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Relationship between fire, climate oscillations, and drought in British Columbia, Canada, 1920–2000

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Abstract

Climate oscillations such as El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are known to affect temperature and precipitation regimes and fire in different regions of the world. Understanding the relationships between climate oscillations, drought, and area burned in the past is required for anticipating potential impacts of regional climate change and for effective wildfire-hazard management. These relationships have been investigated for British Columbia (BC), Canada, either as part of national studies with coarse spatial resolution or for single ecosystems. Because of BC's complex terrain and strong climatic gradients, an investigation with higher spatial resolution may allow for a spatially complete but differentiated picture. In this study, we analyzed the annual proportion burned–climate oscillation–drought relationships for the province's 16 Biogeoclimatic Ecosystem Classification (BEC) zones. Analyses are based on a digital, spatially explicit fire database, climate oscillation indices, and monthly precipitation and temperature data with a spatial resolution of 400 m for the period 1920–2000. Results show that (1) fire variability is better related to summer drought than to climate oscillations, and that (2) fire variability is most strongly related to both, climate oscillations and summer drought in southeastern BC. The relationship of area burned and summer drought is strong for lower elevations in western BC as well. The influence of climate oscillations on drought is strongest and most extensive in winter and spring, with higher indices being related to drier conditions. Winter and spring PDO and additive winter and spring PDO + ENSO indices show BC's most extensive significant relationship to fire variability. Western BC is too wet to show a moisture deficit in summer that would increase annual area burned due to teleconnections.

Keywords: area burned, aridity index, Canada, ENSO, PDO, wildfire

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Introduction

Climate oscillations such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) are known to affect temperature and precipitation regimes and area burned in different regions of the world through teleconnections. Understanding the nature of the relationship between climate oscillations, drought, and area burned in the past is required for anticipating potential impacts of regional climate change (Nitschke & Innes, 2008; Balshi *et al*., 2009). It also provides insight into mechanisms underlying interannual variation in fire risk that can inform wildfire management planning (Flannigan *et al*., 2008).

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In western North American, ENSO and PDO primarily influence winter temperature and precipitation regimes (Shabbar & Khandekar, 1996; Mantua *et al*., 1997; Shabbar *et al*., 1997), and thus indirectly affect summer moisture availability (Shabbar & Skinner, 2004) and wildfire occurrence [e.g. in Alaska (Hess *et al*., 2001; Duffy *et al*., 2005)]. ENSO events in the 20th century persisted for 6–18 months, whereas PDO events lasted in the order of 20–30 years; there may have been only two full PDO cycles in the 20th century (Mantua & Hare, 2002). The influence of ENSO and the PDO on wildfire occurrence has been investigated for single ecosystem types, such as subalpine forests (Schoennagel *et al*., 2005) and ponderosa pine forests (Hessl *et al*., 2004), using dendrochronological data. Dendrochronological data may extend over hundreds of years, although such data are usually only available from a limited number of point locations in a region. Other studies have used aggregated fire statistics for large administrative regions, such as countries (e.g. Canada: Skinner *et al*., 1999), states (e.g. Alaska: Hess *et al*., 2001), national forests (Gedalof *et al*., 2005), or ecological regions (Skinner *et al*., 2006), covering periods within the 20th century.

For British Columbia (BC), Canada, relationships between climate oscillations and area burned have been investigated only as part of nationwide studies (Fauria & Johnson, 2006; Skinner *et al*., 2006), with data sets beginning in 1950. Because of this, spatial resolution is very low (2° for Fauria & Johnson, 2006, and 250-km grids for Skinner *et al*., 2006), and the time scale includes only one PDO cycle. Previous studies faced the problem that, in some cases, in complex terrain regions such as BC is, low spatial resolution can complicate the analysis of climate–fire relationships (Flannigan *et al*., 2005; Balshi *et al*., 2009). The effects of climate oscillations on surface weather in BC have been analyzed either as part of national- or continental-scale studies or for single ecosystems. Bonsal *et al*. (2001) found that both ENSO and PDO have significant influence on winter temperature variability in western Canada. Composite analyses showed that the effect of high (low) ENSO indices on winter temperature was stronger during constructive phases compared with high (low) ENSO indices occurring in nonconstructive phases (Bonsal *et al*., 2001). Constructive phases are those in which a negative (positive) $Nino_3$-Index occurs during a negative (positive) PDO phase, whereas a nonconstructive phase is where a negative (positive) $Nino_3$ Index occurs during a positive (negative) PDO phase. The analyses also showed that the PDO alone had a weaker influence on winter temperature than the effect of constructive phases. Similarly, Schoennagel *et al*. (2005) found that, for subalpine forests in the Rocky Mountains, the phase combination of PDO and ENSO ($Niño_3$) influences the strength in the relationship between climate oscillations and fire occurrence.

In our study, we include the investigation of combined effects (additive interaction) of ENSO and PDO on drought and on the interannual variation in annual area burned. BC is divided into 16 regions following the Biogeoclimatic Ecosystem Classification system (BEC). The goals of this study are to show how the relationship between interannual variation in annual area burned and climate oscillations (ENSO, PDO and their combined effects) varies between zones, and to identify those BEC zones for which the relationships are strongest. The nature and strength of the influence of climate oscillations on seasonal drought and relationships between interannual variation in annual area burned and seasonal drought also are investigated for each individual BEC zone. This multiphase approach helps to determine whether the area burned–climate oscillation relationships are drought-induced. In contrast to previous studies, our study is based on fire and drought data with high spatial resolution for the entire province of BC for the period, 1920–2000.

Materials and methods

Study area

The study area encompasses the province of BC, which is located in western Canada and falls between latitudes ca. 48°N and 60°N, with a total land area of about 950 000 km^2. Except for the northeastern plains, the province is covered by the north–south-oriented Cordilleran mountain system of western North America. Climatic conditions in BC vary primarily with proximity to the Pacific Ocean, topography, and latitude. Although the Rocky Mountains restrict westward flow of cold continental arctic air masses from central Canada, the Coast Mountains represent a barrier for moisture-laden west winds. This setting results in a strong west–east gradient in precipitation and continentality, as well as in a marked rainshadow effect. Owing to this climatic and orographic variation, the study area covers a variety of ecosystems, extending from temperate rainforests on the Pacific coast to boreal forests in the northeast. The province is divided into 16 sub-regions, or zones, following the Biogeoclimatic Ecosystem Classification system (BEC, Table 1; Meidinger & Pojar, 1991). The BEC zones represent landscape types, each with broadly homogeneous natural vegetation and climate. We assume that climate oscillations have zone-specific effects on summer drought and interannual variation in area burned.

