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Climate-induced fire regime amplification in Alberta, Canada

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Abstract

Acting as a top-down control on fire activity, climate strongly affects wildfire in North American ecosystems through fuel moisture and ignitions. Departures from historical fire regimes due to climate change have significant implications for the structure and composition of boreal forests, as well as fire management and operations. In this research, we characterize the relationship between trends in climate and fire regime characteristics, for a study area predominantly in Alberta, Canada. We examined trends of fire and climate in northwestern boreal forests using time series analysis of downscaled historical annual climate, fire history (1970–2019), and fire severity (the impacts of wildfire on plants and organic biomass; 1985–2018). We represented fire severity using the relativized burn ratio (RBR) calculated from multispectral Landsat imagery. The climate of the study area has significantly warmed and dried over the past 50 years. Over the same period the annual number of large wildfires, area burned, and fire sizes in the study area significantly increased. Furthermore, the likelihood, area, and number of extreme short-interval reburns (≤15 years between fires; 1985–2019) also significantly increased. During the study period, the portion of forested unburned islands within fire perimeters significantly declined, and fire severity (RBR) increased in open conifer and mixedwood forests. These fire regime changes are significantly correlated with annual climate variability, and a path analysis supports the hypothesis that annual climate patterns have led to fire regime shifts. The increasing fire activity in this region has implications for forest ecology and habitat availability, as the disruption of the fire regime is likely to alter forest recovery. Managers may face increasing challenges to fire suppression if the observed trends of increasing hotter and drier annual climate in the study area persist, driving extreme fire activity.

1. Introduction

Boreal forests represent the largest terrestrial biome, and are of substantial global importance due to their role in providing ecosystem services and storing biogenic carbon [1, 2]. The northern latitudes where boreal forests occur are experiencing the fastest current rates of warming, leading to concerns over ongoing and anticipated changes to climate-driven disturbance regimes, such as wildfire [3, 4]. Wildfire is the dominant stand-renewing disturbance in the North American boreal forest [5, 6]. Many tree species display evolutionary adaptations to crown fires that kill mature trees, in the form of serotinous or semi-serotinous cones and aerial seedbanks (e.g. *Pinus* spp., *Picea mariana*), and the ability for top-killed individuals to resprout through vegetative reproduction from belowground structures (e.g. *Populus* spp., *Betula* spp.) [7]. These adaptations allow boreal forests to recover after a wildfire, promoting similar forests to those that existed prior to the disturbance through rapid tree recruitment and eventual stand self-replacement [8]. After a wildfire, biomass must accumulate for adequate fuel availability to support the next fire, and propagules need time to develop into a mature forest before another disturbance

occurs. In northern boreal forests, another severe wildfire typically recurs before forest succession over time alters vegetation communities from that initially established, such that that immediate post-fire regeneration largely determines the mature forest composition and structure [9].

Despite adaptations that impart boreal forests with resilience to wildfire disturbance, changes to fire regimes (characteristic patterns of wildfire occurrence, such as fire sizes, fire frequencies, or fire severities) can push forests beyond thresholds for ecosystem recovery, leading to long-lasting changes [10]. Changes to fire regimes occurring more rapidly than the typical life spans of extant vegetation lead to a mis-match with the life-history strategies of plants that have evolved over past ecological time scales, triggering ecosystem reorganizations [11, 12]. High fire intensities at the time of burning generally lead to high fire severity (biomass loss and plant mortality from fire) [13, 14]. Fire severity can affect the tree species composition of post-fire forests [15, 16], and in some instances, uncharacteristically severe burning can mediate shifts away from pre-fire vegetation communities [17, 18]. Short-interval wildfires in boreal forests (i.e. repeated wildfires that occur in close succession) also alter post-fire recruitment, promoting changes from dense conifer forests to open, broadleaf, or shrub-dominated vegetation, with repeated fires reinforcing such changes [19, 20].

In Canada, wildfires burn over 1.6 Mha, annually [6, 21]. Trends indicate that area burned in Canada has increased over time since the 1970s, particularly in western regions [21], with such changes predominantly due to increasingly severe fire weather [22, 23]. In some western North American biomes climate change has been associated with increasing area burned [24], and higher levels of biomass combusted than historically occurred [25]. Such changes to fire regimes may significantly alter boreal forest composition through repeated disturbances or high-intensity burning causing a lack of seed sources for stand self-replacement [11]. Where fire regime shifts arise, they may have lasting effects on Canadian boreal forest structure and function, altering ecosystem services such as carbon storage and water cycling [26, 27].

Although climate-driven increases in recent fire activity are documented in diverse forested ecosystems, such as the western United States [24, 28, 29], and Australia [30], analyses of fire regime-shifts in western Canada have been limited (but see [22, 23, 31]). Satellite-derived fire severity metrics [32] calculated from multispectral imagery, and land cover data [33], are only recently available for all fires across this region. This newly available data allows for refined analyses that capture both climate and fuel effects on wildfire. To address this knowledge gap, we sought to determine how the fire regime has

