Emergence of anthropogenic fire regimes in the southern boreal of Canada

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Abstract

While radiative forcing and thus land surface temperatures have been shown to positively correlate with fire severity, precipitation, and lightning strike frequency, the effects of human activity on fire regimes remain difficult to disentangle from geophysical drivers given co-variation between these factors. Here, I analyze fire regimes in the 1919-2012 period across Canada and compare national trends to those of a latitudinal and elevational gradient in a region experiencing exponentially increased anthropogenic activity in recent decades. Located along the Canadian Rocky Mountains, the region is intended to serve as a proxy for future continental conditions under current anthropogenic trajectories. Based on the findings, I argue that, for the first time in millennia, fire regimes in the southern boreal zone have shifted on average from large, lightning-caused fires to frequent, small, human-caused fires adjacent to human transportation corridors. While warming is known to produce more severe fuel conditions, human factors such as frequent fire ignitions, active fire suppression, industrial and recreational activity, and forestry (i.e., stand aging) likely explain the reduction in mean fire size and annual area burned. Here, I provide the first evidence of a southern boreal transition to Anthropocene fire regimes without historical analogue, representing a dramatic departure from the conditions in which these forests evolved. With ~28 Pg carbon stored in Canada’s managed forests and interspecific variation in albedo, these novel fire regimes carry direct implications for the Earth’s climate system.

Introduction

The evolutionary history and paleorecord of North America's boreal forests reflect millennia of cold, dry, and fiery conditions (Gavin et al., 2007; He et al., 2012; Hu et al., 2006; Kelly et al., 2013; Tinner et al., 2008). Global change in the Anthropocene (Crutzen and Stoermer, 2000) has shifted each of these three conditions. Over the past half-century, boreal forests warmed at twice the rate of the global mean (Intergovernmental Panel on Climate Change, 2014). In southwestern Canada, recent climatic change produced warmer and wetter conditions, significantly reduced snowfall, and related reductions in cryomass (Intergovernmental Panel on Climate Change, 2014), or total mass of surface and ground water in a frozen state. Warming is projected to accelerate in the near-term (Smith et al., 2015), with the highest rates of warming expected to occur in mountainous regions (Miller, 2013) and higher latitudes. The northernmost regions are experiencing the most severe temperature extremes of the past 600 years through polar amplification (Miller, 2013; Tingley and Huybers, 2013).

The North American boreal is projected to migrate northward under warming, inducing a net terrestrial loss of carbon storage (Koven, 2013; Scheffer et al., 2012). At lower elevations and latitudes, extant tree species are expected to regenerate less frequently following disturbance under warming, due to an increased frequency and magnitude of physiological drought (Barichivich et al., 2014; Intergovernmental Panel on Climate Change, 2014; Nitschke et al., 2010). Together, changes to regeneration and fire regimes may explain diminished recruitment rates observed for Canada in recent years (Boisvert-Marsh et al., 2014; de Lafontaine and Payette, 2011; Zhang et al., 2015). A reduction in area burned, without a compositional shift toward deciduous trees, may further accelerate warming through reduced albedo (Amiro et al., 2006).

Large stand-replacing fires have characterized circumpolar boreal forests for millennia, reflected in the fire-resisting, -avoiding, and -embracing evolutionary strategies of the resident tree species (Kelly et al., 2013; Rogers et al., 2015). Changes to fire regimes carry particular importance in the North American boreal, where fire has been shown to regulate carbon flux (Bond-Lamberty et al., 2007), energy partitioning (Amiro et al., 2006), compositional change, and tree migration (de Lafontaine and Payette, 2011; Gavin et al., 2013). Warming has increased the severity of fuel conditions in the boreal by increasing evaporative demand (Barichivich et al., 2014; Intergovernmental Panel on Climate Change, 2014) and permafrost thaw (Baltzer et al., 2014; Camill, 2005), accelerating carbon loss through an increased depth of ground-layer burning, particularly for peatlands (Turetsky et al., 2011, 2015).

Recent burn rates for the North American boreal have been reported in excess of Holocene (~11.7 kybp) fire regime limits (Kasischke and Turetsky, 2006; Kelly et al., 2013; Marlon et al., 2013). The global area burned rapidly accelerated with the Industrial Revolution before declining over the past century (Marlon et al., 2008, 2013). Unprecedented high burn rates (short fire rotation periods) are evident for the Alaskan boreal in recent years (Kelly et al., 2013; Turetsky et al., 2011). Yet, Alaska shows little agreement with other regions of the North American boreal. The eastern Canadian boreal shows a fire frequency and biomass burning maximum ~ 4.5 kybp and a steady decline thereafter, currently at a 7,000-year low, due to decreased insolation, shorter fire seasons, and increased precipitation (Marlon et al., 2008, 2013).

