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ORIGINAL ARTICLE

The climate space of fire regimes in north-western North America

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ABSTRACT

Aim Studies of fire activity along environmental gradients have been undertaken, but the results of such studies have yet to be integrated with fire-regime analysis. We characterize fire-regime components along climate gradients and a gradient of human influence.

Location We focus on a climatically diverse region of north-western North America extending from northern British Columbia, Canada, to northern Utah and Colorado, USA.

Methods We used a multivariate framework to collapse 12 climatic variables into two major climate gradients and binned them into 73 discrete climate domains. We examined variation in fire-regime components (frequency, size, severity, seasonality and cause) across climate domains. Fire-regime attributes were compiled from existing databases and Landsat imagery for 1897 large fires. Relationships among the fire-regime components, climate gradients and human influence were examined through bivariate regressions. The unique contribution of human influence was also assessed.

Results A primary climate gradient of temperature and summer precipitation and a secondary gradient of continentality and winter precipitation in the study area were identified. Fire occupied a distinct central region of such climate space, within which fire-regime components varied considerably. We identified significant interrelations between fire-regime components of fire size, frequency, burn severity and cause. The influence of humans was apparent in patterns of burn severity and ignition cause.

Main conclusions Wildfire activity is highest where thermal and moisture gradients converge to promote fuel production, flammability and ignitions. Having linked fire-regime components to large-scale climate gradients, we show that fire regimes – like the climate that controls them – are a part of a continuum, expanding on models of varying constraints on fire activity. The observed relationships between fire-regime components, together with the distinct role of climatic and human influences, generate variation in biotic communities. Thus, future changes to climate may lead to ecological changes through altered fire regimes.

Keywords

Burn severity, climate, fire cause, fire frequency, fire regime, fire season, human influence, North America, pyrogeography, wildfire.

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INTRODUCTION

Fire is a keystone process of most North American ecosystems, acting as a major organizing influence on vegetated landscapes across the continent. The fire-regime concept (Gill, 1975; Heinselman, 1981) includes characteristics of fire occurrence in a distinct space–time window (Krebs *et al.*, 2010). In recent decades, descriptions of fire regimes have included the frequency, seasonality, size, type (i.e. surface or crown), severity and intensity of fire in areas ranging in size from single forest stands to the global scale (Archibald *et al.*, 2010; Whitlock *et al.*, 2010). Through linked and feedback processes with vegetation, the local fire regime modulates the distribution of vegetation, species and communities, influencing ecosystem structure and function (Weber & Flannigan, 1997; Keeley *et al.*, 2009). Fire frequency in an area affects plant communities, for instance, by disrupting tree growth cycles and the availability of seeds, whereas fire size influences landscape patchiness and the regeneration of local vegetation communities. Fire seasonality may constrain vegetation recovery and influences fire intensity and burn severity (Zedler, 1995; Stocks *et al.*, 2002), which is a measure of ecosystem change and fuel consumption that may determine post-fire vegetation dynamics (McHugh & Kolb, 2003; Parks *et al.*, 2014). Thus, it is important to consider fire-regime components together, in order to understand the collective properties of fire in a region and its influence on ecosystem function.

Fires occur where suitable conditions and resources for fire ignition and spread coincide across environmental gradients. Conceptual models of biogeographical gradients of fire have been proposed, recognizing that the distribution of fuel and moisture limits fire activity and size (Meyn *et al.*, 2007; Parisien & Moritz, 2009; Bradstock, 2010). Globally, fire frequency varies reliably along gradients of productivity and fuel availability in drier regions, and gradients of temperature in wetter, biomass-rich areas (Krawchuk & Moritz, 2011; Pausas & Ribeiro, 2013). Just as the distribution of fire varies along climate gradients, it also varies along gradients of land management (Haire *et al.*, 2013). Humans influence fire regimes via ignition, suppression and other land-use practices that alter fuel availability, type and continuity. Such influences can entirely decouple natural environmental controls of fire regimes (Syphard *et al.*, 2007; McWethy *et al.*, 2013).

Recognizing the influence of fire regimes on ecosystem function and the relationship between fire and environmental gradients, recent quantitative work has examined fire-regime components of fire frequency, burn severity and intensity along gradients of fuel abundance and moisture (e.g. Murphy *et al.*, 2013; Parks *et al.*, 2014). Components of the fire regime such as fire seasonality, cause and size have not been incorporated in such a framework, nor have anthropogenic factors been adequately integrated. Research to date has been limited by the lack of consistent spatial data describing the activity and characteristics of fire at the scale of broad environmental gradients. The increasing availability of regional and continental data, however, facilitates the analysis of fire regimes along extensive environmental gradients and provides an opportunity for a deeper understanding of underlying drivers.

The goal of this study is to increase understanding of the spatial pattern of fire-regime components and their relationships to one another and to human influence in a broad climatic context. To meet this goal we examine fire regimes within a quantitative framework, integrating both human and climatic gradients. We: (1) collapse climatic variables into two climate gradients that define the climate space of the study area using a multivariate technique; (2) position fire-regime components of a spatial database of large fires along these climate gradients and a gradient of anthropogenic influence; and (3) explore relationships among fire-regime components and their drivers.

MATERIALS AND METHODS

Study area

The study area is defined by the boundary of the Great Northern Landscape Conservation Cooperative (*c.* 1.2×10^6 km^2), which includes much of the north-western United States and the Canadian provinces of British Columbia (BC) and Alberta (Fig. 1a). The area's broad environmental gradients include diverse climate, geology, vegetation and land uses (Ecological Stratification Working Group, 1995; Commission for Environmental Cooperation, 1997). Elevation in this region ranges from 8 m to 3966 m above sea level (Fig. 1b). Climate in the area is dominated by a north-to-south gradient of increasing temperature and decreasing summer precipitation and an east-to-west gradient of maritime influence and increasing winter precipitation. Mean annual temperature ranges from −6.1 to 13.7 °C and mean annual precipitation from 214 to 4808 mm (Fig. 1c,d). Precipitation falls predominantly in the winter and winter moisture is especially dominant in coastal areas. Northern and near-coastal high-elevation areas are the wettest in the region, contrasting with arid southern valleys, such as those in the Columbia River Basin. Terrain influences climate substantially, as temperature decreases and precipitation increases with elevation. Mountain ranges affect precipitation throughout the study area, with distinct rain shadows to the east of the Rocky and Cascade mountain ranges (Commission for Environmental Cooperation, 1997).