BEC and landcover data

The newest vector geographic information system (GIS) layer of the Biogeoclimatic Subzone/Variant Mapping was used (ftp://ftp.for.gov.bc.ca/HRE/external/!publish/becmaps/GISdata/CurrentVersion; January 2006). For detailed information on the biogeoclimatic ecosystem classification system, see http://www.for.gov.bc.ca/HRE/becweb/system/index.html. We used land cover data based on an intersection of the biogeoclimatic ecosystem classification with a provincial base map that delineate the three land classes: land, freshwater, and permanent ice or snow. Land (including

Table 1 Biogeoclimatic Ecosystem Classification zones of British Columbia

Biogeoclimatic zone					
Abbreviation	Full name	Total size in BC (%)	Percentage of flammable land per zone (%)*	Percentage of flammable area burned by fires >20 ha during 1920–2000 (%)	Mean summer aridity index 1920–2000 (absolute)
BAFA	Boreal Altai Fescue Alpine	7.9	89.1	0.9	0.9
BG	Bunchgrass	0.3	90	8.9	0.3
BWBS	Boreal White and Black Spruce	16.5	97.7	20.8	0.6
CDF	Coastal Douglas-fir	0.3	98.4	14.6	0.3
CMA	Coastal Mountain–heather Alpine	4.6	55.6	0.5	1.4
CWH	Coastal Western Hemlock	11.4	96.7	6.4	1.1
ESSF	Engelmann Spruce–Subalpine Fir	18.0	99	8.6	0.8
ICH	Interior Cedar–Hemlock	5.8	94.2	23.5	0.7
IDF	Interior Douglas-fir	4.7	96.8	18.0	0.4
IMA	Interior Mountain–heather Alpine	1.7	67.1	1.4	1.0
MH	Mountain Hemlock	3.7	97.1	0.8	1.2
MS	Montane Spruce	3.0	99.2	19.9	0.6
PP	Ponderosa Pine	0.4	92.6	22.8	0.3
SBPS	Sub-Boreal Pine–Spruce	2.5	97.5	12.6	0.5
SBS	Sub-Boreal Spruce	10.9	93.4	14.2	0.6
SWB	Spruce–Willow–Birch	8.4	98.7	7.7	0.7

*In this study, land covered by permanent ice and snow or by freshwater was considered not flammable.

urban areas and cropland) was considered the flammable area of a zone (Table 1).

Fire data

The analyses used a digital, spatially explicit fire database developed from administrative fire records, forest inventories, and remote sensing data, by researchers from the Canadian Forest Service, Pacific Forestry Centre, Victoria, and the BC Ministry of Forests and Range Research Branch (Taylor & Thandi, 2003). The fire database contains all fires reported in BC between 1920 and 2000 (total of 16 559) that exceeded 20 ha in size [except for fires that occurred in the national parks (about 470 000 ha) and fires occurring in a 32-km strip on each side of the Canadian Pacific Railway between the Alberta border and Port Moody before 1930 (about 3 million ha); Taylor & Thandi, 2003)]. Fire records include date of discovery, location, extent and cause (person or lightning). The fire season in Canada usually extends from April to mid-October but can last longer in BC (Stocks *et al*., 2002). For each BEC zone, the annual proportion burned was calculated as percentage of flammable area. For the remainder of the paper annual proportion burned will be referred to as 'area burned' except for figure legends and table headings. Area burned data were log-transformed for further analysis to reduce their skewness (McCune & Grace, 2002) and detrended (Supporting Information 1) in order to account for trends in mapping intensity and anthropogenic influence such as land use or fire suppression, as this study focuses on interannual variation in area burned and its relationship to climate. Detrending was also necessary to obtain stationary time-series, a prerequisite for the use of correlation analysis (Yevdjevich, 1964). For the remainder of the study, area burned refers to log-transformed, detrended data. For the SWB (Spruce–Willow–Birch) BEC zone, area burned data were used only after 1941, because regime shift-detection analysis after Rodionov (2006) revealed a steep increase in mean area burned in 1942 (see Supporting Information 1). The SWB zone is located in BC's northern interior, and the observed scarceness of records before 1942 is likely due to incomplete mapping in this remote area.

Climate oscillation indices

Climate oscillation indices considered in this study were the Niño$_3$ Index and the Pacific Decadal Oscillation Index (PDO; Supporting Information 1). The Niño$_3$ Index (Smith & Reynolds, 2004) is a measure of ENSO variability: it reflects tropical Pacific atmosphere–ocean variability. Monthly Niño$_3$ values are from the ERSST.v2 dataset (Smith & Reynolds, 2004). By definition, a positive Niño$_3$ Index indicates a warming of the ocean in the east Pacific. The PDO reflects the atmosphere–ocean variability in the North Pacific (Hare, 1996;

Mantua *et al*., 1997). PDO data were obtained from Mantua and Hare (http://jisao.washington.edu/pdo/PDO.latest, accessed on March 16, 2006). According to Bonsal *et al*. (2001), positive (negative) PDO values represent negative (positive) sea surface temperature (SST) anomalies over the east–central north Pacific, and positive (negative) SST anomalies along the North American west coast. Monthly values of the indices were standardized and linearly detrended before seasonal values and additive interactions were calculated.

Seasons were defined as follows: December–February (DJF) = winter; March–May (MAM) = spring; June–August (JJA) = summer; September–November (SON) = autumn. Winter was dated to the January of the year. The total number of climate variables included in the study was 21 (Table 2). For the remainder of this paper, standardized, detrended climate oscillation indices are referred to as indices, or by their respective names.