More recently, early season warming has produced an increase in spring fire size, with variation in fire patterns attributable to climate-related water table changes and post-glacial topography (Ali et al., 2009, 2012). Regions of the western Canadian boreal similarly show declines in area burned linked to increased precipitation over the past century (Meyn et al., 2013). These studies indicate that co-varying patterns of solar radiation, temperature, precipitation, physiological drought, and human activity explain global variability in the area burned, with human activity playing an increasingly important role post-industrialization (Marlon et al., 2008). The critical role of human activity is shown by a recent analysis of global burned area (Andela et al., 2017). While short-term efficacy of fire suppression was shown for Alberta (Cumming, 2005), long-term efficacy remains poorly understood.

In Scandinavia, boreal fire regimes shifted to their present state in the 17th century due to increased human activity (Niklasson and Granström, 2000). In Niklasson & Granström (2002), the fires-per-unit-area-time metric was used to indicate physical energetic constraints in the configuration of fire regimes, based on fire frequency, size, and area burned per unit time, following research on phase transitions in the classical Forest Fire Model (Drossel and Schwabl, 1992; Malamud et al., 1998). A recent analysis of global fire regimes supports the presence of both physical energetic constraints and human-dominated fire regimes (Archibald et al., 2013). Archibald *et al.* (2013) estimated energetic constraints from an expanded feature set that includes fire frequency, size, intensity, season length, return interval, and area burned per unit time.

Similar to Niklasson & Granström (2000), Archibald *et al.* (2013) demonstrate that fire frequency and size are inversely proportional for a given area burned per unit time. Fire frequency strongly regulates fire intensity, while areas with shorter fire return intervals have higher area burned per unit time. Longer fire seasons are related to higher human activity levels, although difficult to uncouple from anthropogenic warming. Maximum fire size is characterized by exponential decay and has a logarithmic relationship with area burned per unit time that quickly approaches an asymptote (Archibald et al., 2013).

These findings reflect fundamental relationships between fire, climate, vegetation, and human activity, supporting the theory of dual energetic controls (fuels and weather) on area burned per unit time along productivity gradients (Archibald et al., 2013; Meyn et al., 2007, 2010). These studies also indicate that human activity poses a third fundamental energetic constraint on fire regimes in the Anthropocene, alongside fuels and weather. Human activity may explain recent changes to fire regimes in actively managed forests of southwestern Canada by providing greater energetic inputs (ignitions), producing many small fires near human hotspots, while reducing energy stores and spread potential (harvest, fuels management, and fire suppression). These past-century changes to management are hypothesized to be evident in the historical fire record.

Following pan-boreal (Bradshaw et al., 2009; Laurance et al., 2014) and regional trends (Braid and Nielsen, 2015; Linke and McDermid, 2012), previous work has shown that increased economic development in western Alberta expanded the road network into formerly remote areas, facilitating increased access and use for economic and recreational purposes. Expanded human activity is further evident in an increase in other linear features, such as oil and gas pipelines, seismic lines, and power lines, as well as point features including one-hectare well-sites (Linke and McDermid, 2012). While a number of studies have assessed disturbance patterns here (Forest et al., 2008; Laberee et al., 2014; Nielsen et al., 2008), existing studies do not explain the drivers of long-term disturbance variability critical to predicting future patterns in simulation studies. Existing datasets may contain valuable information for discerning relationships in space and time between human activity and fire, necessary for simulating disturbance-related changes to understory solar irradiation. In the following sections, the effects of past-century warming and increased human activity on fire regimes are assessed.

Materials and methods

Here, changes in the statistical patterns of historical wildfire data across western Alberta and Canada are analyzed. The analysis focuses on climatic and anthropogenic changes to fire, including variation in elevation, latitude, cause, size, frequency, and area burned along multiple temporal resolutions, including annual, seasonal, monthly, and daily intervals. Fire seasons were calculated as meteorological quarterly seasons. The analysis is structured to focus on proxies of climatic change and human activity, based on known historical changes and the findings of previous studies in the region. Although there exists significant variation in fire regimes across Canada, national fire patterns provide a baseline for separating regional variation from overall trends.

For the regional analysis, three data sources were used: the latest Canadian National Fire Database (NFDB) fire perimeter data, NASA Shuttle RADAR Topography Mission (SRTM) version 2 data processed using standard correction techniques (Reuter et al., 2007), and Natural Regions and Subregions of Alberta for the biogeoclimatic zones (Natural Regions Committee, 2006). The data were subset to western Alberta and zonal statistics calculated for the minimum, mean, and maximum elevation, as well as slope and aspect for each fire. The latitude and longitude for each fire centroid was also calculated. The NFDB contains many relevant fire attributes including the year, month, day, cause, source, and size. Using the year, month, and day values, the ordinal date and season of fires were calculated. Using values for the elevation, latitude, and ordinal date of each fire, foliar moisture content (FMC) was calculated for each fire. To calculate FMC values, standard equations were applied from the Canadian Fire Behavior Prediction (FBP) System (Hirsch, 1993).