Vegetation across the study area reflects its broad environmental gradients and is very diverse, ranging from deserts to rain forests to alpine tundra. The majority of the area is forested and consists of subalpine, rolling slopes and hills at lower elevations, and forest plateaus to the north (Fig. 1e). These coniferous forests experience wildfires that vary in their characteristics and rates of recurrence. Wildfires occur less frequently at high elevations and in temperate and coastal rain forests. In the warm southern valleys and areas

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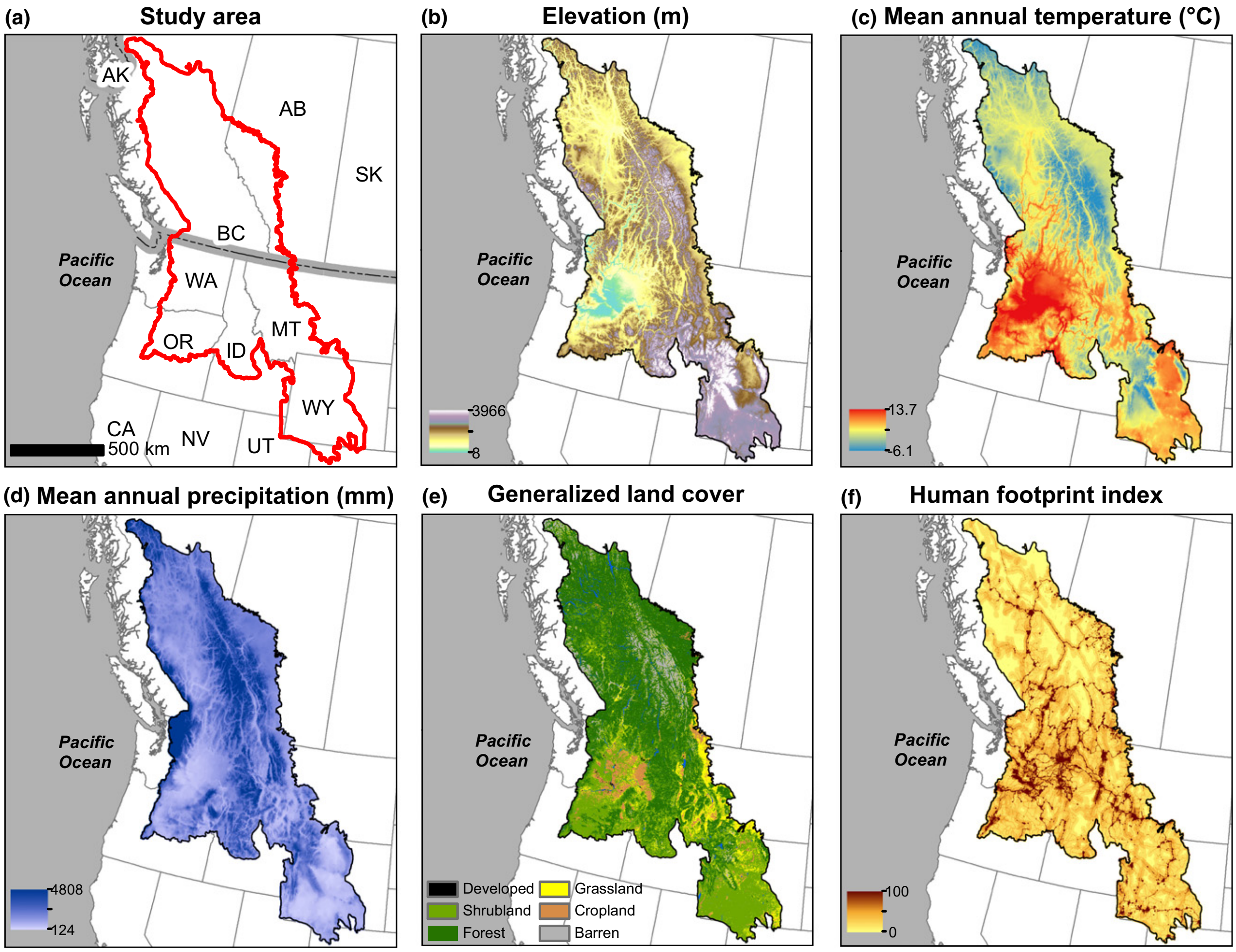

Figure 1 Characterization of the study area's natural and human features. (a) The study area within North America showing, (b) elevation, (c) mean annual temperature, (d) mean annual precipitation, (e) land cover generalized from the Global Land Cover Characterization Project (2002) and (f) human footprint index (Sanderson *et al.*, 2002).

of lower-elevation savanna-like vegetation, shrublands and grasslands occur (Commission for Environmental Cooperation, 1997). Some of the study area is managed for commercial forestry, especially the interior north, and many valleys have undergone significant conversion to agricultural and rangeland uses (Commission for Environmental Cooperation, 1997). Despite these anthropogenic land uses, the study area has a relatively low population density and much of it remains in a broadly natural state (Fig. 1f).

Climate and elevation data

A digital elevation model (DEM) of the study area was used to downscale climate data for analysis. The DEM was compiled from: (1) the US National Elevation Dataset Digital Elevation Model (sinks filled) (US Geological Survey/Earth Resources Observation & Science (USGS/EROS), 2003); (2) the BC Gridded DEM Product (Province of British Columbia, 2002); and (3) the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map 2 (ASTER GDEM Validation Team, 2011). The DEM was resampled to a continuous 2-km resolution raster with an Albers equal-area conic projection. This resolution and projection was applied to all spatial data. The DEM of the study area was used in Climate WNA (Wang *et al.*, 2012) to downscale climate data from the PRISM Climate Group for the 1981–2010 climate normals period (Daly *et al.*, 2002). Additional climate grids produced using thin-plate smoothing splines in the ANUSPLIN climate model for the same climate normals period were provided by Natural Resources Canada (McKenney *et al.*, 2011). We selected a set of 12 complementary climate variables representing gradients of moisture and energy (Table 1). These variables were used to characterize the climate space of the study area.

Fire data: perimeters and their attributes

The international study area presented challenges to data development because of inconsistencies in methods and metrics amongst the various data sources; however, we have

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Table 1 Energy and moisture climate variables used to model the climate space of the study area. Abbreviations of the variable names, data sources and the range of values for each variable, as produced by Natural Resources Canada (NRCan) or in the Climate WNA model are provided below. Climate grids were derived from 1981–2010 climate normals.