changed over time in Alberta, Canada, and whether such dynamics relate to observed climate change. Specifically, our goal was to characterize the relationship between trends in climate and fire regime characteristics of: (a) fire activity (number of fires, fire size, and area burned), (b) frequency of fires (fire intervals), and (c) fire severity amongst forest types.
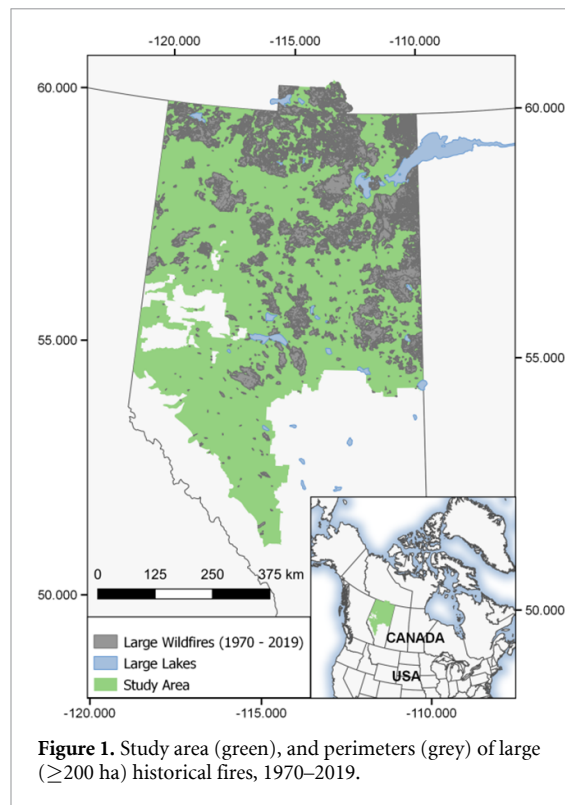
2. Methods and data sources

2.1. Study area

The study area consists of 60% of the province of Alberta, Canada, and a small portion of the Northwest Territories where Wood Buffalo National Park (WBNP) extends into the territory (figure 1). The study area is made up of 409 350 km^2 of boreal forest and foothills, and generally consists of a rolling plain, with some high plateaus in the north. The region has a cool (mean annual temperature of 0 °C) dry climate and receives approximately 450 mm of precipitation annually, mostly falling during the summer [34]. Within Alberta, the study area extent is limited to the forest protection area (the 'green zone'), where fire history data has been most consistently collected, and fire suppression is practiced. For this reason, the analysis excludes prairie, agricultural, and urbanized areas of the province.

The forests of the study area are predominantly composed of tree species that are resilient to historical wildfire conditions, which are dominated by high-intensity fires. The study area forests are characterized by conifer species of *Picea mariana* (black spruce), *P. glauca* (white spruce), *Pinus banksiana* (jack pine), *Larix laricina* (eastern larch), and broadleaf species of *Populus tremuloides* (trembling aspen), *P. balsamifera* (balsam poplar), and *Betula papyrifera* (paper birch). In the foothills (southwestern region of study area), species composition is similar, except *Pinus contorta* var. *latifolia* (lodgepole pine) replaces jack pine, and *Abies balsamea* (balsam fir) occurs [34].

The boreal forests of Alberta have historically experienced large and infrequent (mean fire return interval of 45 to hundreds of years [35]) wildfires that are predominantly lethal to trees. Although small fires (e.g. ≤2 ha) are more numerous, large fires (≥200 ha) contribute the vast majority of area burned (97%) [36]. Wildfires are a natural occurrence in the study area, and Indigenous peoples practiced cultural fire use in this region which influenced fire regimes [37, 38]. Approximately half of all fires in this area are lightning-ignited and half are human-caused; however, lightning fires are responsible for most of the burned area [35]. The study area undergoes intensive fire suppression throughout, with some exceptions in national parks (e.g. WBNP) and some small special management areas [35, 39].

Figure 1. Study area (green), and perimeters (grey) of large (≥200 ha) historical fires, 1970–2019.

2.2. Climate and fire regime data

We summarized climatological and fire regime metrics for the entire study area, by creating aspatial seasonal and annual time series. To examine the effect of climate variability on fire regimes, we downscaled historical climate data using the software *ClimateNA* [40] for the years 1970–2019. This technique downscales values using bilinear interpolation of climate values from neighbouring cells (4 neighbours), followed by an elevation adjustment with linear regression (i.e. lapse rates). Gridded climate variables (0.5° × 0.5°) were downscaled to a 28 km East-West × 52 km North-South grid of points with known elevations [41]. We converted all climate variables into deltas (Δ) by subtracting the historical climate normals (1951–1980) of individual points from each value of the annual time series for the same point (i.e. deltas were calculated point-by-point). To produce time series, we then averaged the delta values from all points for each climate variable and each year, to produce a single annual mean delta value for the study area, per variable. We selected seasonal climate variables with known links to wildfire, including spring, summer and total annual precipitation (PPT, mm), spring and summer average maximum temperatures (Tmax, °C), spring and summer mean relative humidity (RH, %), and spring and summer mean vapour pressure deficit (VPD, hPa; calculated from average temperature and RH) [42, 43].