Fire rotation period (FRP), or fire cycle, is a commonly applied metric to indicate the rate of burning, with lower values indicating greater severity (Wagner, 1978). FRP is the average time required for the sum of fire sizes within an area to equal the area in size, calculated over a given time interval. FRP is often presented alongside the mean fire return interval (MFRI), the average time interval between fires for a given area or site, as well as time-since-last-fire.

$$FRP = \text{time interval} / (\text{sum of fire sizes burned in area} / \text{area size})$$

$$MFRI = \text{time interval} / \text{number of fires in site or area}$$

Hence, FRP is the area-normalized MFRI. Applied to individual sites, FRP is equal to MFRI. By normalizing for area, FRP provides more information about fire regimes at scales greater than the individual site. MFRI values calculated for areas of different sizes are not directly comparable, unless normalized for area, which yields FRP. FRP is applied in the historical fire regime analysis. While other changes in the distribution of fires provide additional information, FRP provides a single robust metric for fire regimes.

Fire size distributions were analyzed to detail variation in western Alberta and national patterns, as well as changes to fire regimes between periods. This work follows a study on lightning-caused fires in the boreal mixedwood region of Alberta, using the former LFDB (Cumming, 2001) that showed that fire models should use a truncated exponential distribution to prevent over-predicting large fires. Here, a Weibull distribution was fit to log-transformed fire sizes. A right-tail Anderson-Darling maximum-goodness-of-fit estimation was used to adjust for power-law behavior at the tail of the distribution. Hartigan's dip test was used to test for bimodality. The expectation-maximization (EM) algorithm and Bayesian Monto Carlo Markov

Chain (MCMC) simulations were used to fit a mixed normal distribution. Changes to fire size distributions were confirmed by Kullback-Leibler divergence and the Earth Mover's Distance (EMD), or Wasserstein metric, commonly used for comparing empirical probability mass functions (Gottschlich and Schuhmacher, 2014).

Fire regimes were temporally segmented using the binary segmentation algorithm (Scott and Knott, 1974). While other change-point detection algorithms were tested, including pruned exact linear time (Killick et al., 2011), e-divisive (Matteson and James, 2013), and e-divisive with medians (James et al., 2014), binary segmentation showed optimal sensitivity to small variations in the given task. Thus, binary segmentation was applied to classify fire regime periods. First, fire regime periods were classified with *a priori* knowledge on changes to management and climate. Periods of 30 years are used for compatibility with studies using 30-year climate normal data. The four *a priori* fire regime periods are as follows: Pre-Suppression (1923-1952); Early Suppression (1953-1982); Global Change (1983-2012); and, overlapping the Global Change period, the Most Recent Decade (2003-2012). The Global Change period corresponds to an acceleration of global change conditions (Steffen et al., 2007). The most recent decade is included to represent recent trends independent of the three 30-year periods.

Software used to conduct this work includes ArcGIS 10.2 for spatial analysis, ENVI-IDL 5.2 for processing synthetic aperture RADAR data, R 3.1 for statistical analysis, and Python 2.7 for automation. The *seas* package for R was used for date-time conversion (Toews et al., 2007), while the *fwi.fbp* package for R was used to calculate FMC values (Wang et al., 2014). The *changepoint* (Killick and Eckley, 2014), *ecp* (James and Matteson, 2015), and *BreakoutDetection* (James et al., 2014) packages for R were used to test change-point algorithms for classifying fire regime periods.

Results

Across the full 90-year period in western Alberta, mean, maximum, and minimum fire sizes declined. Fire frequency initially declined at an inflection point near 1950 before increasing rapidly since approximately 1990. On average, over the 90-year period, fires declined in size by 142.6 ha per year, annual area burned declined by 3,450 ha per year, and fire frequency increased by 5.44 fires per year (Figure 1).