Climate variable	Abbreviation	Source	Max	Min
Mean annual temperature (°C)	mat	Climate WNA	13.7	−6.1
Maximum temperature warmest month (°C)	maxtw	Climate WNA	36.4	6
Minimum temperature coldest month (°C)	mintc	Climate WNA	1.8	−23.2
Temperature range (°C)	trange	Climate WNA	31.7	13.9
Isothermality (°C)	isotherm	NRCan	46	18
Annual precipitation (mm)	aprec	Climate WNA	4808	124
Summer precipitation* (mm)	sumprec	Climate WNA	951	9
Winter precipitation* (mm)	wintprec	Climate WNA	1602	10
Precipitation seasonality† (%)	seasprec	Climate WNA	82	14
Annual climate moisture index (cm)	cmi	NRCan	4432	−1248
Degree days > 5 °C (GDD)	dd5	NRCan	2872	0
Growing season length‡ (days)	growsl	NRCan	339	16

*Summer from July through September, winter from January to March.
†Percentage of annual precipitation in winter months.
‡The growing season was determined using temperature-based rules, starting when the mean daily temperature was ≥ 5 °C for 5 consecutive days beginning March 1. The growing season ends when the average minimum temperature is < −2 °C beginning August 1.

produced a consistent transnational fire database for this region. Fire-perimeter data across the study area were retrieved from the Canadian National Fire Database (CNFDB; Canadian Forest Service, 2013) and from the Monitoring Trends in Burn Severity project (MTBS; Eidenshink *et al.*, 2007). These fire datasets were combined by merging cross-border fires into a single perimeter polygon. The resulting database was limited to fires larger than 385 ha that burned during the 1984–2011 time period, reflecting the timeline and processing methods of the MTBS, and includes both wildfires and prescribed burns. Although the 385-ha threshold excluded small fires, large fires are responsible for the vast majority of the area burned in this region (Stocks *et al.*, 2002; Stephens, 2005) and research suggests that the inclusion of only large fires is a reasonable modelling choice for subcontinental scales (Parisien *et al.*, 2012). The combined fire database included 1897 fires (see Fig. S1 in Appendix S1 of the Supporting Information).

Attributes of fire size, ignition cause and Julian day of ignition were necessary for the characterization of the fire regime. Both of our source databases include final fire size and presumed ignition dates, and these were consolidated in the final database. The CNFDB includes ignition cause (human or lightning) attributes, whereas the MTBS database does not (with the exception of prescribed burns, which are identified). We added ignition causes to the MTBS-delineated fires in the US from three sources: (1) Spatial Wildfire Occurrence Data for the United States, 1992–2011 (Short, 2014); (2) Federal Fire Occurrence Data: 1980–2012 DOI, USFWS and USFS (US Department of the Interior *et al.*, 2013); and (3) the Wildland Fire History 1980–2003 database (Bureau of Land Management, 2004). Causes were matched to MTBS fire perimeters from other fire databases if: (1) the two fires matched in MTBS Fire ID; or (2) the fires matched in fire name, date and approximate size. Eighty-nine per cent of fires in the transnational database had an identified cause and the remainder were classified as ‘unknown’.

Fire data: severity

Burn severity has been defined as the degree of fire-induced change to vegetation and soils, and is often inferred from Landsat-based metrics, such as the differenced normalized burn ratio (dNBR) (Eidenshink *et al.*, 2007; Parks *et al.*, 2014). For the US portion of our study area dNBR images for each fire were retrieved from the MTBS website. Because Canada does not have an equivalent national initiative to characterize burn severity, we consulted MTBS staff and replicated methods for image processing and dNBR calculation for Canadian fires. This analysis used multispectral imagery from the Landsat 5 and 7 satellite sensors retrieved from the USGS Global Visualization Viewer website (US Geological Survey, 2014) and computed in the R package LANDSAT, version 1.0.8 (Goslee, 2011; R Core Team, 2013). To process dNBR for Canadian fires we carefully sampled 56 fires across the variation in climate space (Fig. S1).

Human footprint

The human influence in the study area was represented by the Wildlife Conservation Society Global Human Footprint Index version 2, 2005 (HFI; Sanderson *et al.*, 2002). The HFI is a synthesis of nine datasets representing population density, land transformation, accessibility and electrical power infrastructure. These datasets were combined by rescaling input data to range from 0 to 10 and summing the scores to

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produce the HFI data. The HFI served as a proxy for the human influence on fire regimes and may incorporate information linked to increases in fire (Krawchuk *et al.*, 2009; Parisien *et al.*, 2012).

Analysis

To characterize climatic variation of the study area the 12 climate variables (Table 1) were collapsed into two orthogonal components using principal components analysis (PCA). Only the first two axes of the PCA were retained as they adequately described the majority (76%) of the variability. A varimax rotation was applied to tighten the relationship between the PCA axes and the underlying climate variables. Climate space was defined according to these two gradients, independent of the spatial location of the climate data, following the methods of Batllori *et al.* (2014). This two-dimensional climate space was then stratified into 12 × 12 homogeneous and equally spaced climate domains (CDs), each encompassing the same fraction of climate variability. The relative rarity of each CD was calculated from its geographical extent as: number of pixels in each CD^{-1}.

We positioned each fire within the CDs, allowing us to examine the climate space of fire-regime components. The mean value of each rotated PCA axis within a fire perimeter defined the fire's position and determined in which CD it was located. Components of the fire regime were assessed using the averages of the fires that had burned within each CD. Fire frequency was calculated as the average area burned per year, per unit area of the CD (Bergeron *et al.*, 2001). The fire season was represented by the median presumed Julian start day of fires. Mean fire size within a CD was log-transformed to reduce the skew of this distribution. Burn severity was represented by the mean 90th percentile of dNBR for fires in the CD. Finally, fire cause within each CD was represented as a continuous variable using the percentage of ignitions caused by lightning. As not all fires had data for each fire-regime component metric (i.e. severity, season and cause) the number of fires used for calculation of average values within a CD varied among components. Fire intensity and fire type, two other fire-regime metrics, were not examined because of data limitations.

To examine fire-regime components in both climate and geographical space, we created a dual representation. Spaces were displayed side by side, allowing a complementary interpretation of fire regimes across the study area. Each 2-km^2 pixel of the study area was assigned to one of the 73 CDs based on its values on the two climate gradients, and then mapped back to geographical space as that CD. The HFI and the two rotated PCA axes, although not fire-regime components, were also summarized in climate and geographical space to aid in interpretation. Although vegetation provides the fuel that fires burn, it was not explicitly included as a factor to define fire regimes because it is dynamic, often modified by both anthropogenic and natural disturbances and unknown at the time a fire burned. At the spatial extent of our study, however, major vegetation types are largely a function of climate and thus are implicitly captured by the variables we used (Brovkin *et al.*, 1997; Metzger *et al.*, 2013).

