western Canada (Lawson and Armitage 2008), including montane forests of south-eastern British Columbia (Chavardès *et al.* 2019). During the four years with high fire synchrony, our findings suggest that fuels across most of the ecozone had low moisture content even before peak fire season making them more susceptible to combust in the advent of an ignition. Synergistic with annual precipitation, PDSI values during the summer revealed regionally dry conditions implying fine fuels and the duff layer were susceptible to readily ignite and then spread fire (Chavardès *et al.* 2020). In addition to the association with pronounced drought and low precipitation in the year of fire, we found that high fire synchrony was associated with antecedent summers that were wetter than average. In comparable dry forests with similar species composition in western North America, wetter than normal climate promotes the growth and connectivity of fine fuels, which increases the likelihood of enhanced fire spread when drier than normal conditions return (Westerling *et al.* 2003; Collins *et al.* 2006).

Although high fire synchrony in the Montane Cordillera Ecozone was driven by droughts extending from the previous year into peak fire season, the magnitude of drought and distribution of precipitation were spatially variable across the ecozone during each of the four years with high fire synchrony. For example, in 1831 and 1896, pronounced drought conditions covered most of the ecozone except in the west, where conditions were normal to moderately wet. Even under these conditions, our western study areas included trees that recorded fires. In low- to mid-elevation dry mixed-conifer forests of the Central Interior Plateau, like in the Cariboo represented by study areas 1–4 or the Stein River valley represented by study areas 5 and 6, fuels can be sufficiently desiccated by relatively short periods of warm, dry weather within the fire season overcoming annual-scale climatic controls on fire occurrence (Heyerdahl *et al.* 2007, 2012; Harvey *et al.* 2017). As explained by Gedalof *et al.* (2005)