We analysed time series of fire activity (fire size, area burned, and number of fires) for the period of 1970–2019. We applied a minimum fire size threshold of ≥2 ha for analyses of fire activity. We calculated historical fire sizes and area burned, using the Canadian National Fire Database (CNFDB) polygon and point-based fire maps. For fires <200 ha in size, we used the CNFDB point location fire data [44]. We used polygon fire maps [45] to represent large fires, which we defined as fires ≥200 ha [36]. The CNFDB polygon data incorporates area burned maps provided by the province of Alberta, where such maps are typically produced from interpretation of post-fire aerial photographs or digital imagery [45]. Due to inconsistent availability of fire agency data in national park areas, we used the National Burned Area Composite (NBAC) fire perimeters in these regions. The NBAC polygons are derived from multispectral imagery from the Landsat satellite series [46]. We merged fire perimeters that crossed jurisdictional boundaries that had been mapped as separate fires. We then clipped all fire perimeters to the study area boundary. If fire maps had excluded unburned residuals, we restored them so that perimeters indicated outer fire edges only and did not exclude the unburned areas within. Before calculating fire sizes from polygons, we removed waterbodies [47] from fire perimeters. Fire reporting practices have changed over time (e.g. minimum fire sizes reported), and may differ between agencies (Alberta vs. Parks Canada). The time period used for analysis (1970–2019), minimum fire size threshold (2 ha), and use of the point data for small fires and polygon data for large fires were designed to correct for these limitations and policy changes [45].

From the fire regime datasets described above, we calculated annual statistics of annual area burned (AAB, log[ha])), median and 90th percentile fire size (log[ha]), total number of fires (*N* fires; ≥2 ha), total number of large fires (*N* large fires; ≥200 ha), and the percentage of large fires (% Large fires) from 1970–2019. Wildfires in the Alberta boreal forest typically occur every 45 to upwards hundreds of years [35]. For this research, we defined a 'short interval reburn' as the recurrence of two overlapping fire events within 15 years of one another, reflecting a substantial departure from this normal fire frequency, often causing significant forest vegetation change [20]. We identified reburned areas from overlapping fire perimeters of large fires only (≥200 ha). We limited the analysis of reburned areas to fire overlaps with a minimum area of 2 ha, corresponding to the minimum fire size analysed in this study. As the fire record for this study began in 1970, the earliest a 15-year reburn could be detected is 1985, hence we limited analysis of reburns to a subset of more recent fire occurrence (1985–2019). We calculated the area reburned by fires in a given year (log[ha + 0.1]), the number of reburns, and the likelihood of a large fire becoming a reburn in a given year (% reburns; annual number of reburns/annual number of fires ≥200 ha).

We conducted the analysis of fire severity for the period 1985–2018, within large fires. We represented fire severity using relativized burn ratio (RBR) maps [48], published in the Alberta Fire Severity Atlas [32]. In this dataset, RBR was calculated from mean composited Landsat-TM, -ETM, and -OLI multispectral imagery and included a phenological offset for comparability between fires, following the methodology of Parks *et al* [32, 49]. Remotely sensed fire severity data was coupled with land cover data, also produced from Landsat satellite imagery [33]. To identify forested pixels, we combined land cover from 1984 and 2014 and used successional rules to produce a land cover product where each pixel was assigned to the vegetation type corresponding to the most advanced successional phase it attained during for the period (barren < low vegetation < broadleaf forest < mixedwood forest < conifer forest; supplementary material SI.1 available online at stacks.iop.org/ERL/17/055003/mmedia). We did this to account for post-disturbance succession and to ensure that disturbed forests were not misclassified as early successional vegetation types (e.g. shrublands, barrens), but rather were identified as the most mature forest type that occupied the pixel during the time series. We restricted analyses of trends in fire severity to pixels that were classified as a forest vegetation type in the combined 1984 and 2014 map; therefore, open wetlands, waterbodies, grasslands, barrens, shrublands are excluded from the statistics reported for trends in burn severity over time.

We produced time series of unburned, low, moderate, and high severity AAB, and their relative proportions, using severity thresholds derived from field data reported by Whitman *et al* [32] for large fires, for which we obtained fire severity. We then developed fire severity time series for each forest type of interest using continuous RBR values. We calculated the annual median RBR values by forest type. The analysis of continuous RBR values was limited to the boreal forest region to correspond with the extent of land cover data. Four southern foothills fires included in the fire regime time series did not fall into this region and are excluded from the severity analysis. We removed areas that had reburned from analyses of burn severity, in order to examine only 'first-entry' burning. All climate and fire time series are described in table 1.

2.3. Time series analysis

We conducted time series analyses in *R* [50]. We tested whether nonparametric linear trends existed for each time series by calculating Theil-Sen slopes. We determined the significance ($p \leqslant 0.05$) of linear trends using a one-sided Mann-Kendall trend test in the *EnvStats* package [51]. If an autocorrelation function indicated the time series data were temporally (serially) autocorrelated, we instead used a modified Mann-Kendall trend test for serially correlated data [52] from the *modifiedmk* package [53].

In order to examine the relationship between time series, we calculated Pearson correlation coefficients and significances of the correlation between time series, using a phase-randomized surrogate correlation for serially correlated data in the *astrochron* package [54, 55]. For those time series that exhibited a significant linear trend, we detrended the data (subtracted the linear trend) before conducting any cross-correlation in order to reduce the likelihood of reporting a spurious correlation.

Finally, we conducted a path analysis to test our hypotheses of the existence of direct effects of climate on three measures of fire activity. We computed the path analysis using the *lavaan* package [56], with time series from a selection of uncorrelated climate (Pearson's $r < |0.5|$) and fire activity variables, which we log-transformed. We hypothesized that seasonal (spring and summer) climate variables integrating both fuel moisture and temperature (VPD) that had significantly increased, as well as annual precipitation (PPT), which significantly decreased, would significantly explain fire activity variables that demonstrated significant trends over time, following the methods and results of others [57]. For this analysis we selected the annual number of large fires, total area burned, and 90th percentile fire size to represent shifting fire regimes within the study area. The fitted models test our hypothesis that all climate variables significantly contributed to variability in all fire regime variables, with paths connecting all three climate variables to each fire regime variable.