To examine cause-and-effect relationships between components of the fire regime, as well as the fire regime drivers of HFI and climate, bivariate (pairwise) regression models were built for all plausible relationships. Only CDs that included ≥ 5 fires during the study timeline were included in the regression analysis. The relationships were plotted and the strength, expressed as the deviance explained (*DE*), of significant ($P \leq 0.05$) models was represented in a relational diagram. To assess the link between fire-regime components and climatic and anthropogenic drivers of the fire regime such relationships were evaluated using multivariable models. Regressions were produced where each fire-regime component (independent variable) was predicted as a function of both climate gradients and HFI. The contribution that is 'unique' to each variable, that is, the fraction of the *DE* of a model that is not contained in any other variable, was assessed by omitting each predictor variable of interest and calculating the decrease in *DE* relative to the full model. All regression models were produced as self-fitting generalized additive models (GAMs) with the proper family for each data distribution, using the R package MGCV, version 1.8-4 (Wood, 2006; Frequency: Gamma, Size: Quasipoisson, Severity: Gaussian, Cause: Quasibinomial, Season: Gaussian, HFI: Quasibinomial). GAMs were constrained to limit overfitting (gamma = 2). All analyses were conducted in the R statistical environment, version 3.1.1 (R Core Team, 2013).

RESULTS

The primary climate gradient in the study area was a latitudinal gradient of temperature and summer precipitation, as indicated by the PCA factor loadings, with temperature increasing to the south and summer precipitation increasing to the north (Fig. 2a,b). The secondary gradient was longitudinal, following continentality and winter precipitation, with continental and winter-dry climates increasing eastward (Fig. 2a,c). The stratification of the climate gradients into units of homogeneous variance yielded 73 unique CDs that collectively comprise the climate space of the study area (Fig. 3a). When represented in geographical space the CDs ranged in size from approximately 1.89×10^5 km^2 (most common climate) to 4 km^2 for the least common CD (Fig. 3b,d). Rarer CDs had fewer fires per unit area during the study timeline, whereas common CDs were largely those with more fires (Figs 3b & 4). Rare CDs represented microclimates that are generally less conducive to large fires, such as mountain peaks and maritime areas.

Each fire-regime component varied across the climate space and geographically throughout the study area, as did HFI (Fig. 4; see Table S1 for units and ranges and Fig. S2 for coefficients of variation in Appendix S1). The large fires examined in this analysis did not populate the entire climate space; only 33 of the 73 CDs experienced fires and only 24

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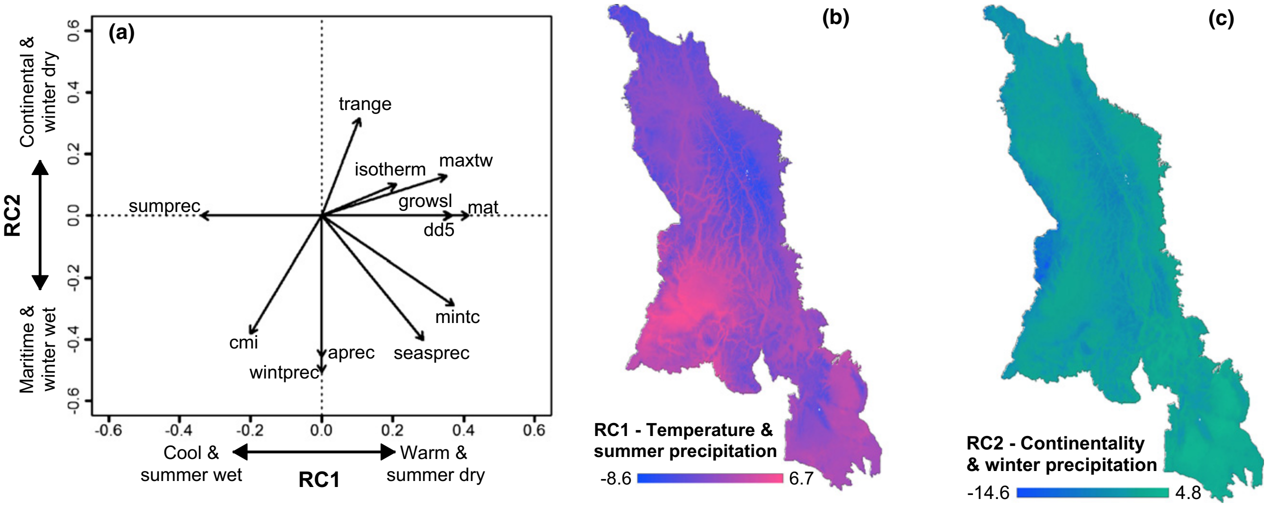

Figure 2 The primary climate gradients in the study area identified through a principal components analysis of climate data. (a) Biplot of the climate gradients of temperature and summer precipitation, and continentality and winter precipitation, as represented by rotated components (RC) 1 and 2; (b) spatial distribution of the temperature and summer precipitation gradient scores (RC1) and (c) spatial distribution of the continentality and winter precipitation gradient scores (RC2). Abbreviations of climate variables represented in the biplot (a) are explained in Table 1.

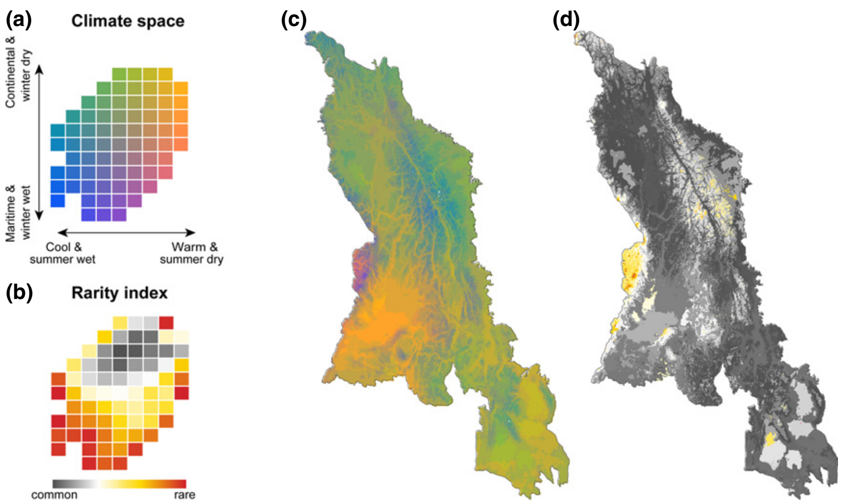

Figure 3 The climate space of the study area encompassing the total variability in regional climate, represented as (a) a 12 × 12 binning of the climate space resulting in 73 distinct climate domains (CDs), (b) the relative area (i.e. rarity) of each CD within the study area, (c) the spatial distribution of CDs and (d) the rarity of the CDs represented spatially. Note that colour scales in (a) and (b) match those in (c) and (d), respectively.