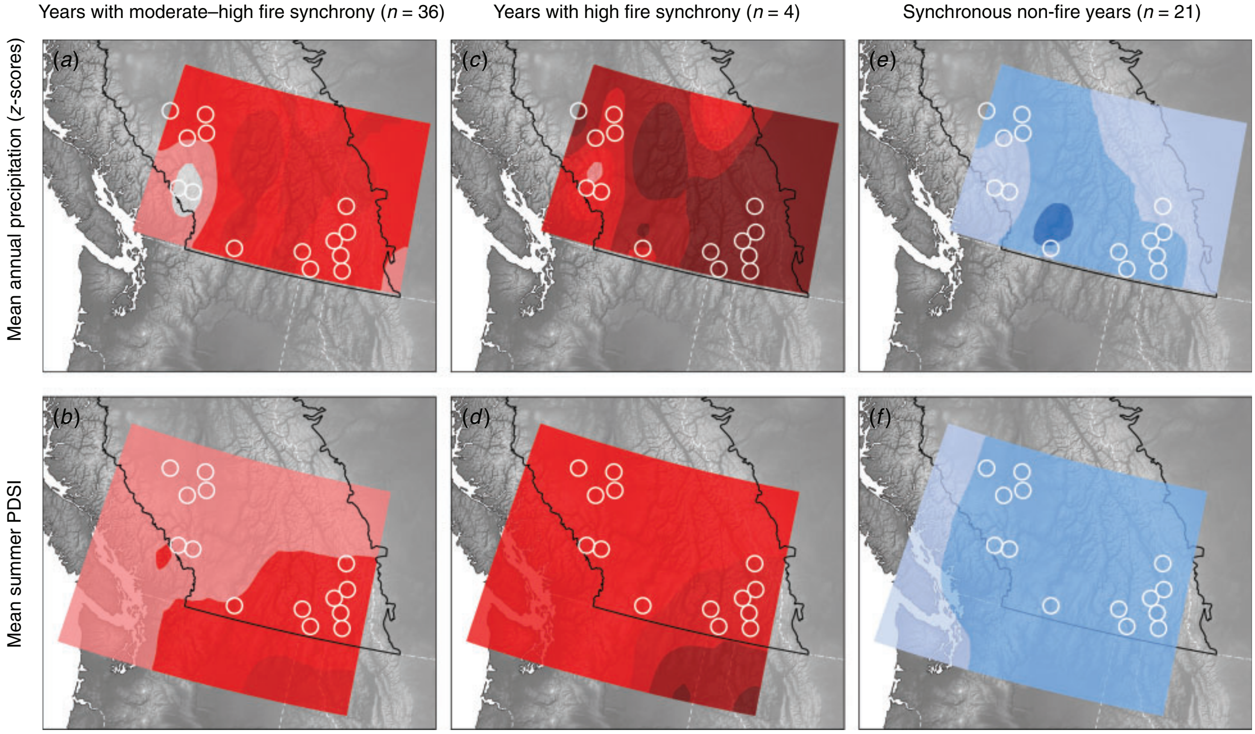

Fig. 7. Reconstructions of mean annual precipitation *z*-scores, and mean summer Palmer Drought Severity Index (PDSI) values interpolated across the Montane Cordillera Ecozone from 1746–1945 during years with synchronous events (moderate–high fire synchrony, high fire synchrony or synchronous non-fire years). As per the wetness scale of Fig. 2, darker tones of red and blue indicate drier or wetter conditions, respectively, whereas grey indicates near normal conditions. Open white circles indicate the centroids for the 14 fire-history studies.

and Macias Fauria *et al.* (2011), warm, dry or windy weather for periods of only two to three weeks during the fire season can lower the moisture content of grasses, fine surface fuels from Douglas-fir and ponderosa pine, and the duff layer, enabling fire ignition and spread. Following short fuel-drying periods, low- to moderate-severity fires tend to scar rather than kill trees. Based on the rich historical fire records pooled from our 14 study areas, it appears that low- to moderate-severity fires burned frequently, even in wetter than normal conditions.

Factors driving regional drought

Understanding the drivers of fire-season drought is key for anticipating and planning contemporary fire management. At the inter-annual scale, historical fire synchrony in the Pacific North-west region coincided with dry climate related to warm phases of the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO; Kitzberger *et al.* 2007; Heyerdahl *et al.* 2008*b*). Although these coarse-scale studies included study areas in British Columbia, similar findings have not been replicated for individual study areas in western Canada. Fire-climate analyses using fire-scars by Schoennagel *et al.* (2005), Harvey and Smith (2017) and Chavardès *et al.* (2018) documented no significant relationships, whereas Macias Fauria and Johnson (2006) reported cool phases of ENSO and PDO coincided with increased fire activity in the modern fire record over most of the Montane Cordillera Ecozone. Improved understanding of how rain shadow effects, climatic transition zones (Watson and Luckman 2005; Macias Fauria and Johnson 2008; Harvey and Smith 2017) and temporal instability (Knapp *et al.* 2002) influence ENSO and PDO teleconnections within the Montane Cordillera Ecozone remains a priority knowledge gap.

At intra-annual time scales of days to weeks, fire synchrony coinciding with droughts is consistent with research on contemporary fires that show increased fire activity associated with mid-tropospheric anomalies that form upper-atmosphere blocking ridges in western North America (Johnson and Wowchuck 1993; Skinner *et al.* 1999; Gedalof *et al.* 2005). Mechanistically, blocking ridges weaken and displace the polar jet stream northward, allowing regionally persistent warm and dry conditions, which dry fuels and facilitate the ignition and spread of fires (Jain and Flannigan 2021). Due to global climate change, these manifestations are expected to increase in frequency with a diminished temperature gradient between the North Pole and Equator leading to weaker mid-latitude winds in western North America (Karnauskas *et al.* 2018).

Extreme temperatures, prolonged fuel drying and persistent conditions conducive to fire (Jain and Flannigan 2021) typify the 2017, 2018 and 2021 fire seasons in the Montane Cordillera Ecozone in British Columbia. These three years set provincial area-burned records of >868 000 to 1.3 million hectares per year (Natural Resources Canada 2021). In 2017, ~530 000 ha burned in dry forests of the province, encompassing plots in five of our