3. Results

Between 1970 and 2019, statistically significant trends in many of the climate variables indicate that the climate in the study area trended warmer and drier over time (table 2). Specifically, maximum summer temperatures significantly increased ($\beta = 0.029$, $p < 0.001$), spring and summer became significantly drier, as represented by both RH and VPD, and although spring and summer precipitation did not have significant trends, total annual precipitation significantly decreased ($\beta = -0.725$, $p = 0.039$) (table 2; figures 2(a) and (b)).

During the same period, measures of fire regime characteristics, particularly those related to fire activity, significantly increased (table 3). The number of large ($\geqslant$200 ha) fires and percentage of ignitions becoming large fires both significantly increased ($\beta = 0.300$, $p = 0.011$; $\beta = 0.501$, $p < 0.001$ respectively), indicating a shift towards the dominance of large fires. Similarly, the median fire size showed no change, but annual 90th Percentile fire sizes increased ($\beta = 0.018$, $p < 0.001$), indicating a shift in the extremes of fire events in this

Table 1. Variables used for time series analysis of fire regimes.

| Variable name	Abbreviation	Units	Time series duration	Data source
Spring maximum temperature	Spring Tmax	°C	1970–2019	[40]
Summer maximum temperature	Summer Tmax	°C	1970–2019	[40]
Spring precipitation	Spring PPT	mm	1970–2019	[40]
Summer precipitation	Summer PPT	mm	1970–2019	[40]
Total precipitation	Total PPT	mm	1970–2019	[40]
Spring relative humidity	Spring RH	%	1970–2019	[40]
Summer relative humidity	Summer RH	%	1970–2019	[40]
Spring vapour pressure deficit	Spring VPD	hPa	1970–2019	[40]
Summer vapour pressure deficit	Summer VPD	hPa	1970–2019	[40]
Number of fires	*N* fires	*n*	1970–2019	[44–46]
Number of large fires	*N* large fires	*n*	1970–2019	[45, 46]
Percentage of large fires	% large fires	%	1970–2019	[44–46]
Median fire size	Fire size	log(ha)	1970–2019	[44–46]
90th Percentile fire size	90th Percentile fire size	log(ha)	1970–2019	[44–46]
Annual area burned	AAB	log(ha)	1970–2019	[44–46]
Percentage area burned by large fires	% Burned by large fires	%	1970–2019	[44–46]
Number of reburns	*N* reburns	*n*	1985–2019	[45, 46]
Percentage of reburns	% Reburns	%	1985–2019	[45, 46]
Area reburned	Area reburned	log(ha + 0.1)	1985–2019	[45, 46]
Area unburned	Area unburned	log(ha)	1985–2018	[32, 33]
Area low severity	Area low severity	log(ha)	1985–2018	[32, 33]
Area moderate severity	Area moderate severity	log(ha)	1985–2018	[32, 33]
Area high severity	Area high severity	log(ha)	1985–2018	[32, 33]
Percentage unburned	% Unburned	%	1985–2018	[32, 33]
Percentage low severity	% Low severity	%	1985–2018	[32, 33]
Percentage moderate severity	% Moderate severity	%	1985–2018	[32, 33]
Percentage high severity	% High severity	%	1985–2018	[32, 33]
Dense conifer median RBR	Dense conifer RBR	NA	1985–2018	[32, 33]
Open conifer median RBR	Open conifer RBR	NA	1985–2018	[32, 33]
Broadleaf median RBR	Broadleaf RBR	NA	1985–2018	[32, 33]
Mixedwood median RBR	Mixedwood RBR	NA	1985–2018	[32, 33]
Treed wetland median RBR	Treed wetland RBR	NA	1985–2018	[32, 33]

Table 2. Nonparametric linear trends in climate (1970–2019). *P*-values derived from variance-corrected Mann-Kendall tests for temporally autocorrelated variables are indicated with the symbol †. All other *p*-values are from normal Mann-Kendall tests. *P*-values indicate the significance of one-sided hypothesis tests. Significant ($\alpha \leq 0.05$) *p*-values are bolded.

Climate variable (Δ)	Theil-Sen slope (β)	*p*-value
Spring Tmax (°C)	0.005	0.228†
Summer Tmax (°C)	0.029	**<0.001†**
Spring PPT (mm)	−0.143	0.166
Summer PPT (mm)	−0.370	0.128
Total PPT (mm)	−0.725	**0.039**
Spring RH (%)	−0.018	**0.015†**
Summer RH (%)	−0.054	**<0.001†**
Spring VPD (hPa)	0.001	0.235†
Summer VPD (hPa)	0.017	**<0.001†**

study area. Similarly, significant increases in AAB ($\beta = 0.024$, $p < 0.001$) paralleled the concurrent increases in the occurrence and size of large fires (table 3; figure 2(c)). We also detected significant changes in fire frequency, as represented by the reburning within ≤15 years between fires. The area reburned ($\beta = 0.067$, $p = 0.002$), number of short-interval reburns ($\beta = 0.278$, $p < 0.001$), and likelihood of large fires causing a reburn (% Reburns; $\beta = 1.157$, $p = 0.001$) all also significantly increased between 1985 and 2019 (table 3; figure 2(d)).