CDs had ≥ 5 fires. The subset of climates that experienced fires during the study time period defined the climate space of fire and consisted of the more continental and moderately summer-wet CDs. Fires were most frequent and largest in those CDs at the centre of this climate space (Fig. 4a,b). Burn severity was highest in CDs with moderately continental, warm climates (Fig. 4c). The median day of fires was in midsummer throughout all CDs (Fig. 4d), but the distribution of fire seasonality varied in geographical space with the northern reaches of the study area generally igniting earlier in the year and the south later. The majority of fires were lightning-ignited and these fires clearly dominated a central climate space (Fig. 4e). Human influence, as represented by HFI, was highest in warm climates and decreased with temperature (Fig. 4f); the southern half of the study area has a higher HFI than the north.

Fire size, burn severity and frequency of fires (proportion burned per year) were interrelated (Figs 5 & 6). Fire size increased as a function of increasing burn severity (deviance explained; *DE* = 53.4%, *P* = 0.003), and the frequency and size of fires significantly explained one another (*DE* = 47.3%, *P* = 0.003; *DE* = 46.5%, *P* = 0.001). Ignition cause was

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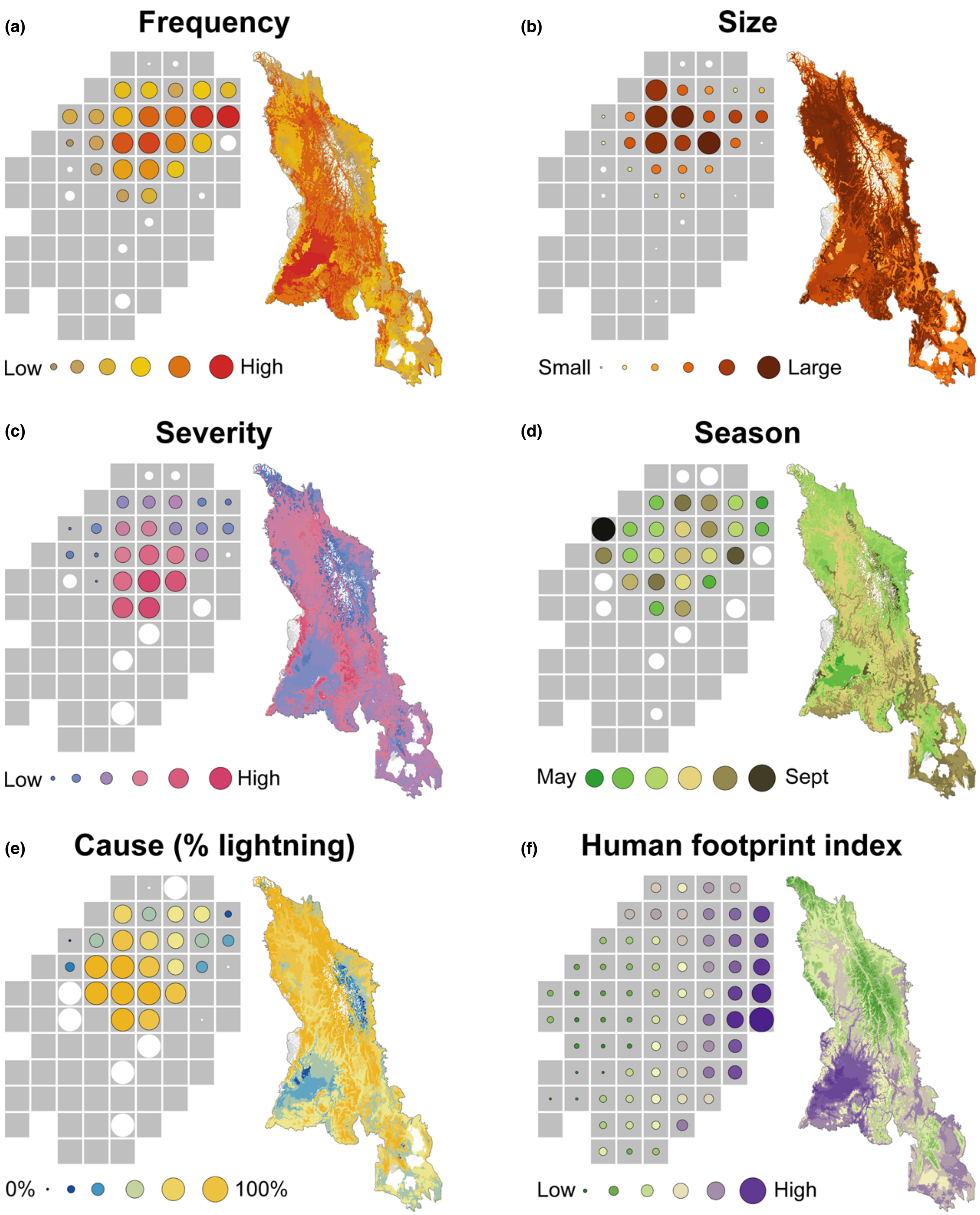

Figure 4 Fire-regime components and human footprint index (HFI) summarized within climate domains (CDs), including (a) frequency (annual area burned per unit area); (b) log mean fire size; (c) mean 90th percentile burn severity; (d) median day of the fire season; (e) cause, represented as the percentage of lightning-caused fire ignitions and (f) mean HFI by CD in both climate and geographical space. Where CDs do not have a graduated symbol in the HFI panel (f) the HFI is equal to 0 (e.g. mountain tops). Symbol sizes and colours are scaled together to represent increasing and decreasing values of each fire regime component and HFI. The values of fire-regime components and HFI within a CD are represented in geographical space in the same colour, CDs where < 5 fires occurred during the study timeline are represented in white, and CDs with no fires are represented in grey. For the range of values and variance of fire-regime components see Appendix S1.