Temperature, precipitation data and aridity index

Monthly mean temperature and monthly precipitation data with a spatial resolution of 400 m for the period 1920–2000 were generated by Wang *et al*. (2006) using their scale-free climate model, ClimateBC (Hamann & Wang, 2005; Wang *et al*., 2006, http://www.genetics.forestry.ubc.ca/twang/climate_modeling.htm). This model combines historical monthly climate variability data (CRUTS 2.1 data; Mitchell & Jones, 2005) with downscaled parameter-elevation regressions on independent slopes model (PRISM) monthly climate normal data (Daly *et al*., 2002). The monthly temperature and precipitation data were used to calculate the mean monthly and seasonal temperature, precipitation, and aridity indices for the flammable portion of each BEC zone for each year of the investigation period, 1920–2000. Seasons were defined as stated in the last section. The aridity index is defined as AI = P/PET where P is the monthly precipitation in mm and PET is the monthly potential evapotranspiration in millimetres (United Nations Environment Programme, 1992). PET is calculated according to Thornthwaite (1948). Parameters (e.g. the AI) describing climate not just as absolute amounts of energy and water but as the interaction between the two, have been shown to ‘successfully explain several patterns and processes in nature’ (Stephenson, 1998). For example the dryness of fuel and thus predisposition for fire at a site depends not only on the amount of precipitation (P) but also on the energy (represented by PET) available to dry the fuel. According to United Nations Environment Programme (1992), the AI is classified as described in Table 3. For the period of investigation, in summer, some BEC zones are semi-arid in nearly all years, others are humid in most years (for mean summer AI, see Table 1). Therefore in this study, the AI is used as a measure of moisture availability rather than as a measure for aridity only.

Seasonal AI data for each BEC zone were tested for normality (Shapiro-Wilks’s *W* test), and log-transformed if the data were significantly different from the normal distribution. The data were linearly detrended, as the goal of this study is the investigation of interannual variability. For the remainder of this paper, seasonal AI will be referred to as seasonal drought.

Table 2 Climate oscillation indices used in this study. Lags of indices preceding the fire year by more than one year were not considered (e.g. LLwin-indices)

Seasonal values of indices	
WinNino	Winter Niño$_3$
SprNino	Spring Niño$_3$
SumNino	Summer Niño$_3$
FallNino	Fall Niño$_3$
WinPDO	Winter PDO
SprPDO	Spring PDO
SumPDO	Summer PDO
FallPDO	Fall PDO
Seasonal additive interactions	
WinN + P	Winter Niño$_3$ + winter PDO
SprN + P	Spring Niño$_3$ + spring PDO
SumN + P	Summer Niño$_3$ + summer PDO
FallN + P	Fall Niño$_3$ + fall PDO
One-year lags of indices are indicated by LL, e.g. LLSprNino3 means that the spring Nino3 Index 1920 gets the value of spring Nino3 Index 1919	
LLSprNino	One-year lag of spring Niño$_3$
LLSumNino	One-year lag of summer Niño$_3$
LLFallNino	One-year lag of fall Niño$_3$
LLSprPDO	One-year lag of spring PDO
LLSumPDO	One-year lag of summer PDO
LLFallPDO	One-year lag of fall PDO
LLSprN + P	One-year lag of spring Niño3 + spring PDO
LLSumN + P	One-year lag of summer Niño3 + summer PDO
LLFallN + P	One-year lag of fall Niño3 + fall PDO

Table 3 Classes of the Aridity Index (AI) according to United Nations Environment Programme (1992)

Category	AI
Hyperarid	AI < 0.05
Arid	0.05 < AI < 0.20
Semi-arid	0.20 < AI < 0.50
Dry subhumid	0.50 < AI < 0.65
Moist subhumid	0.65 < AI < 1.0
Humid	AI > 1

Autocorrelation and correlation analysis

Time series of area burned and seasonal drought for all BEC zones, and oscillation indices were analyzed for autocorrelation. Autocorrelation reduces the number of independent samples. The number of independent samples has to been taken into account when calculating the significance of the correlation between two time-series. This was done by calculating the effective sample size n' according to Dawdy & Matalas (1964), as a first approximation of the number of independent samples: $n' = n\left(\frac{1-r_1 r_1'}{1+r_1 r_1'}\right)$, where r_1 is the first-order correlation coefficient of one time-series, and r_1' is the first-order correlation coefficient of the other time series (Dawdy & Matalas, 1964; 8-III, equation 8-III-45).

If either time series is not serially correlated, the effective sample size equals the sample size. Following Dawdy & Matalas (1964) a time-series is considered random if its first order autocorrelation is not significant at the 95% level.

None of the BEC zones shows significant first-order autocorrelation in area burned or seasonal drought, and are thus considered random. Seven of 21 climate indices (WinPDO, SprPDO, SumPDO, SprN + P and the respective 1-year lags of the latter three) show significant first-order autocorrelation. Because the significantly autocorrelated oscillation indices were always correlated with random time-series, the effective sample size equals the sample size, and the test of significance for the correlation between random variables based on the *t*-test could be used (Dawdy & Matalas, 1964). Pearson's and Spearman's rank correlation analyses were used to analyze the relationship between interannual variability in area burned, oscillation indices and seasonal drought for each BEC zone. For those variables not normally distributed even after log-transformation, both Pearson's correlation coefficients and Spearman's Rank correlation coefficients were calculated. However, as results hardly varied qualitatively and quantitatively, only the Pearson's correlation coefficients will be mentioned in the following sections. In this study, significant correlations were those for which $P < 0.05$.

Results

Relationship between area burned and climate oscillation indices

Although some BEC zones have some significant correlations of area burned with oscillation indices in common, almost every zone has a unique combination of significantly correlated indices (Table 4). In this section, BC's BEC zones are classified, based on the nature of the significant correlations between area burned and climate indices, and then those oscillation indices that show the strongest and most extensive significant relationship with area burned are highlighted.