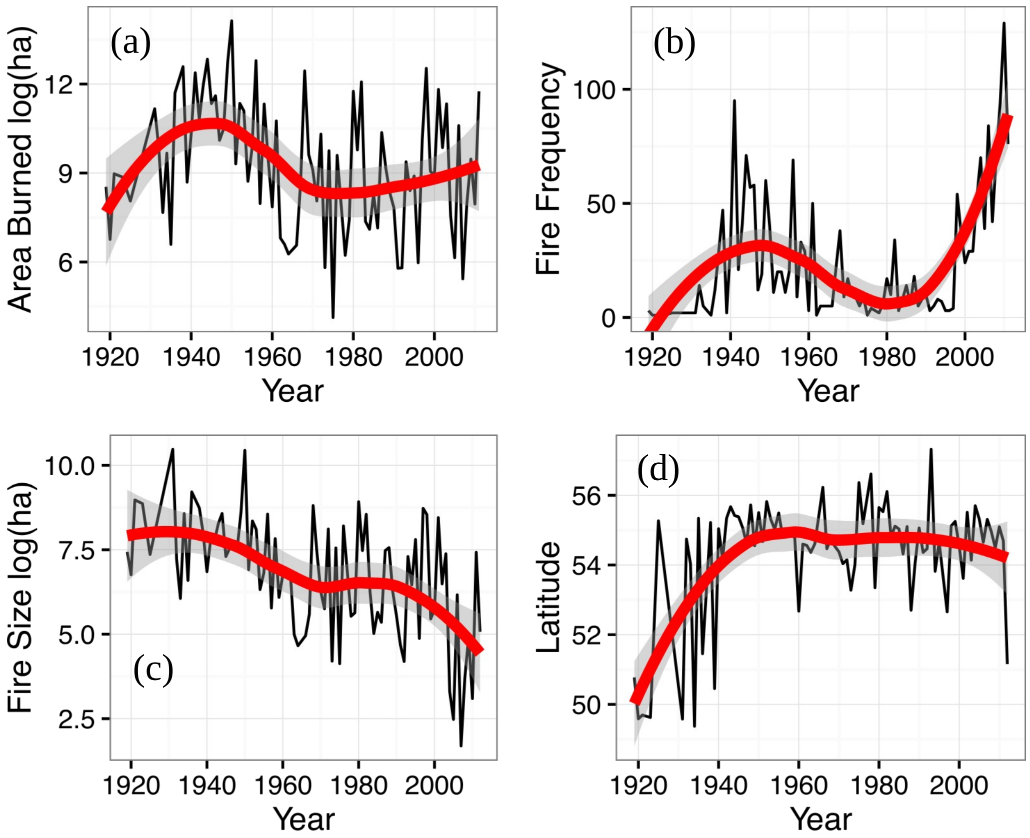

Figure 1. Mean annual trends for fires along western Alberta, 1919 to 2012: (a) log of area burned; (b) fire frequency; (c) log of fire size; (d) latitude in WGS84 (decimal degrees) coordinates; loess smoothing with 95% confidence interval shown

In western Alberta, comprised predominantly of boreal forests, an inflection point in fire regimes is apparent near 1970, with patterns in area burned, mean fire size, and mean fire latitude changing thereafter; a rapid rise in fire frequency began a decade later (Figure 3.1). The abruptness of the ~ 1970 and 1990 inflection points suggest a change in management, the former potentially linked to an increase in oil and gas development in the boreal known to occur at the time. An observed linear decrease in area burned and increase in fire frequency was independent of elevation (high-elevation mean = -4607 ha/year, +3.3 fires/year; low-elevation mean = -29643 ha/year, +2.2 fires/year) and latitude (high-latitude mean = - 31211 ha/year, +3.0 fires/year; low-latitude mean = - 3039 ha/year, +2.4 fires/year), based on median fire elevation and latitude. FRP increased by 298% between the Pre-Suppression (1923-1952) and Global Change (1983-2012) periods, indicating a three-fold reduction in fire regime severity during a period of warming (Intergovernmental Panel on Climate Change, 2014).

FRP increased by 166% between the Pre-Suppression and Early Suppression (1953-1982) periods, before increasing by another 50% between the Early Suppression and Global Change periods. FRP in the Most Recent Decade (2003-2012) reflects patterns of the Global Change period it overlaps, shorter by 0.1% at 923.9 years (Table 4.2). However, Most Recent Decade fires were approximately twice as frequent and half the size of Global Change period fires (*MFRI* Δ = -45%; annual *frequency* Δ = +82%; *MFS* Δ = -43.3%). The stability of FRP values between the Global Change and Most Recent Decade periods is indicative of the temporal depth of past-decade trends (Table 1).

Table 1. Fire regime statistics by period for western Alberta; mean fire return interval (MFRI) is shown in years for the full region rather than the mean site value, where Burned = 1 / MFRI * MFS * Years; FRP = Area / Burned * Years

Period	**Burned (ha)**	**Area (ha)**	**Fire Rotation Period (FRP, years)**	**Mean Fire Return Interval (MFRI, years)**	**Mean Fire Size (MFS, ha)**
1923-1952	3,224,691	24,972,634	232.3	0.011	1,148.4
1953-1982	1,211,806	24,972,634	618.2	0.020	811.1
1983-2012	809,967	24,972,634	925.0	0.020	545.1
2003-2012	270,287	24,972,634	923.9	0.011	308.9

Differences in the mean and variance of fire size between Early Suppression and Global Change periods were not statistically significant at a *p*-value threshold of 0.05 ($t = 1.69$, *p*-value = 0.09; $F = 1.19$, *p*-value = 0.06). Area burned declined substantially between these periods ($Burned_{ES}$ = 1,211,806 ha, $Burned_{GC}$ = 809,967 ha, Δ = -33.1%), even though remote monitoring improved. While MFRI remained stable across the Early Suppression and Global Change periods ($MFRI_{ES}$ = 0.0201, $MFRI_{GC}$ = 0.0202, Δ = +0.5%), mean fire size (MFS) declined at a rate equivalent to that of area burned (MFS_{ES} = 811 ha, MFS_{GC} = 545 ha, Δ = -33%). Thus, a decline in mean fire size best explains the reduction in area burned under warming in wester Alberta. This is particularly evident in the Most Recent Decade, where FRP (area burned) was similar to the Global Change period it overlaps (Δ = -0.2%) as MFRI (fire frequency) increased by 81.8%.