The total extent of forested unburned, low-, moderate- and high-severity classes within fire perimeters all significantly increased (table 4; figure 2(c)). Landscape patterns of fire and fire severity also underwent changes between 1985 and 2018. Although all levels of fire severity within fire perimeters significantly increased in tandem with area burned, the *percentage* of unburned residuals within fire perimeters significantly decreased in this period, due to the higher proportion of area burned at moderate severity over time (table 4; figure 2(e)). Fire severity (Median RBR) in burned forests was stable for dense conifer and broadleaf forests, but significantly increased over time in mixedwood and open conifer forests (table 4; figure 2(f)).
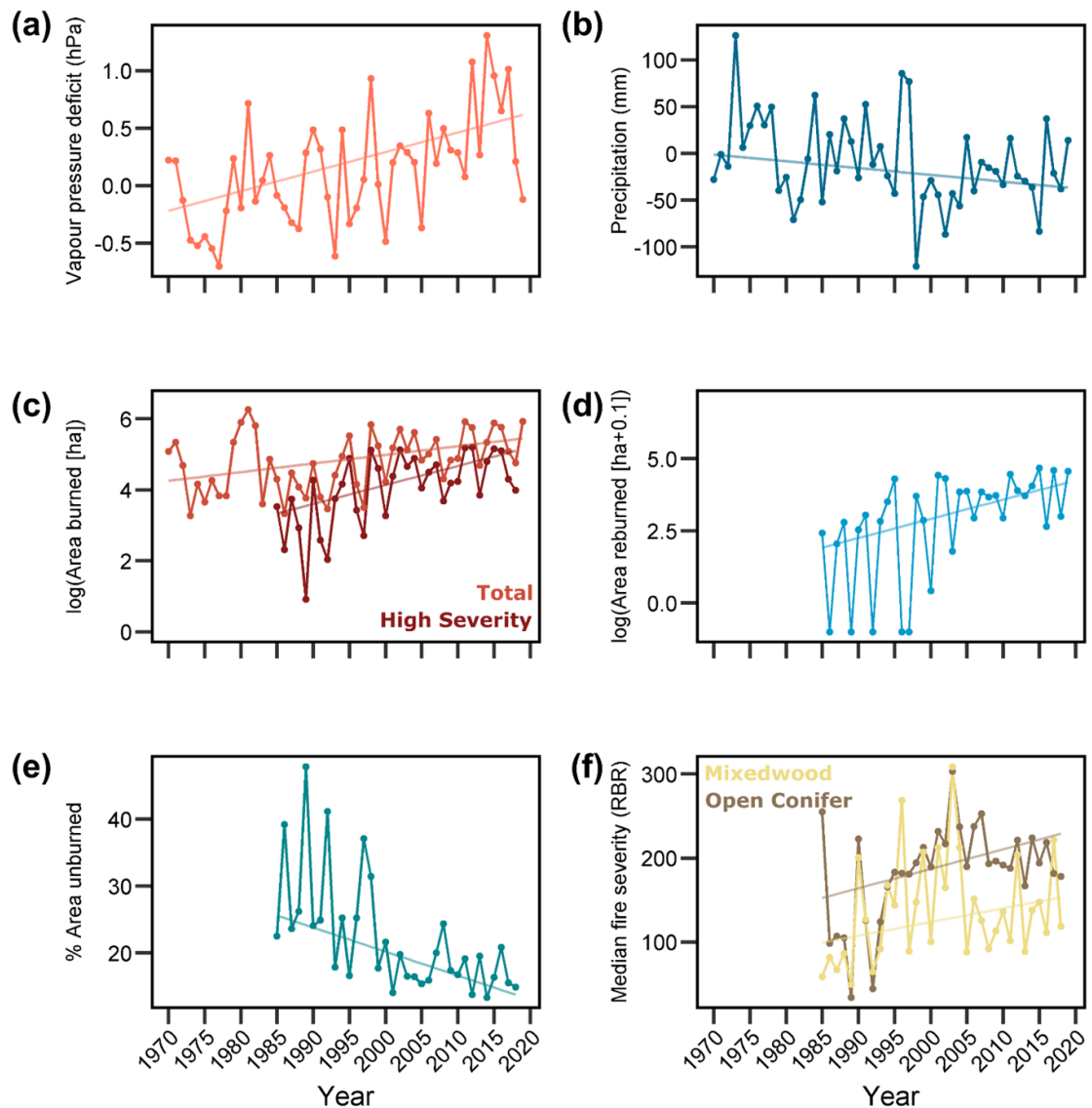
Figure 2. Selected time series of climate (a) summer mean vapour pressure deficit, (b) annual precipitation; fire activity (c) area burned, (d) area reburned within 15 years or less between fires; and fire severity variables, (e) the percentage forested area within fire perimeters occupied by unburned islands, (f) fire severity as represented by the relativized burn ratio (RBR; annual median) in burned mixedwood and open conifer forests. Straight lines indicating Theil-Sen's slopes represent significant nonparametric trends. Slopes, *p*-values, and significance of these and other time series are reported in tables 2–4.

Climate variables were significantly temporally correlated with various fire regime measures (figure 3). Specifically, summer climate variables generally had more significant relationships with fire activity and fire severity than spring climate. Warm summers and springs, dry summers with low precipitation, and arid fire season weather, as represented by RH and VPD, were positively associated with the number of large fires, the percentage of large fires out of overall number of fires, the extremes of fire size (90th percentile), and the overall area burned (figure 3(a)). Annual climate variability had significant but typically weaker relationships with the occurrence of short-interval reburns. Similarly, dry years with reduced precipitation and arid fuel conditions (RH and VPD) are associated with the number of

reburns and the area reburned, but not the per cent annual number of reburns (figure 3(a)).