With respect to the correlation between area burned and oscillation indices in BEC zones, BC can be divided into three regions (Fig. 1): the western (Maritime) region where zones do not show any significant correlation with any of the 21 oscillation indices used in this study. Owing to their location on the windward side of the Coast Mountains, they are the wettest ecological zones of BC, and are humid even in summer in most years. [An exception is the CDF, which is located in the rain shadow of Vancouver Island and the Olympic Mountains (USA), usually has semi-arid summers (Table 1), and shows a tendency for negative correlations ($P < 0.10$)]. The southeastern (Montane) region covers the southern two-thirds of BC located east of the Coast Mountains. The eight BEC zones in this region show significant positive correlations of area burned with climate indices, and a ninth zone shows a tendency for positive correlations [PP, located in the interior valleys of southern BC, ($P < 0.10$)]. The northeastern (Boreal and Taiga) region of BC covers the northern third of the province; it is located east of the Coast Mountains and is composed of three BEC zones showing significant negative correlations of area burned with climate indices. These zones have long and (extremely) cold winters and short growing seasons in common; here, summers are cool at higher elevations and in the interior, but are warm in the more continental northeastern portion of the Boreal and Taiga region.

Although significant correlations between area burned and climate indices for zones belonging to the southeastern and the northeastern regions are of opposite sign, there are only two zones with the same specific combination of significant correlations but opposite sign (BAFA and BG; Table 4). Significant positive correlations between interannual variation in area burned and oscillation indices in the southeastern region range from $r = 0.22$ to 0.31, whereas significant negative correlations in the northeastern region range from $r = -0.22$ to -0.27 (Table 4). The BEC zones showing the strongest relationship between interannual variations in area burned and oscillation indices are located in southeastern BC (Table 4). Overall, correlations between area burned and oscillation indices are weak.

Individual indices that show significant correlation with area burned vary with BEC zone (Table 4). Out of the 21 climate indices analyzed, winter PDO (Fig. 2) and spring PDO and SpringNiño$_3$ + PDO (SprN + P) show the most extensive significant relationships to area burned in BC. Relationships indicate that for much of southeastern BC, years with large area burned are significantly correlated with high PDO and high Niño$_3$ +

Table 4 Pearson's correlation (r) between interannual variation in detrended log-transformed annual proportion burned and detrended, standardized climate oscillation indices

	Significant negative correlation: northeastern BC (Boreal and Taiga region)			Significant positive correlation: southeastern BC (Montane region)							
	BAFA	BWBS	SWB	BG	ESSF	ICH	IDF	IMA	MS	SBPS	SBS
WinNino											0.25
SprNino											0.31
WinPDO					0.26	0.28		0.29	0.25		
SprPDO					0.29	0.27			0.25		
SumPDO		−0.24									
FallPDO		−0.22									
WinN + P						0.23		0.24			0.26
SprN + P					0.25						0.29
FallN + P		−0.23									
LLSprNino	−0.26		−0.27	0.25							
LLFallNino						0.24	0.24			0.22	0.26
LLFallPDO											0.22
LLSprN + P	−0.23			0.23							
LLFallN + P											0.28

Significance level is $p < 0.05$. For full names of BEC zones, see Table 1. The four BEC zones (CDF, CMA, CWH, MH) located in western BC (Maritime region) and the Ponderosa Pine (PP) zone located in the interior valleys of southern BC do not show a significant correlations with any of the analyzed climate oscillation indices.

PDO in the winter and spring preceding the fire season. The same is valid for 1-year lagged fall Niño$_3$ (Table 4).

Relationship between area burned and seasonal drought

In order to check whether a large annual area burned is drought-induced, the relationships between area burned and seasonal drought were analyzed for each BEC zone. All but one BEC zone show significant negative correlation with summer drought (Table 5); a large area burned is thus related to drier summers. The strength of this relationship varies between zones (Table 5) and is strongest in southeastern as well as at low elevations in western BC (Fig. 3). In the interior valleys of southern BC (BG and PP zones) and at subalpine elevations along the coast (MH zone), a larger area burned is additionally related to preceding drier winters, whereas at lower (ICH zone), middle (MS zone) and subalpine elevations (ESSF zone) in the BC interior, a larger area burned is additionally related to drier springs (Table 5). In none of the BEC zones is area burned significantly related to fall drought. For all zones except the valley bottoms of the major river valleys in southern interior BC (BG zone), the relationship between summer drought and area burned is stronger than for the other three seasons (Table 5).

The relationship between area burned and lagged drought was also investigated in order to determine whether area burned is significantly related to drought conditions of the previous year. This was found to be the case for the interior plateau only (correlation of area burned with 1-year lagged winter drought in the SBS zone: $r = -0.22$), where a drier winter in the previous year is significantly correlated with a drier summer in the fire year.

Overall, drought in the year preceding the fire year does not seem to be important for the area burned in BC's BEC zones.

Relationship between climate oscillation indices and seasonal drought

The relationship between oscillation indices and seasonal drought as represented by the AI was investigated for each BEC zone in order to determine whether the area burned–climate oscillation link occurs via drought. Significant negative correlations between oscillation indices and seasonal drought in BC's BEC zones are weakest and constrained to a relatively small area in western BC in the main fire season summer, whereas they are stronger and wider in fall with a focus on southwestern BC, and strongest and extending over almost entire BC in winter and spring (Fig. 4, Supporting Information 2). These results are consistent with the finding that mainly spring and winter oscillation indices show significant correlations with area burned.