In western Alberta, the ratio of human- to lightning-caused fires increased from 0.93:1 to 1.39:1 (+33%) between the 1970s and 2000s. A spatial analysis of historical ignitions in western Alberta using NFDB point data demonstrates the proximity of small fires to areas of human activity, typically major roads and river valleys (fire distance from roads: mean = 2.2 km, standard deviation = 4.8 km; fire distance from roads or surface water: mean = 297 m, standard deviation = 363 m), supporting a human origin (Figure 2).

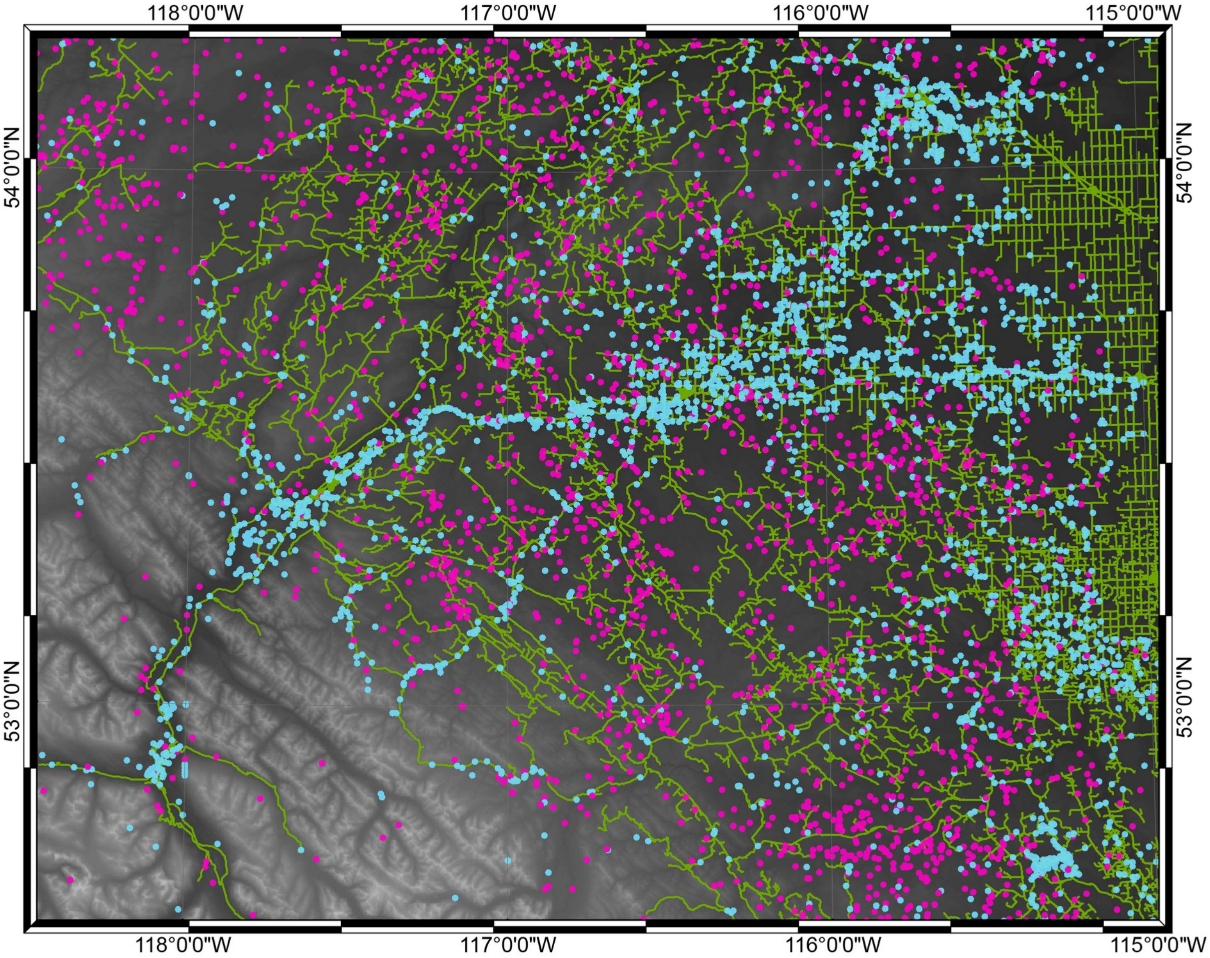

Figure 2. Fire adjacency to roads by cause overlaid on SRTM 90 m elevation data in the vicinity of Hinton, Alberta in NAD83 UTM 11N coordinates with WGS84 graticules: light blue = human-caused; magenta = lightning-caused; green = roads; top = north

Between the 1980s and 2000s, as Alberta's population doubled, the mean distance of fires from roads declined by 40%, from 2.3 to 1.4 km. The mean distance of fires from roads or surface water (rivers and lakes; proxies of human activity) declined by 32% across the same 30-year period, from 318 to 216 meters. Concurrently, annual fire frequency increased by 33%, from 6,035 to 9,054 fires, in the point data. The increasing influence of human activity in Alberta's fire regimes is apparent in the percentage of the total area burned attributable to sources over the past three decades (Figure 3).