Correlations between climate and burn severity were strongest with precipitation and RH variables. Dry springs and dry years were significantly associated with increased area burned of all severity classes. The proportion of forested unburned area within large fire perimeters was greater in years with higher precipitation, whereas the proportion of total area burned at high severity was reduced in years of higher precipitation and increased in summers where conditions were particularly arid (low RH). The proportion of moderate severity burned areas was most strongly associated with dry springs (PPT), whereas low severity burned proportion was significantly associated with increases in summer fuel moisture (high RH).

Table 3. Nonparametric linear trends in fire regime characteristics (1970–2019, fire sizes, area burned, number of fires; 1985–2019, reburns). Large fires are fires ≥200 ha in size. Areas have been log-transformed. *P*-values derived from variance-corrected Mann-Kendall tests for temporally autocorrelated variables are indicated with the symbol †. All other *p*-values are from normal Mann-Kendall tests. *P*-values indicate the significance of one-sided hypothesis tests. Significant ($\alpha \leq 0.05$) *p*-values are bolded.

Fire regime variable	Theil-Sen slope (β)	*p*-value
N fires	−0.026	0.487
N large fires	0.300	**0.011**
% Large fires	0.501	**<0.001**†
Fire size (log(ha))	0.003	0.210†
90th percentile fire size (log(ha))	0.018	**<0.001**†
AAB (log(ha))	0.024	**<0.001**†
% Burned by large fires	0.185	**0.001**
N reburns	0.278	**<0.001**†
% Reburns	1.157	**<0.001**†
Area reburned (log(ha + 0.1))	0.067	**0.002**†

Table 4. Nonparametric linear trends in annual fire severity of large fires within the study area (1985–2018). Fire severity analyses were limited to forested pixels and large fires (⩾200 ha). Areas have been log-transformed. *P*-values derived from variance-corrected Mann-Kendall tests for temporally autocorrelated variables are indicated with the symbol †. All other *p*-values are from normal Mann-Kendall tests. *P*-values indicate the significance of one-sided hypothesis tests. Significant ($\alpha \leq$ 0.05) *p*-values are bolded.

Fire severity variable	Theil-Sen slope (β)	*p*-value
Area unburned (log(ha))	0.042	**<0.001**†
Area low severity (log(ha))	0.047	**<0.001**†
Area moderate severity (log(ha))	0.055	**<0.001**†
Area high severity (log(ha))	0.054	**<0.001**†
% Unburned	−0.358	**<0.001**†
% Low severity	0.148	0.143
% Moderate severity	0.294	**<0.001**†
% High severity	0.072	0.328
Dense conifer RBR	−1.072	0.171
Open conifer RBR	2.325	**0.026**†
Broadleaf RBR	0.996	0.086
Mixedwood RBR	1.630	**0.029**

Annual climate variability also significantly affected burn severity in different forest types, as represented by annual median RBR values. Years and summers with higher precipitation were correlated with reduced burn severity in dense conifer, open conifer, and broadleaf forests. Arid (summer VPD) and warm (summer Tmax) conditions were also associated with increased fire severity in broadleaf forests, and dry summers (low RH) were associated with increased fire severity in broadleaf, conifer, and open conifer forests.
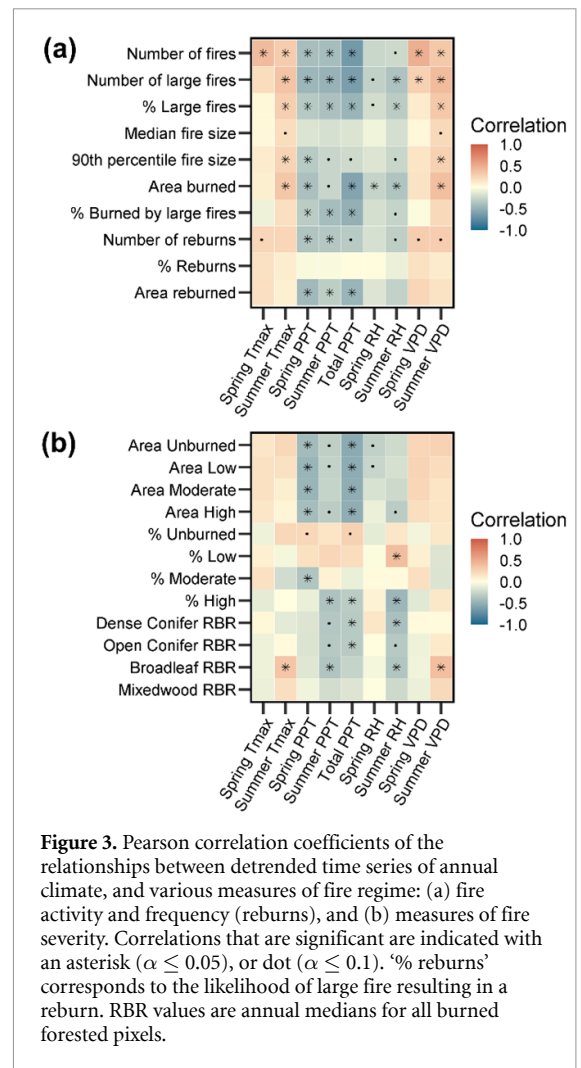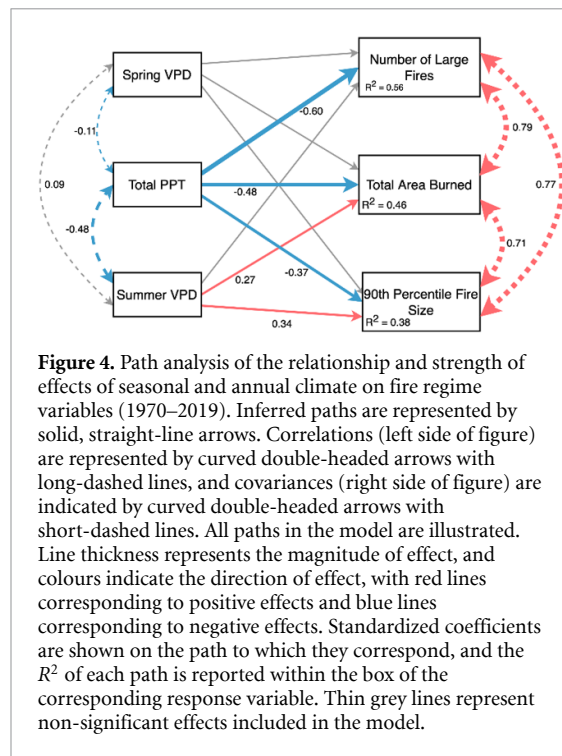