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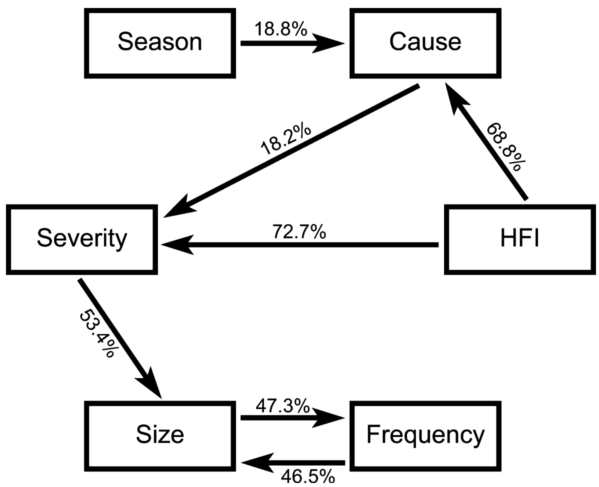

Figure 5 Conceptual schematic model of significant ($P \leq 0.05$) relationships amongst fire-regime components as well as human footprint index (HFI), identified through bivariate regression analyses. The direction of an arrowhead indicates the dependent variable in the regression. Arrow labels represent the fit of the relationship regression, calculated as the deviance explained (*DE*).

significantly related to season, with lightning-caused ignitions increasing through the summer and declining into the fall ($DE = 18.8\%$, $P < 0.001$). Burn severity varied as a function of ignition cause ($DE = 18.2\%$, $P = 0.037$). We include only significant, plausible relationships here. For example, HFI as a function of fire-regime components is not reported, nor cause as a function of fire size.

Human influence, as represented by HFI, was a significant predictor of both burn severity ($DE = 72.7\%$, $P < 0.001$) and ignition cause ($DE = 68.8\%$, $P < 0.001$) (Figs 5 & 6). All fire-regime components also varied along the climate gradients (RC1 and RC2; Appendix S2). Fire size was not significantly predicted by either gradient alone, but the multivariable model with fire size as a function of both RC1 and RC2 was significant ($DE = 78.8\%$, $P < 0.001$; Table 2). Fire frequency increased with increasing temperature and summer dryness ($DE = 19.9\%$, $P = 0.015$), while burn severity increased until moderate conditions on the RC1 gradient were reached and then declined with increasing temperature and summer dryness ($DE = 61.1\%$, $P < 0.001$). Increasing continentality and winter precipitation had a negative relationship with burn severity ($DE = 20.6\%$, $P = 0.026$). The median Julian day of fires (season) declined as a function of RC1 ($DE = 16.8\%$, $P = 0.047$) and the cause of fires showed a unimodal relationship with RC1 ($DE = 58.2\%$, $P < 0.001$). Ignition cause was also significantly predicted by RC2 ($DE = 35.7\%$, $P < 0.001$). HFI is strongly linked to RC1 and increases with both increasing temperature (RC1; $DE = 88.8\%$, $P < 0.001$) and continentality (RC2; $DE = 27.6\%$, $P = 0.011$).

Examining the unique contribution of climate (RC1, RC2) and HFI in predicting each fire-regime component helped identify the relative contribution of anthropogenic drivers when controlling for climate (Table 2). The multivariable models strongly predicted fire frequency, size, ignition cause and burn severity. The analysis of unique contributions shows that HFI contributes relevant and distinct information in predicting the fire-regime components.

DISCUSSION

The climate space of fire

This study combines approaches from two different, yet related, branches of wildfire studies: a classic fire-regime analysis that provides summary statistics of well-established fire-regime components (Gill, 1975) and a climate-gradient analysis of wildfire (Murphy *et al.*, 2013; Parks *et al.*, 2014). The method of fire regime characterization presented here enhances our understanding of climate–fire relationships, enables the development of predictive models of future fire projections (e.g. Moritz *et al.*, 2012; Boulanger *et al.*, 2014) and allows us to compare diverse fire regimes from across broad areas in a standardized, consistent manner.

We defined our study area's climate space using PCA, which was effective in collapsing climate variability of the study area into a primary gradient comprising temperature and summer precipitation and secondary gradient of continentality and winter precipitation. Climate gradients such as these play an important role in determining the large-scale distribution of fuels, burning conditions, and ignition sources (Thuiller *et al.*, 2005; Rehfeldt *et al.*, 2012). Fire activity has historically fluctuated with climate and continues to do so, despite a measurable human influence on fire-regime components (Kipfmueller & Swetnam, 2000; Westerling & Swetnam, 2003). Thus, understanding the climate space of current fires and human influence provides a foundation to examine how projected changes in climate may change fire regimes.

Whereas fires occurred throughout the study area during the study time period, they were limited to a distinct subregion of the climate space, which defined the climate space of fire. Fire frequency (proportion of area burned per year) and size were highest at the core of the climate space of fire, supporting the idea that fires primarily occur in an environmental middle ground where favourable climatic conditions for fuels, ignitions and conditions conducive to burning overlap, whereas fire is limited at extremes of precipitation and temperature in the climate space (Parisien & Moritz, 2009; Krawchuk & Moritz, 2011). These central CDs with relatively high fire activity (frequent, large and severe) were primarily coniferous montane and subalpine forests where fuel production is relatively high and conditions are often conducive to burning (e.g. the BC interior and the Idaho/Montana Bitterroot wilderness areas). During the time period examined, fires were uncommon in relatively dry, warm environments where fuel production is limited (e.g. Wyoming sagebrush steppe) and rare in maritime and winter-wet climates (e.g. the BC coast), with very