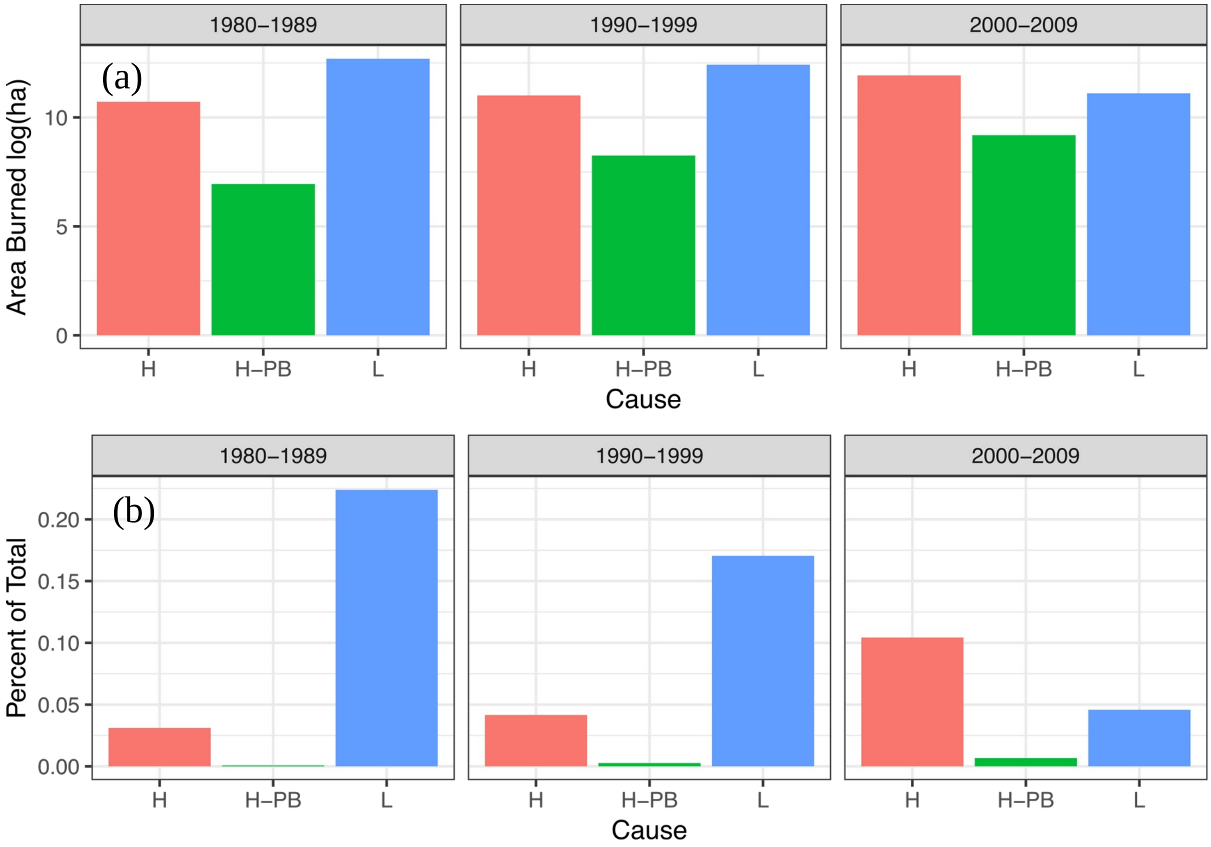

Figure 3. Decadal area burned by fire source for western Alberta; (a) absolute area burned (ha); (b) percent of total area burned (ha); most fires were unknown in origin (not shown); H = human-caused; H-PB = prescribed burn; L = lightning

A decline in the relative influence of lightning on the total area burned in Alberta was offset by an increase in the percentage of area burned explained be human-caused fires. Between the 1970s and 2000s, the area burned increased by 34% in summer, fire frequency increased in spring and summer, and mean fire size increased by 83% in fall and 60% in spring for western Alberta (Tables 2a and 2b).

Table 2a. Fire regime change by season

Season	**Area**	**Number**	**Mean Size**
Spring	-6.8%	+13.5%	-60%
Summer	+7.6%	+1%	+16.6%
Fall	-2.2%	-18.2%	+82.9%

Table 2b. Current fire seasonality

Season	**Area**	**Number**	**Mean Size**
Spring	63.2%	51.2%	123%
Summer	33.8%	39.2%	86%
Fall	2.4%	6.8%	35%

An analysis of fire seasonality related to the 'spring dip' in foliar moisture content (FMC) using standard formulations from the Canadian Fire Behavior Prediction System (Forestry Canada Fire Danger Group, 1992; Wotton et al., 2009), shows that the standard FMC equations are not suitable for western Alberta. Here, the modeled spring dip in FMC occurs approximately two months after the peak in fire frequency and size (Figures 4a and 4c) that likely corresponds to the true spring dip (Alexander and Cruz, 2013; Tymstra et al., 2007). The log of fire size shows the strongest density at 138 DOY (late April), followed by a second peak ~ 1 week later at a substantially larger fire size (Figure 4a). Meanwhile, modeled spring dip occurs at 200 DOY (Figure 4c). Across the full time period, fires declined in size following a structural change around 1990 (Figure 4b). In recent years, fires were most frequent and concentrated earlier in the season, with longer fire seasons (Figure 4d).