Figure 3. Pearson correlation coefficients of the relationships between detrended time series of annual climate, and various measures of fire regime: (a) fire activity and frequency (reburns), and (b) measures of fire severity. Correlations that are significant are indicated with an asterisk ($\alpha \leq 0.05$), or dot ($\alpha \leq 0.1$). '% reburns' corresponds to the likelihood of large fire resulting in a reburn. RBR values are annual medians for all burned forested pixels.

The path analysis results indicate that total annual precipitation had a strong negative effect on all three measures of fire activity chosen to represent the fire regime (figure 4). Spring VPD did not significantly contribute to any of the three fire regime variables, whereas increasing values of summer VPD increased total area burned and 90th percentile fire size. Spring and summer VPD were negatively related to total annual precipitation. The annual number of large fires, total area burned, and 90th percentile fire size strongly covaried, indicating that they tend to increase and decrease concomitantly, annually.

4. Discussion

Climatic changes in the Alberta boreal forest region have created warmer and drier conditions since the 1970s, with our analyses identifying clear top-down climatic influences on many components of the fire regime in this large area. Almost all indicators of fire activity we examined increased in this period, and none significantly decreased, indicating that the local fire regime is shifting towards patterns of more frequent, severe, and extensive fire, likely in response

Figure 4. Path analysis of the relationship and strength of effects of seasonal and annual climate on fire regime variables (1970–2019). Inferred paths are represented by solid, straight-line arrows. Correlations (left side of figure) are represented by curved double-headed arrows with long-dashed lines, and covariances (right side of figure) are indicated by curved double-headed arrows with short-dashed lines. All paths in the model are illustrated. Line thickness represents the magnitude of effect, and colours indicate the direction of effect, with red lines corresponding to positive effects and blue lines corresponding to negative effects. Standardized coefficients are shown on the path to which they correspond, and the R^2 of each path is reported within the box of the corresponding response variable. Thin grey lines represent non-significant effects included in the model.

to climate change. In the study area, the percentage of large fires (≥200 ha) has significantly increased, and furthermore, extremes of fire size (90th percentile) have increased over time. The growing occurrence of large fires has contributed to an overall increase in area burned between 1970 and 2019. Notably, the trends in AAB and area reburned presented here were observed in data measured on a log scale, indicating that such increases are nonlinear and are accelerating. During the period of analysis (50 years), average summer temperatures in Alberta increased by 0.89 °C (supplementary material SI.2). An additional ∼2 °C increase is expected in this region by 2050 (RCP 8.5) [58]. Although we observed a significant decrease in annual precipitation over time, projections suggest that precipitation in the study area may increase by 2%–7% in the next 30 years (RCP 8.5) [58]. These projected increases of precipitation, should they arise, are unlikely to be adequate to offset the increased evaporative demand from warmer temperatures in most surface fuels [59].

The results of this study are broadly consistent with those described for the western Canadian boreal forest [21], and across the north American boreal region [60]. Other research has documented increasing fire activity across the boreal biome, with notable examples of recent increases in burning in Alaska [61] and the Sakha republic [62]. Others have found that climate is a strong historical control of the distribution of wildfire in western boreal forests [63]. The trends of increasing wildfire occurrence and their significant relationships to climate documented here offer additional evidence to support a growing

understanding that climate change impacts on wildfire are already unfolding, with serious implications for countries with boreal forests [24, 64, 65].