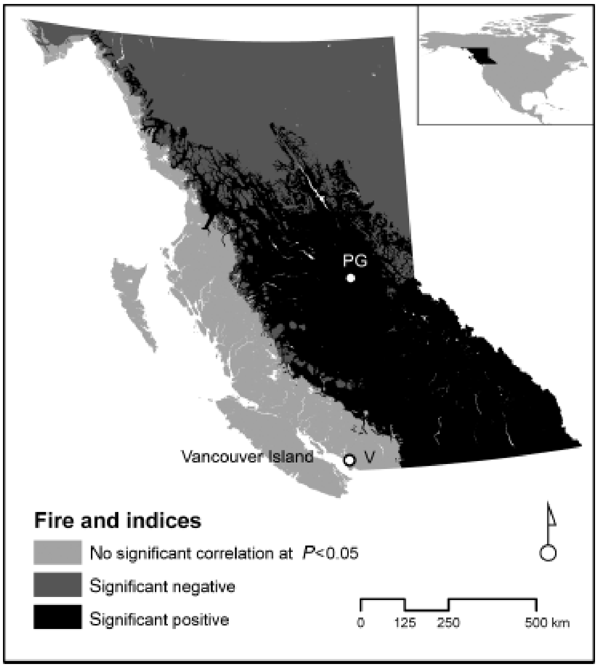

Fig. 1 Pearson's correlation between detrended, log-transformed annual proportion burned per BEC zone and climate oscillation indices. Light gray: BEC zones located in the southwestern (Maritime) region of BC: Coastal Douglas-fir (CDF), Coastal Mountain-heather Alpine (CMA), Coastal western Hemlock (CWH) and Mountain Hemlock (MH), black: BEC zones located in the southeastern (Montane) region of BC: Bunchgrass (BG), Engelmann Spruce-Subalpine Fir (ESSF), Interior Cedar-Hemlock (ICH), Interior Douglasfir (IDF), Interior Mountain Heather Alpine (IMA), Montane Spruce (MS), Sub-Boreal Pine-Spruce (SBPS) and Sub-Boreal Spruce (SBS), dark gray: BEC zones located in the northeastern (Boreal and Taiga) region of BC: BAFA (Boreal Altai Fescue Alpine), Boreal White and Black Spruce (BWBS) and Spruce-Willow-Birch (SWB). White areas represent non-flammable areas (permanent ice and snow, fresh water), which were excluded from the analysis. V: City of Vancouver; PG: City of Prince George.

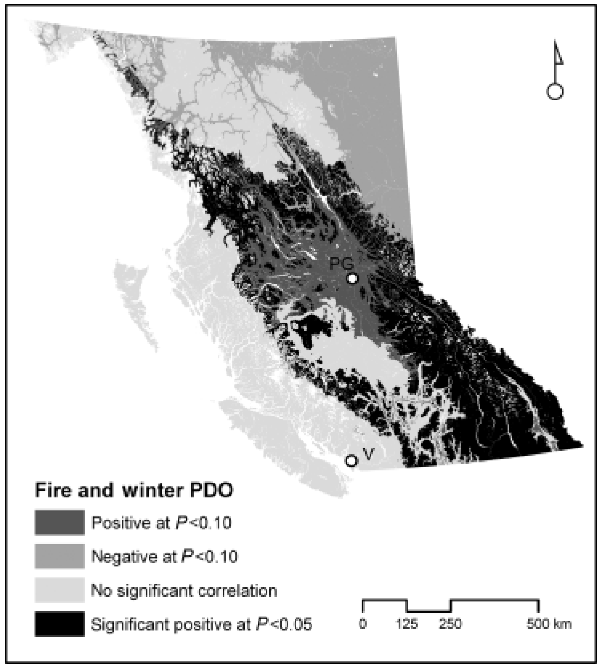

Fig. 2 Pearson's correlation between detrended, log-transformed annual proportion burned per BEC zone and winter PDO. Annual proportion burned in BEC zones located in western BC shows no significant correlation ($P<0.05$) with winter PDO (light gray area). Four BEC zones located in southeastern BC (ESSF, ICH, IMA, MS) show a significant positive correlation with winter PDO ($P<0.05$; black area), two zones (PP, SBS) located in the southeast show a tendency for a positive correlation ($P<0.10$; dark gray area). The BWBS zone located in northeastern BC shows a tendency for a negative correlation with winter PDO ($P<0.10$; middle gray area). White areas represent nonflammable areas (permanent ice and snow, fresh water), which were excluded from the analysis. V: City of Vancouver; PG: City of Prince George.

The following oscillation indices show the strongest and most extensive significant relationships to seasonal drought in BC, and are listed for each season; all of these are negative correlations. Winter drought is related mainly to winter Niño_3 + PDO. Spring drought is mainly related to spring Niño_3 + PDO and spring PDO. Summer drought is related mainly to the PDO index of the preceding winter (winPDO), suggesting that the water deficit in winter is strong enough to be carried over into summer. However, the area where the latter relationship is significant is small and constrained to portions of coastal BC (CDF and CMA zone; Fig. 4). Fall drought is related mainly to fall PDO, fall Niño_3 + PDO and summer Niño_3. In the case of the summer Niño_3 Index, this suggests the summer water deficit is large enough to be carried over into fall.

Discussion

We have shown that annual proportion burned is related stronger to summer drought than to climate oscillations in all sixteen BEC zones, and that it is most strongly related to both, climate oscillations and summer drought in southeastern BC. The relationship of area burned and summer drought is strong for lower elevations in western BC as well. In the following sections we will first discuss the limitations of this study and debate the adjustment of significance levels for multiple tests before discussing our results concerning the fire–climate oscillations–seasonal drought relationships.

Limitations

The fire database, although exceptional in historical and geographical extent, has its limitations due to spatial

Table 5 Pearson's correlation of log-transformed, detrended annual proportion burned per BEC zone with seasonal drought (AI)

BEC zone	Pearson's correlation of annual proportion burned with			
	Winter AI	Spring AI	Summer AI	Fall AI
BAFA	−0.08	−0.16	**−0.46**	0.11
BG	**−0.26**	−0.03	−0.20	−0.14
BWBS	−0.08	−0.12	**−0.31**	0.05
CDF	−0.17	0.04	**−0.40**	−0.12
CMA	−0.04	−0.14	**−0.45**	0.00
CWH	−0.07	−0.12	**−0.57**	0.09
ESSF	−0.21	**−0.24**	**−0.60**	0.03
ICH	−0.14	**−0.22**	**−0.71**	−0.02
IDF	−0.07	−0.21	**−0.55**	−0.08
IMA	−0.12	−0.10	**−0.52**	0.13
MH	**−0.25**	−0.02	**−0.44**	0.20
MS	−0.13	**−0.22**	**−0.64**	−0.01
PP	**−0.25**	−0.05	**−0.52**	−0.11
SBPS	−0.18	−0.08	**−0.39**	0.03
SBS	−0.18	−0.20	**−0.56**	0.11
SWB	0.03	0.04	**−0.33**	0.05

Significance at least $P<0.05$ in bold. Negative correlations indicate that a large annual proportion burned is related to drought.