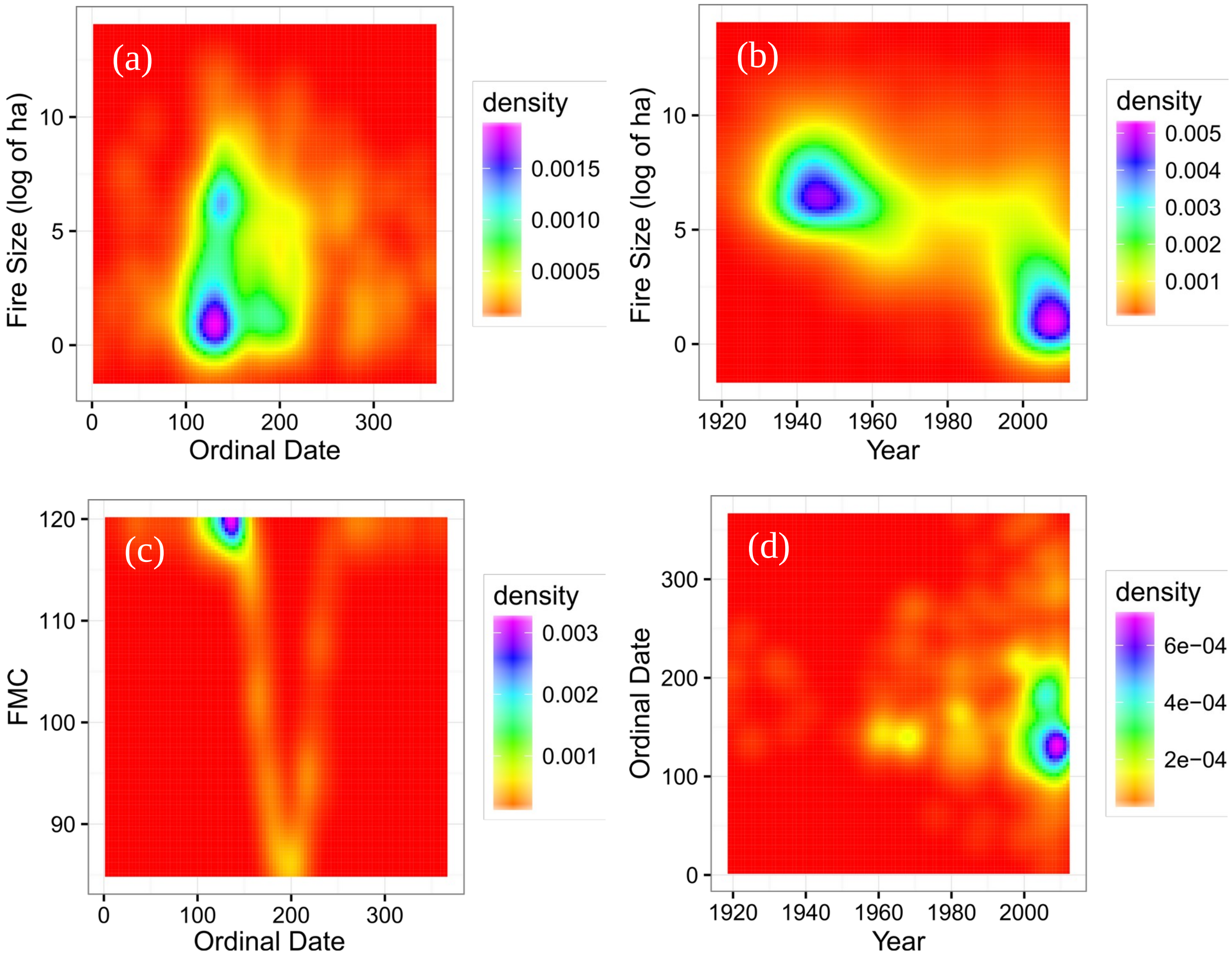

Figure 4. Two-dimensional kernel density estimation for fire frequency by ordinal date and year for western Alberta, 1919 to 2012: (a) log of mean fire size by ordinal date; (b); log of mean fire size by year (c) modeled foliar moisture content (FMC) by ordinal date; (d) fire ordinal date by year

Across Canada, an increasing rate of area burned declined at a similar inflection point around 1990, when mean fire size and latitude declined as fire frequency rapidly increased (Figure 5). Between the 1990s and 2000s, fires nationwide declined in mean latitude at a rate of

14 km/year while fires in western Alberta declined at a rate of 24.4 km/year. Nationwide and in Alberta, lightning-caused fires decreased and human-caused fires increased in mean latitude during the period (nationwide = -6/+1.6 km/year; Alberta = -5.9/+1.5 km/year). Characteristic of the boreal, large lightning-caused fires >= 200 ha increased in mean latitude by 5.4 km/year nationwide and decreased by 10.1 km/year in Alberta. Since 1920, fires >= 200 ha shifted northward at a mean rate of 5.2 km/year ($R^2 = 0.13$; $p < 0.001$) nationally.