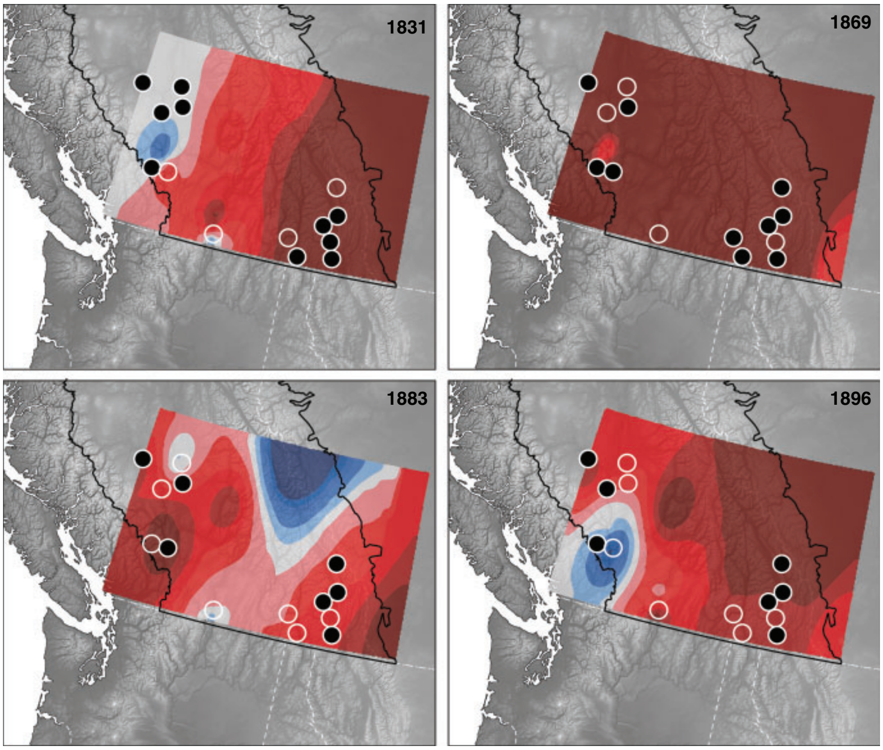

Fig. 8. Mean annual precipitation *z*-scores interpolated across the Montane Cordillera Ecozone during four years with high fire synchrony. As per the wetness scale of Fig. 2, darker tones of red and blue indicate drier or wetter conditions, respectively, whereas grey indicates near normal conditions. Black circles with white outlines indicate fire-history studies that recorded a fire during the given year, whereas open white circles indicate fire-history studies that did not record a fire during the given year.

14 study areas. Interestingly, this level of fire occurrence indicated only moderate fire synchrony, despite the record area burned at the provincial scale.

Changes during the 20th century

A decline in fire scar occurrence, indicating decreased low- to moderate-severity fires across the Montane Cordillera Ecozone after 1945, parallels findings from western North American forests (Hessburg *et al.* 2019). Decreased fire occurrence reflects disruption of Indigenous fire stewardship as early as the late 1800s, imposition of fire exclusion policies at the turn of the 20th century (Lake and Christianson 2019), then modernisation of fire suppression organisations after 1945 (Pyne 1982, 2007). These human impacts were reinforced by a period of regional climate that was less conducive to fire through the 1940s to 1970s (Meyn *et al.* 2010*a*; Daniels *et al.* 2011; Higuera *et al.* 2015). Although historical fire-weather data from the 20th century show many fire seasons include days when fires could have burned (Chavardès *et al.* 2019, 2020), ignitions were readily suppressed, reducing the occurrence of synchronous fires causing scars across our study areas. As a result of decreased fire activity, forest demography analyses revealed changes in fuel abundance and structure including persistent ladder fuels and increased tree density and canopy closure in many forests of the Montane Cordillera Ecozone (Marcoux *et al.* 2015; Harvey *et al.* 2017; Brookes *et al.* 2021), like in forests of the western USA (Hessburg *et al.* 2019). Prolonged fire-free intervals lead to an increase in fuel abundance in dry forests, which in turn facilitate higher intensity fire, driving high tree mortality with negative consequences for forest recovery (Stephens *et al.* 2013; Stevens-Rumann *et al.* 2018; Leclerc *et al.* 2021). Combined with our findings that short-term variations in weather interact with fuel abundance to drive fire occurrence, the disruption of historical fire frequency may also mark the onset of reduced forest resilience across the Montane Cordillera Ecozone after the mid-20th century.

As the climate of western North America continues to become more conducive to fire via increasing temperatures, prolonged fire seasons and increasing lightning ignitions (Krawchuk *et al.* 2009; Flannigan *et al.* 2013), fire activity is also increasing. Significant increases in annual area burned was first reported in the western United States (Westerling *et al.* 2006; Higuera *et al.* 2015; Westerling 2016). In Canada, the number of large fires (area $>$ 200 ha) has doubled, and the annual area burned has increased significantly since 1959, largely due to lightning-ignited fires in northern and western forests (Hanes *et al.* 2019). Event attribution modelling of the 2017 wildfires in British Columbia by Kirchmeier-Young *et al.* (2019) corroborates these findings in the Montane Cordillera Ecozone. They showed that anthropogenic climate change drove maximum temperature anomalies, increased area burned by at least 7-fold, and exacerbated fire behaviour by at least 2-fold.