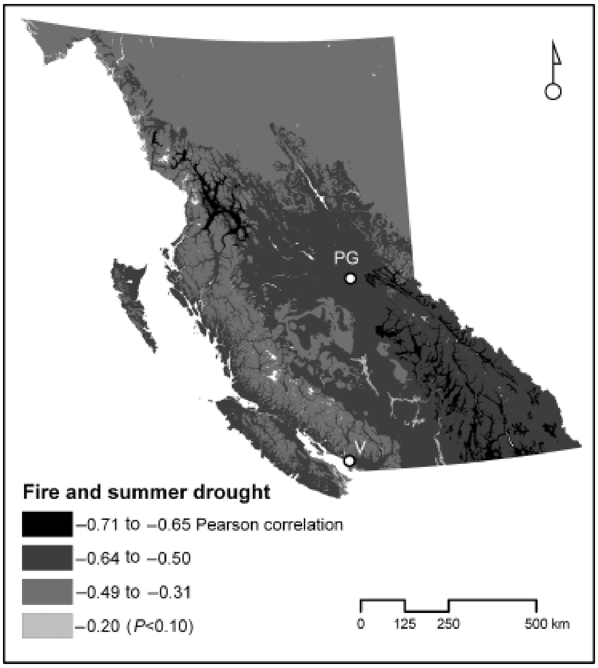

Fig. 3 Pearson's correlation between detrended, log-transformed annual proportion burned per BEC zone and summer AI (summer drought). The significant negative correlation indicates that, for all but one BEC zone (BG zone), a larger annual proportion burned is related to drier summers (e.g., a lower summer AI). The small BG zone located in the deep valleys of southern interior BC shows the same tendency (light gray, $P<0.10$). White areas represent nonflammable areas (permanent ice and snow, fresh water), which were excluded from the analysis. V: City of Vancouver; PG: City of Prince George.

and temporal variation in mapping methodologies, mapping intensity, and precision. The percentage of all fires >20 ha that were reported and are contained in the database likely varied over time and space, depending on fire-suppression policy, available resources and techniques, and remoteness of the area burned. Mapping of smaller fires is likely incomplete in remote areas and in earlier years. As in other regions of Canada (e.g. Ontario; Martell & Sun, 2008), fire suppression might have influenced area burned – at least in the more populated regions of BC – over recent decades. According to Pyne (2008), fire suppression in BC was effective during the 1960s and 1970s because of sufficient resources and mild fire seasons. Nonetheless, no shifts in the annual area burned data in any of the BEC zones suggest a major impact of fire suppression on area burned. Fire data suggest that land-use changes, changes in mapping intensity and quality, and changes in fire suppression led to gradual change in area burned. This was accounted for in this study by checking the fire data for trends and regime shifts in each BEC zone. Trends were removed before analyzing the data for relationships in interannual variation. For one zone (SWB) located in the remote north of BC and showing a steep increase in area burned in 1942 but only two years with fire before 1942 (1940 and 1941), data were used only for the period 1942–2000.

The *a priori* definition of fire regions based on the biogeoclimatic ecosystem classification system of BC allows the province to be classified into spatial units according to ecological criteria. This approach represents a top-down approach based on the assumption that climate oscillations have zone-specific impacts on summer drought and on the interannual variation in area burned. This is plausible, because BEC zones represent landscape types with broadly homogeneous natural vegetation types and climates. BEC zones follow the climatic and ecological gradients of the province primarily related to proximity to the Pacific Ocean, topography, and latitude (see section on study area and Supporting information 3). Using BEC zones as subregions necessitates the use of high-resolution fire and climate data since BEC zones often represent narrow elevational bands (Supporting information 3). Although fires in a zone are (of course) not completely evenly distributed there are no major spatial concentrations or biases. A disadvantage of this top-down approach may be that, for fragmented zones such as the BAFA or for zones with a very large north-south exten-