Not only have area burned and area burned at high severity sharply increased, we also detected significant increases in fire severity, in terms of both the reduced proportion of unburned islands within fire perimeters, and an increase in median remotely sensed fire severity in some forest types. Such changes in fire severity are notable given the strong control pre-fire fuels exert over burn severity [66, 67]. Although boreal forests are adapted to lethal crown fires, high-severity fire can reduce serotinous conifer seed viability for species like jack pine (*Pinus banksiana*) and black spruce (*Picea mariana*) [68, 69], and alter soil substrates for tree regeneration [15, 17]. A greater area burned at high severity over time may promote vegetation and forest changes, such as a decrease in density of post-fire conifer tree regeneration [68, 70], and a shift towards less flammable broadleaf tree species dominance, to the detriment of conifer species, black and white spruce (*P. glauca*) in particular [18, 27, 71]. The proportion of forested unburned islands has significantly decreased over time. This change in the spatial pattern of fire severity in boreal forests also has implications for post-fire regeneration of obligate-seeder tree species, such as white spruce, which require surviving individuals to repopulate burned areas from forest edges [7]. As the area burned at high severity increases, a larger area of the Alberta boreal forest region may recover with an altered structure and composition, and such effects may be compounded by increasing drought stress that affects seedling recruitment [17, 20, 72].

As area burned increases, subsequent fires are more likely to encounter other recently burned areas [73, 74]. Although recent burns often resist reburning for upwards of 30 years due the limited availability of fuels [74–76], we detected a significant increase in the number of short-interval reburns and probability of reburning. Increasing likelihood and extent of short-interval wildfires in this region may have implications for forest management and ecosystem health, as repeated burning in boreal forests can enable shifts from dense, conifer-dominated forests to open broadleaf woodland, and shrublands [19, 20]. Repeated wildfires can also release legacy carbon stored in forest floors and peat soils, thereby acting as a positive feedback to climate change [77]. Although climate change, in conjunction with increasing fire activity and severity, will likely promote less flammable vegetation and fuel structures in the western boreal biome [78, 79], severe fire weather allows fires to overwhelm fuel-limited areas, and warmer and drier climates may therefore increase the occurrence of reburns [73, 80]. Reburned areas represented a small proportion of the AAB in Alberta, but this trend is increasing within the study area and elsewhere in western North America [73].

The detected changes in Alberta's fire regime, while having clear effects on the state of boreal forests, also have concerning implications for fire management, despite highly successful suppression efforts. Researchers have projected that climate change will challenge fire suppression and initial attack effectiveness [81–83]. Our results implicate ongoing climate change in the growing extremes of fire size and area burned within the study area, despite ever-increasing suppression efforts and expenditures [84, 85]. The increase in the area burned by large fires observed in this study is associated with changes in climate that promote more severe fire weather [86], which may result in rapid fire growth prior to the initiation of suppression actions [87, 88]. The relationship we observed between annual climate variables and reburning, as well as overall trends of increasing fire severity and reburn occurrence, suggest that fire managers will increasingly face weather conditions that enable fires to spread through fuel-limited and low-flammability areas. For example, in 2019, a drought-driven fire in northern Alberta (near and within the communities of High Level and Paddle Prairie) burned a vast (322 373 ha) area of boreal forest consisting of low-flammability broadleaf trees and wetlands. Such occurrences challenge fire management tactics and our understandings of what is 'normal', as recent wildfires and broadleaf forests may no longer function as 'safe zones' or barriers to spread [87, 89].

5. Limitations

This work did not account for some fire regime drivers, such as fuel accumulation over time due to fire suppression and land-use change [90, 91], or changing patterns of ignition sources (e.g. lightning) [92]. Other research shows that the length of the fire season has grown over time [93, 94], but this was not specifically examined in this analysis. It is likely that these factors also affected the fire regime changes we documented, in conjunction with climatic changes; however, the significant correlations and path analysis we conducted do indicate a strong role for climate change in driving the observed fire regime shifts. It is plausible that if we had examined daily fire weather rather than annual climate it would have provided additional insight into wildfire dynamics occurring at finer timescales (e.g. minutes to hours), beyond the scope of this work [95].

6. Conclusion

Over the past 50 years, the climates of western North America have become significantly warmer and drier, associated with concurrent measurable changes in the local fire regime. We detected significant increases in the number of large fires, AAB, and AAB at high severity, as well as increasing fire severity in some forest types. We also found a significant increase in the occurrence of and area burned by short-interval wildfires over the past 30 years. These fire regime changes corresponded to shifts in climate, as indicated by significant correlations and a confirmatory path analysis, adding to evidence that climate change has already altered North American fire regimes [24], acting as a top-down driver of fire occurrence in northern forests [63].

Boreal forests of the study area have historically demonstrated strong resilience to wildfire, with post-fire vegetation predominantly resembling the pre-fire forest composition and structure. As altered post-fire climates and increasing climate-driven fire disturbance interact, it is plausible that their cumulative effects will push forests past a tipping point where a resilient ecosystem response is no longer possible, due to mis-match between fire regime and plant adaptations to fire [96], as observed in conifer forests throughout North America [20, 97, 98]. Fire regime changes such as those documented here promote open broadleaf-dominated forests at the expense of the dense conifer forests that are currently characteristic of this region and offer important habitat for animals such as woodland caribou [71, 78], as well as timber for forestry [1]. Modelling suggests that such vegetation changes would likely be persistent, particularly where they are reinforced by climate-driven increases in fire activity [99, 100]. Fire and forest managers face significant challenges as the fire regime of this region shifts from one that increasingly promotes frequent, severe, and large fires. Such changes may be temporary if fuel-limitation effects or increases in precipitation offset increasingly severe fire weather; however, a transition period while fuel remains abundant could be a volatile time for fire risk [101, 102]. As warming continues, it is likely that the associated changes in fire regimes will in fact persist and accelerate, as indicated by the existence of non-linear trends.

Data availability statement

No new data were created or analysed in this study.

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