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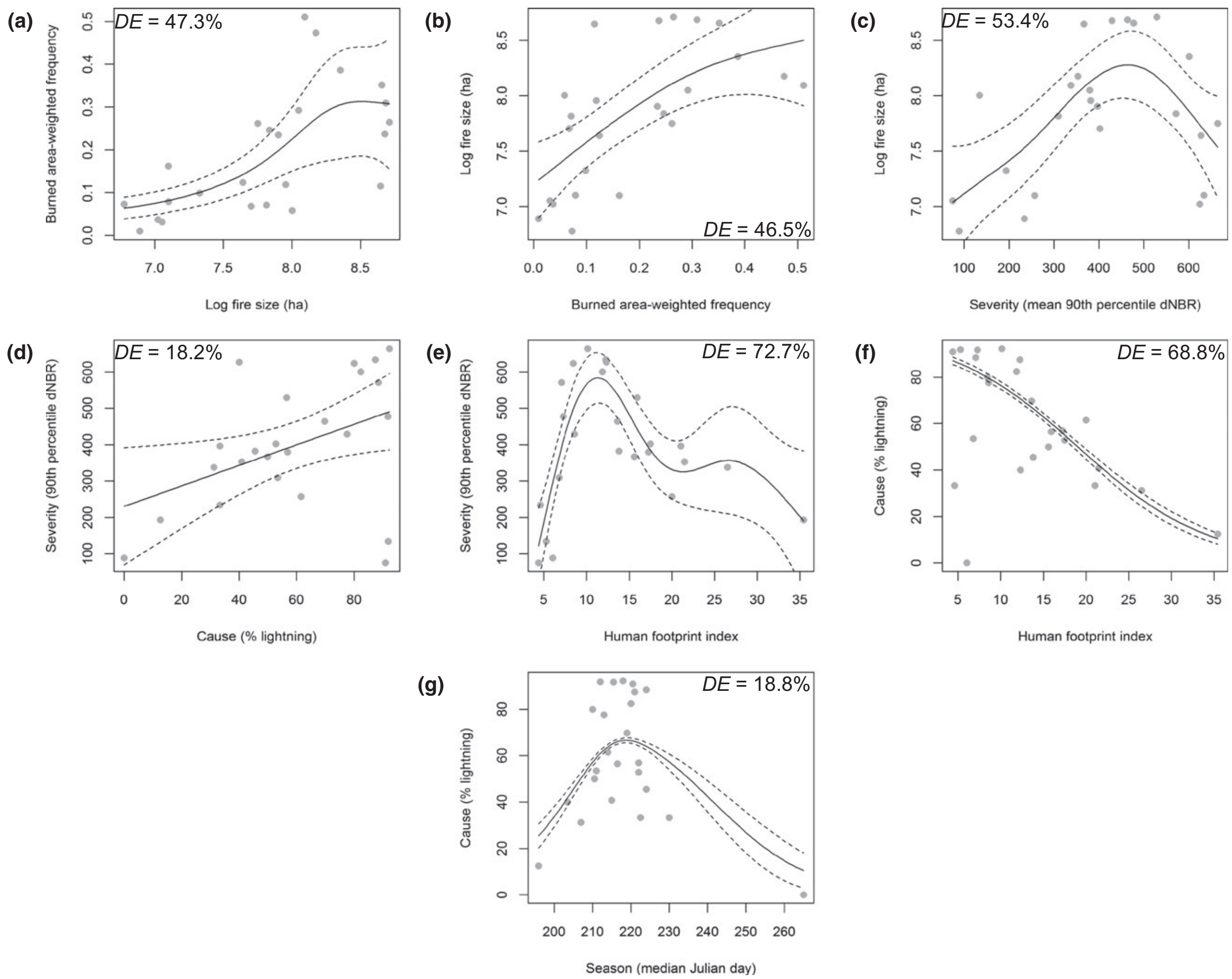

Figure 6 Scatterplots and fitted relationships amongst components of the fire regime and human footprint index (HFI), and deviance explained (*DE*) of the model fits for (a) frequency as a function of fire size; (b) log mean fire size as a function of frequency; (c) log mean fire size as a function of burn severity, as represented by the differenced normalized burn ratio (dNBR); (d) burn severity as a function of ignition cause, represented as a percentage of lightning-caused fire ignitions; (e) burn severity as a function of the human footprint index (HFI); (f) ignition cause as a function of HFI and (g) ignition cause a function of the median day of the fire season. All regressions presented here are significant at a $P \leq 0.05$ level. Units of measurement are average fire-regime components within a climate domain (CD), where a CD had ≥ 5 fires in the period of 1984–2011. Relationships amongst all fire-regime components and HFI reported here are represented in Fig. 5.

high levels of moisture and precipitation that limit fire spread (Meyn *et al.*, 2010).

All components of the fire regime were significantly related to climate gradients, indicating that variability in fire activity across the study area is largely a function of climate. In particular, ignition cause, fire size (as a function of RC1 and RC2) and burn severity appear to be strongly climate-driven (Table 2, Appendix S2). Ignition cause is partially a function of climate, as natural fire activity is dependent on the occurrence of lightning (Wierzchowski *et al.*, 2002). Burn severity and fire size are related to fuel availability and the conditions that allow fires to burn, both of which vary with climate (Littell *et al.*, 2009; Bradstock *et al.*, 2010; Abatzoglou & Kolden, 2013). In this case, the apparent lack of a relationship between RC1 and burn severity (Table 2) is the result of a high correlation between RC1 and HFI, and although the unique contribution of HFI is distinct, it is marginal.

Patterns of the fire-regime components observed within the climate space of fire in this region suggest that climate variation promotes fires with different characteristics (e.g. large size, high frequency), which in turn play a role in defining local vegetation communities. Ongoing climate changes shifting the spatial distribution of climates may therefore alter associated fire-regime characteristics and the pattern of fire on the landscape. Such changes will necessitate corresponding shifts in the geographical ranges of fire-adapted and fire-sensitive species alike (McKenney *et al.*, 2007). Because local fire regimes influence the distribution of species and vegetation communities and heterogeneity of a region (Weber & Flannigan, 1997), changes in the range of

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Table 2 Analysis of the unique contribution of climate and human influence as drivers of the fire regime. Multivariable regressions were produced that predicted fire-regime components as a function of climate, as represented by rotated components 1 and 2 (RC1 and RC2) and human footprint index (HFI). The deviance explained (*DE*) of the full multivariable model is reported below. Unique contributions of RC1, RC2 and HFI to the multivariable model are calculated by omitting each variable of interest and calculating the decrease in *DE* relative to the full model. Unique contributions to the model *DE* are 0 where inclusion of the variable worsened the model fit. Variables that significantly contribute to the full model are identified with asterisks (* $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$).

Fire-regime component	Full model *DE*	Unique contribution to full model		
		RC1	RC2	HFI
Frequency	43.6%	47.6%*	35.1%	17.3%
Size	78.8%	49.8%***	50.2%***	0%
Severity	80.5%	0%	76%**	24%***
Cause	76.7%	28.8%***	55.8%***	15.4%***
Season	19.1%	20%	55%	25%

fire and the variability of fire-regime components may trigger a cascade of ecological changes (Beckage & Ellingwood, 2008; Johnstone *et al.*, 2010). Shifts in vegetation communities as a result of climate change may be strongly mediated by disturbances such as fire (e.g. by opening areas for colonization by invading species; Schneider *et al.*, 2009). These potential changes may be more apparent where fire-regime component characteristics are on the 'edge' of their climate envelope, as future climate change may push these characteristics beyond their current bounds. For example, climate change is projected to increase fire activity in dry, warm biomes. In the case of sagebrush steppe ecosystems this is expected to facilitate colonization by invasive grasses, dramatically altering the ecosystem (Baker, 2006; Balch *et al.*, 2013). The relationships between vegetation, climate and fire are complex, and characterizing the distribution of fires within climate space may provide a foundation for understanding cascading consequences of climate change.