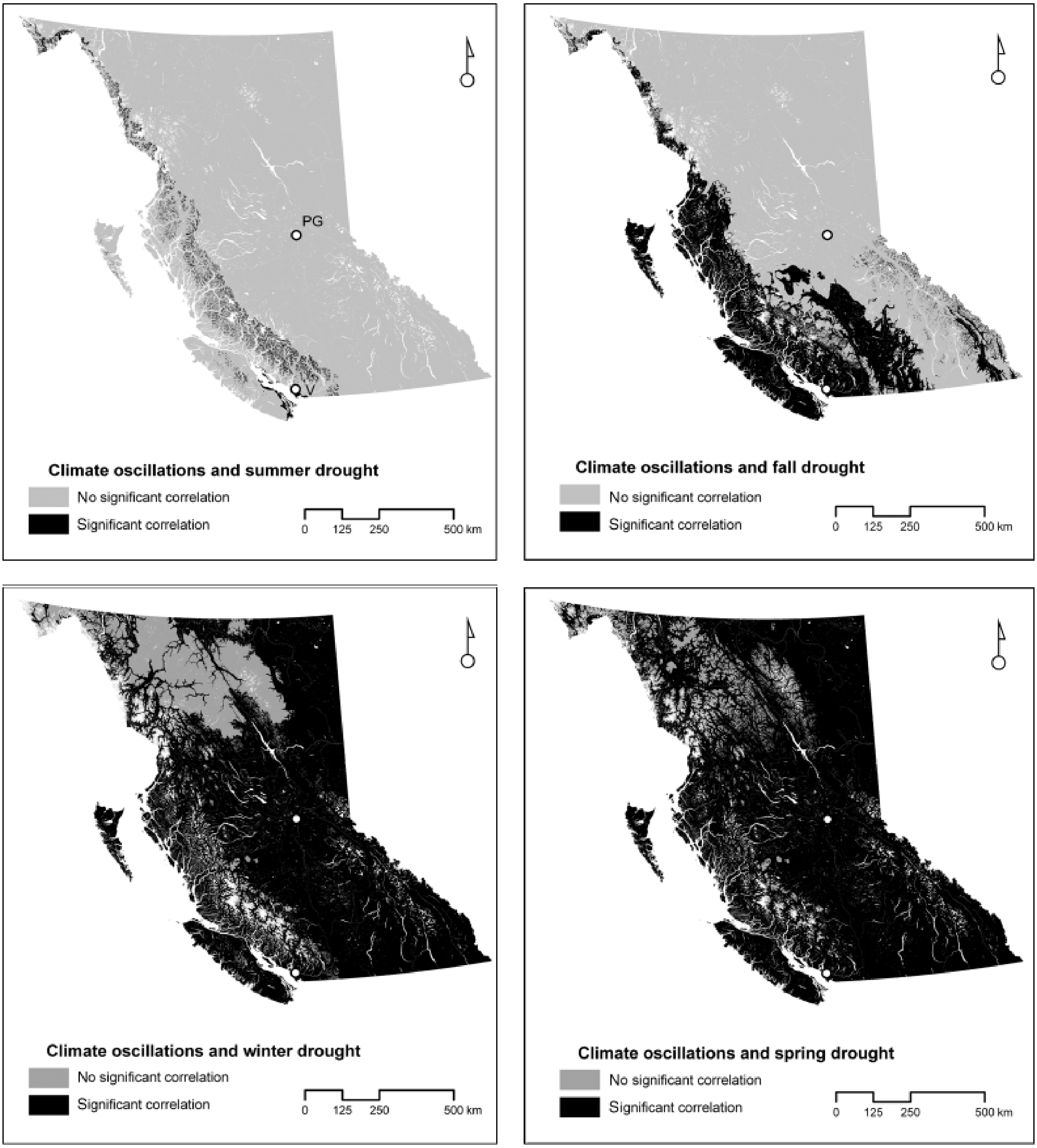

Fig. 4 Relationship between climate oscillations and seasonal drought (aridity indices). Significant negative correlations ($P < 0.05$) between oscillation indices and seasonal drought (AI) in BC's BEC zones range from $r = -0.23$ to -0.36 in summer (two zones: CDF, CMA); from $r = -0.22$ to -0.45 in fall (nine zones: BG, CDF, CMA, CWH, IDF, IMA, MH, MS, PP); from $r = -0.22$ to -0.62 in winter (13 zones: BG, BWBS, CDF, CWH, ESSF, ICH, IDF, IMA, MH, MS, PP, SBPS, SBS), and; from r = -0.22 to -0.51 in spring (14 zones: BG, BWBS, CDF, CMA, CWH, ESSF, ICH, IDF, MH, MS, PP, SBPS, SBS, SWB). See also supporting information SA1. White areas represent nonflammable areas (permanent ice and snow, fresh water), which were excluded from the analysis. V: City of Vancouver; PG: City of Prince George.

sion such as the ESSF, this assumption implies that climate oscillations have the same influence in the north as in the south of BC, which is not necessarily the case.

Precipitation and temperature data gridded at 400 m for 81 years provide complete coverage of BC. Although these data are based on interpolation and modelling of a relatively small number of weather stations, especially those at high elevations and in remote areas and although weather stations were also fewer in earlier times, sophisticated modelling techniques reduce these problems. PRISM data, for example, are generated using a statistical regression model called PRISM. This model contains expert knowledge 'on the spatial patterns of climate and their relationships with geographic features' in form of algorithms (Daly *et al*., 2002). PRISM thus combines human-expertise and statistical methods using knowledge-based system (KBS) technology as a framework (Daly *et al*., 2002). Data expanded into the PRISModel are point station data, a digital elevation model, other spatial data sets, a knowledge base and human-expert parameterization (Daly *et al*., 2002). Climate BC data that combine downscaled monthly climate normal data (PRISM; Daly *et al*., 2002) with historical monthly climate variability data (CRUTS 2.1 data; Mitchell & Jones, 2005) are the best and most detailed surface-weather data covering all of BC that are currently available.

In our study, we did not differentiate between person-caused and lightning-caused fires, but used all fires contained in the database – even though the percentage of area burned by person-caused fires varies greatly between zones and over time. Fire cause does not play a role in predicting fire danger risk (in the sense of a large area burned) at the scale of BEC zones. At that scale, area burned–oscillation indices relationships can be used to decide whether to locate fire suppression resources in the northeast, the southeast or the west of BC. Nonetheless, it would be interesting and helpful for managers to differentiate between person-caused and lightning-caused fires and their relationship to climate oscillations as a next step, as person-caused fires predominantly occur spatially separated (for a map see Supporting Information 1). In areas such as southeastern and northeastern BC where lightning-caused fires and person-caused fires occur in spatial neighbourhood, person-caused fires usually occur at lower elevations than lightning-caused fires. The role of the fire cause on the area burned–climate oscillation relationship and the area burned–drought relationship warrant further studies.

Significance levels and adjustment of P-values for multiple tests

A subject of ongoing debate and research is whether adjustments of significance (p)-levels should be applied to avoid type I errors when multiple statistical tests are conducted to investigate large datasets (Rothman, 1990; Manor & Peritz, 1997; Pernerger, 1998; Savitz & Olshan, 1998; Thompson, 1998; Feise, 2002; Moran, 2003; Verhoeven *et al*., 2005). When performing a large number of correlation tests in a study, each at the same significance level (α), at least some of them are significant due to chance [at $\alpha = 5\%$ one in 20 'significant' correlations will be a random result (Feise, 2002)]. To avoid false rejections of the null hypothesis (type I errors), Bonferroni-type corrections often are applied (Holm, 1979; Verhoeven *et al*., 2005). These aim to maintain the single type I error rate at the desired α-level (usually 5%) by lowering the α-values of each individual correlation test (Verhoeven *et al*., 2005). However, Bonferroni-adjusted P-levels apply to the case of universal null-hypotheses (Rothman, 1990; Perneger, 1998). In our case the universal null hypothesis would be that climate indices in general are not related to fire and drought, respectively, and drought is not related to fire in BC. However, this hypothesis was not raised in our study, and adjustments for multiple tests would be misleading (Perneger, 1998). We acknowledge the possibility that some of the correlations (one in 20) recognized as significant in this study are due to chance. Interpretations of the correlations should be strictly limited to our research objectives: to identify the relevant variables (climate oscillation indices and seasonal drought, respectively) and to determine the strength of the relationship for each BEC zone.