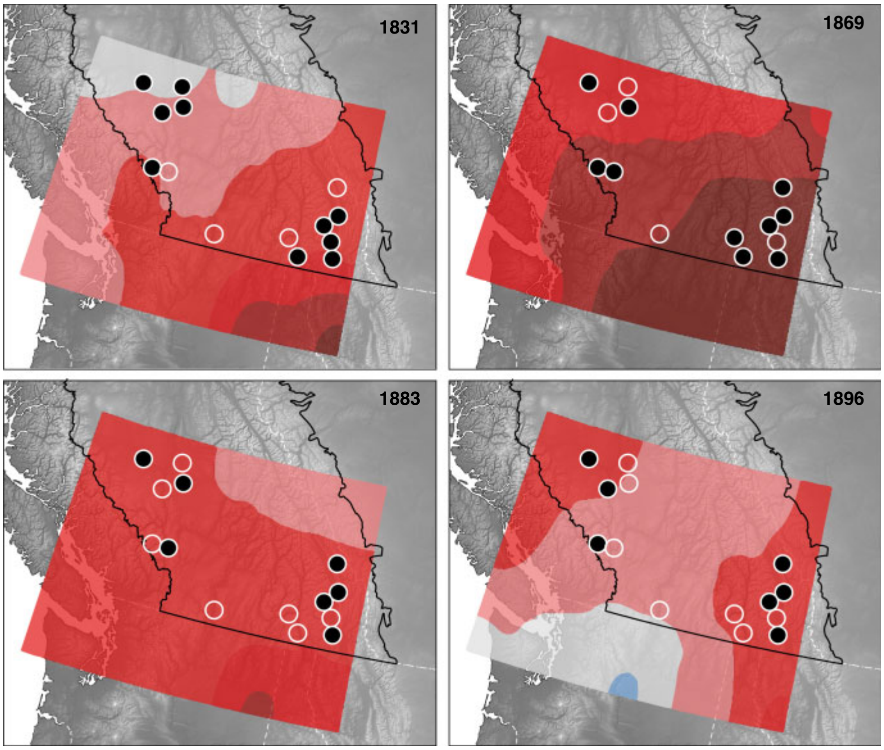

Fig. 9. Summer Palmer Drought Severity Index values interpolated across the Montane Cordillera Ecozone during four years with high fire synchrony. As per the wetness scale of Fig. 2, darker tones of red and blue indicate drier or wetter conditions, respectively, whereas grey indicates near normal conditions. Black circles with white outlines indicate fire-history studies that recorded a fire during the given year, whereas open white circles indicate fire-history studies that did not record a fire during the given year.

Conclusion

Historically, fire synchrony was common in dry forests located across the Montane Cordillera Ecozone in British Columbia, Canada. Fire-scar records showed that moderate–high fire synchrony, when 4 to 10 of our 14 study areas burned in the same year, recurred 36 times over 200 years from 1746–1945, or once every 5.5 years on average. Regionally dry climate in the year leading to and during peak fire season synchronised fires. Four years with high fire synchrony, or once in 50-year events, coincided with pronounced droughts that were preceded by a wet summer that may have enhanced fine fuel abundance and continuity. Decreased fire occurrence and synchrony after 1945 were due to fire exclusion and suppression, reinforced by regional climate that was less conducive to burning for several decades. In absence of fires, fuels have accumulated, potentially increasing the intensity and severity of fires when they burn. Combined with global climate change, many dry forests of British Columbia are increasingly susceptible to synchronous fires that are difficult to suppress and have high social-ecological costs, as observed in 2017, 2018 and 2021 when new records were set for area burned in the province. In 2017, five of our 14 study areas burned, yet this level of fire occurrence suggests only moderate fire synchrony, despite the record area burned. Our analyses suggest that years conducive to moderate–high fire synchrony, similar to or exceeding that of 2017, are likely to recur in dry forests within a decade. This prediction was realised in 2021, when ~1000 fires burned another ~700 000 ha of forests in dry regions of the province (Natural Resources Canada 2021), although none of the plots in our study areas reburned. Quantifying the severity of contemporary fires and deciphering the influences of weather and climate relative to fuel are critical next steps for understanding the ongoing changes to fire regimes and effectively adapting to future fire.

Data availability statement

The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest

The authors declare no conflicts of interest.

Declaration of funding

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