Fire-regime component relationships

Previously unexplored relationships between the fire-regime components were examined in the exploratory regression analysis. In this study area the frequency and size of fires were positively related. Fire size also had a significant, unimodal relationship with burn severity. Large fires tend to have heterogeneous levels of burn severity and may contain larger, continuous areas of severely burned stands (related to higher values of dNBR), whereas smaller fires may be dominated by one level of burn severity (Turner *et al.*, 1994; Birch *et al.*, 2014). Climate domains with the largest fires were associated with moderate values of dNBR and those with smaller fires were associated with higher or lower than average burn severity. This is consistent with the mix of severities found in larger fires that burn areas across large heterogeneous landscapes, for long durations, and under a wide range of weather conditions.

At a regional scale, the associations among fire-regime component characteristics create and perpetuate heterogeneity on the landscape. Fire regimes can have strong influences on vegetation composition and structure; for example the relationship between frequent, low-severity surface fire regimes in open stands of western ponderosa pine (Veblen *et al.*, 2000), the infrequent, high-severity stand-replacing crown fires that characterize more densely-stocked subalpine forests (e.g. Yellowstone National Park; Turner *et al.*, 2003), or the infrequent surface fires that create mosaics of burned and unburned areas in sagebrush ecosystems (Baker, 2006). Variation in burn severity and fire size leads to different successional trajectories for vegetation recovery (Turner *et al.*, 1997; Johnstone & Chapin, 2006), and plant productivity – the production of fuel – is dependent on site characteristics and climate. The patterns and relationships amongst fire-regime components identified here support diversity in vegetative communities at the scale of the study area and within the individual CDs.

Human influence

Human influence and other local factors may override climate drivers of fire in some areas (Guyette *et al.*, 2006; Gavin *et al.*, 2007). The anthropogenic influence in the study area, as represented by HFI, had a discernible influence on fire regimes, although anthropogenic pressure is not as intense in this region as in other parts of North America. HFI also showed strong trends within climate space, as warmer climates were associated with higher HFI values.

Human influence had direct impacts on the ignition cause and season of fires. The study area is dominated by natural lightning ignitions, but we found two distinct regions where human ignitions were the more common source of fire: the Columbia River Basin and the eastern Canadian Rocky Mountains. Despite having similar primary ignition sources, these regions differ in their climatic characteristics and the degree of human influence. The Columbia River Basin in the south-western portion of the study area has a warm, mostly continental climate. Human-caused ignitions dominate in this region because it is extensively modified by anthropogenic land uses. In contrast, the eastern Rockies have a cool climate and low human footprint; yet human ignitions still dominate there because this region lies in a pronounced lightning shadow (Wierzchowski *et al.*, 2002).

Both ignition cause (percentage lightning) and human footprint were related to burn severity, with low burn severity where human-caused ignitions dominated. This may be as a result of where and when fires burn: human-caused fires (both prescribed and accidental ignitions) often occur in the spring under less favourable conditions for high severity, whereas lightning fires may ignite in remote areas where they become large and burn under a range of conditions (Stocks

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et al., 2002). Humans also suppress fires where our values are at risk and introduce fuel treatments with the aim of reducing fire severity (Bowman et al., 2011), potentially influencing burn severity. Although this relationship has not been extensively examined in the fire literature, it is plausible, and constitutes an interesting subject for further research.

The bivariate relationships between HFI and fire-regime components are conflated by the strong relationship between HFI and climate. Humans tend to live in warmer areas and it is difficult to disentangle the separate contributions of climate gradients and human influence (Parisien et al., 2012). Nonetheless, the unique contribution of HFI to multivariable models suggests that human influence helps predict most fire-regime components, and holds distinct information. McWethy et al. (2013) suggest that the human influence on fire regimes and vegetation is highest in areas where natural fire is less common. The relationships between HFI and fire regimes observed here may be amplified at the fringes of the climate space of fire.

Limitations

Some limitations must be considered in interpreting this research. Our study examined fires within the limited time period for which consistent remote sensing imagery was available (1984–2011), we examined only relatively large (≥ 358 ha) fires, and we focused on climate gradients because they are a universal top-down driver. Bottom-up controls on fire, such as ignitions and fuels, can also be essential in determining the fire regime in some regions (Parks et al., 2012). Some of these bottom-up controls are partially captured in the climate gradients modelled here, but not all. For instance, topography can be a dominant control of fire characteristics (Dillon et al., 2011), but its influence may not have been fully captured at the scale of our analysis. The relationship between dNBR and burn severity on the ground remains an area of ongoing research, and some CDs had relatively fewer fires with severity data from which to calculate average 90th percentile dNBR. To offset this problem, however, a stratified random sample in climate space was used for Canadian fires. Thus, the bivariate relationships presented here are an exploratory study that highlights the potential of the climate space approach. Opportunities exist to expand on the climate space model of fire regimes presented here through the inclusion of additional fire-regime components (e.g. intensity, fire type), the application of the model at an extended scale, and with diverse fire occurrence datasets as additional spatial fire occurrence data become available.

CONCLUSIONS

We have characterized and identified the climate space occupied by fire across two primary environmental gradients, along which distinct patterns of fire-regime components occur. Having linked fire-regime components to large-scale climate gradients, we show that fire regimes – just like the climate that controls them – are a part of a continuum, expanding on models of varying constraints on single attributes of the fire regime, such as fire activity. We also integrated a gradient of human influence across the climate space and identified relationships between fire-regime components and human drivers of the fire regime. This analysis of the climate space of fire provides insight into the fire ecology of the study area, recognizing the strong relationship between vegetation, climate and fire and aiding in the characterization of distinct fire regimes. The framework presented here takes into account the role of climate as a top-down control on fire occurrence, while producing quantitative and geographical descriptions of the variability of fire-regime components. We have produced a robust description of current fire regimes and the method presented here enables future monitoring, improved modelling and consistent comparisons of fire regimes in both climate and geographical space. This method provides a potential tool for understanding how future climate change could change fire regimes and the ecosystems with which they interact.

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SUPPORTING INFORMATION

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

Appendix S1 Supplementary figures and data.
Appendix S2 Regressions fitted to climate gradients and fire-regime components.

BIOSKETCH

Ellen Whitman is a fire scientist with the Canadian Forest Service, with broad interests in pyrogeography and applications of remote sensing and spatial data for analysis of wildfire. The research team is focused on modelling the limits of fire across spatial and temporal scales and through refined modelling of topographically-driven fire refugia. The researchers share an interest in identifying drivers of fire and climate refugia and their integration into forest management (https://griffingroups.com/groups/profile/23823/great-northern-lcc-refugia-project).

Author contributions: S.L.H., G.W.C., J.D.C., C.M., M.A.K. and M.-A.P. conceived the ideas. E.W. collected the data and analysed the data with E.B., and E.W., E.B. and M.-A.P. led the writing.

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