Fire–climate oscillations relationships

We have shown that the relationship between interannual variation in annual proportion burned and climate oscillations varies between the BEC zones with respect to strength and nature of the relationship. Therefore, our results give a much more spatially differentiated picture than previous studies do (e.g. Fauria & Johnson, 2006: BC = one fire region; Skinner *et al*., 2006: BC = three ecozones). The zones that show the strongest relationship are located in southeastern BC (Montane region). The oscillation indices showing the most extensive significant relationship to area burned were winter and spring PDO and the additive spring PDO + ENSO index, with higher indices being related to a larger area burned in southeastern BC. This largely agrees with Skinner *et al*. (2006), who found that the warm phase of ENSO and positive phase of PDO involved greater area burned in western and northwestern Canada. We found, however, a tendency ($P < 0.10$) within northeastern BC (the Boreal and Taiga region) that a higher winter PDO index is related to a lower area burned, showing that our higher spatial resolution results in a more differentiated picture. This work suggests that climatic oscillation – area burned relationships are not significant in humid ecosystems (mean summer aridity indices >1.0), have the greatest impact in dry sub humid and moist sub humid ecosystems (mean summer aridity indices of 0.5–0.8), and are less pronounced in semi arid ecosystems (aridity indices $<=0.3$). Overall, relationships between area burned and climate oscillation indices are weak.

Drought–fire relationships

We found, in all but one BEC zone, area burned is significantly related to summer drought conditions. The Bunchgrass zone in the interior valley bottoms of southern BC is the only zone where a larger area burned is related more strongly to winter drought than to summer drought (Table 5). Owing to its high summer temperatures, this grass-dominated landscape is dry enough to allow for fire even in average summers, as drought conditions usually prevail by late June. Thus, in this zone, a winter that is drier than average has a larger influence on area burned than a summer that is drier than average. Concerning the bottoms and lower elevations of the very dry valleys in southern interior BC with a vegetation cover dominated by grasses (BG zone) and open Ponderosa Pine forests (PP zone), our results are supported by Heyerdahl *et al.* (2002), Westerling *et al.* (2003) and Hessl *et al.* (2004). They found that for open low-elevation ponderosa pine forests in the Pacific Northwest that are snow covered in winter, drought in the fire year is decisive, whereas conditions during the previous year appear unimportant. Concerning the subalpine forests (ESSF zone), our results are supported by Schoennagel *et al.* (2005), who found that large fires in the subalpine forests of Jasper National Park coincide with drought during the fire year, whereas antecedent conditions appear unimportant. There is extensive literature about the role of moisture vs. fuel for area burned (for a review see Meyn *et al.*, 2007). Our results suggest that area burned in the BEC zones of BC is limited by moisture rather than by fuel, as there is no significant relationship between increased moisture in the previous seasons (resulting in an increased production of fine fuels) and a greater area burned.

Drought–climate oscillation relationships

We found that all but one BEC zones (BAFA, BC's most extensive alpine zone that is located mainly in the central north, is the exception) show some significant relationship between oscillation indices and drought, with the strength and kind varying between zones and seasons (Fig. 4). The influence of ENSO and PDO – more precisely of PDO and of additive indices – on drought was found to be strongest and most extensive in winter and spring, with higher oscillation indices being related to drier conditions (lower AI). Our results are consistent with Shabbar *et al.* (1997), who found winter precipitation in western Canada is significantly lower during years of ocean warming in the east Pacific, with Kitzberger *et al.* (2007), who found that warmer and drier conditions in the Pacific Northwest relate to years of ocean warming in the east Pacific, and with Mantua *et al.* (1997), who found that the PDO is negatively correlated with winter precipitation, but positively correlated with winter temperature in the Pacific Northwest. The influence of PDO and ENSO on winter temperature is related to differences in the frequency of synoptic-scale circulation patterns (Stahl *et al.*, 2006).

Our study shows that winter PDO and additive index winter Niño3 + PDO are significantly negatively correlated with winter drought throughout most of BC (in 13 of 16 BEC zones), except for an area in the central north and the highest elevations in coastal BC (Fig. 4). Shabbar & Khandekar (1996) found the influence of ENSO on mean surface temperature is strongest during winter and nearly vanishes by spring. We found significant relationships between climate oscillations and spring drought; specifically the additive index spring Niño3 + PDO and spring PDO are significantly negatively correlated with spring drought throughout most of BC, except for small areas in the central north (13 of 16 BEC zones). This suggests the influence of these climate oscillations on drought persists but weakens slightly from winter to spring. Although winter temperature cannot be directly compared with drought, our findings underline the usefulness of investigating effects of additive indices.

Fire, drought and climate oscillations

Annual proportion burned is related stronger to summer drought than to climate oscillations in all sixteen BEC zones. Since the influence of climate oscillations on drought is most extensive and strongest in winter and spring, weaker in fall, and constrained to a small area in the main fire season summer, the influence of climate oscillations on area burned is indirect. Therefore correlations between oscillation indices and area burned are generally weak: only in regions where winter or spring moisture are sufficiently limited to result in a summer moisture deficit are oscillation indices significantly correlated to area burned. This is the case mainly in southeastern BC. In contrast, western BC (the Maritime region) is too wet to show a moisture deficit in summer, although winter drought and spring drought (in the

CMA, summer drought) are significant negatively related to winter and spring oscillation indices.

The relationships between area burned and oscillation indices may be of interest to fire managers, as the lag between winter and spring indices and area burned (the largest portion of it burning in JJA) would allow managers to plan resource allocation further in advance. Further analyses quantifying the impact of climate oscillations, monthly aridity indices and temperature values on annual proportion burned in order to estimate the relevance for management would be valuable [e.g. as Duffy *et al*. (2005) have done for Alaska]. This study is the first to investigate the fire–climate oscillations–drought relationships for the entire province of BC with a high spatial resolution that distinguishes between the 16 BEC zones. Because of this, it gives a much more differentiated picture for BC than previous studies do.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Detrending and regime shift analysis of fire data. Climate oscillation index data. Geographic distribution of lightning and person-caused fires in British Columbia.

Table S1. Pearson correlation between seasonal drought and climate oscillation indices in British Columbias's biogeoclimatic zones.

Table S2. Biogeoclimatic zones of British Columbia.

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