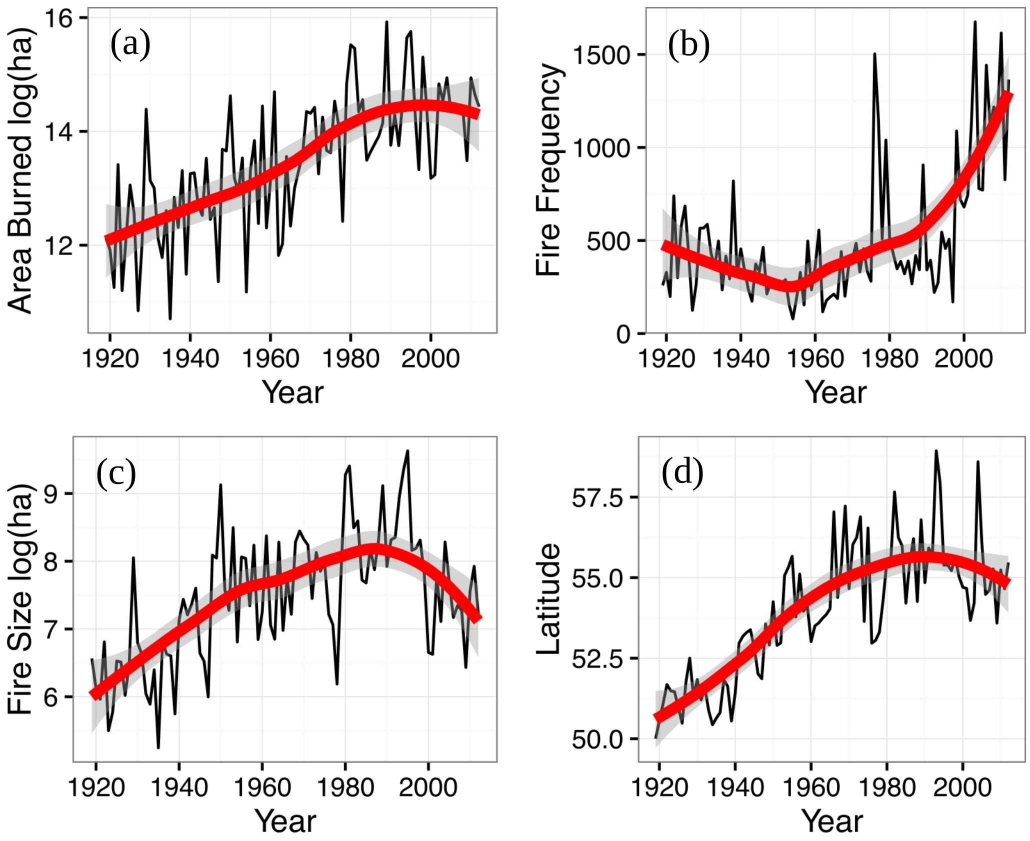

Figure 5. Mean annual trends for fires Canada-wide, 1919 to 2012: (a) log of area burned; (b) fire frequency; (c) log of fire size; (d) latitude in WGS84 (decimal degrees) coordinates; loess smoothing with 95% confidence interval shown; NFDB data prior to 1960 are known to be incomplete

For the *a priori* classification in western Alberta, the Pre-suppression period (1923-1952) is characterized by frequent fires and the largest annual area burned, while the Early Suppression period (1953-1982) shows a sharp decrease in fire frequency and annual area burned, with the lowest overall rates of each. The Global Change period (1983-2012) exhibits a rapid increase in fire frequency but a relatively flat annual area burned. The Most Recent Decade (2003-2012), shows the most rapid increase in fire frequency and the most rapid decline in mean fire size, accompanied by a decline in area burned.

For western Alberta and Canada, fire regime period classification using the binary segmentation change-point detection algorithm produced fire regime periods distinct from the *a priori* classification. In Alberta, based on time-series of annual area burned and fire frequency (Figures 6a and 6b), the algorithm shows an initial fire regime segmentation from the late 1930s to the early 1960s, followed by another regime from the 1960s to the 1990s, and final regime characterized by an increase in fire frequency from the 1990s to 2012. For Canada-wide fires, the algorithm shows little consistency between fire regimes for the univariate annual area burned and fire frequency time-series (Figures 6c and 6d). Nevertheless, the annual area burned time-series shows approximate agreement with the *a priori* classification, with regime periods falling from the early 1920s to ~ 1950, ~ 1950 to late 1960s, 1960s to late 1970s, and late 1970s to 2012.

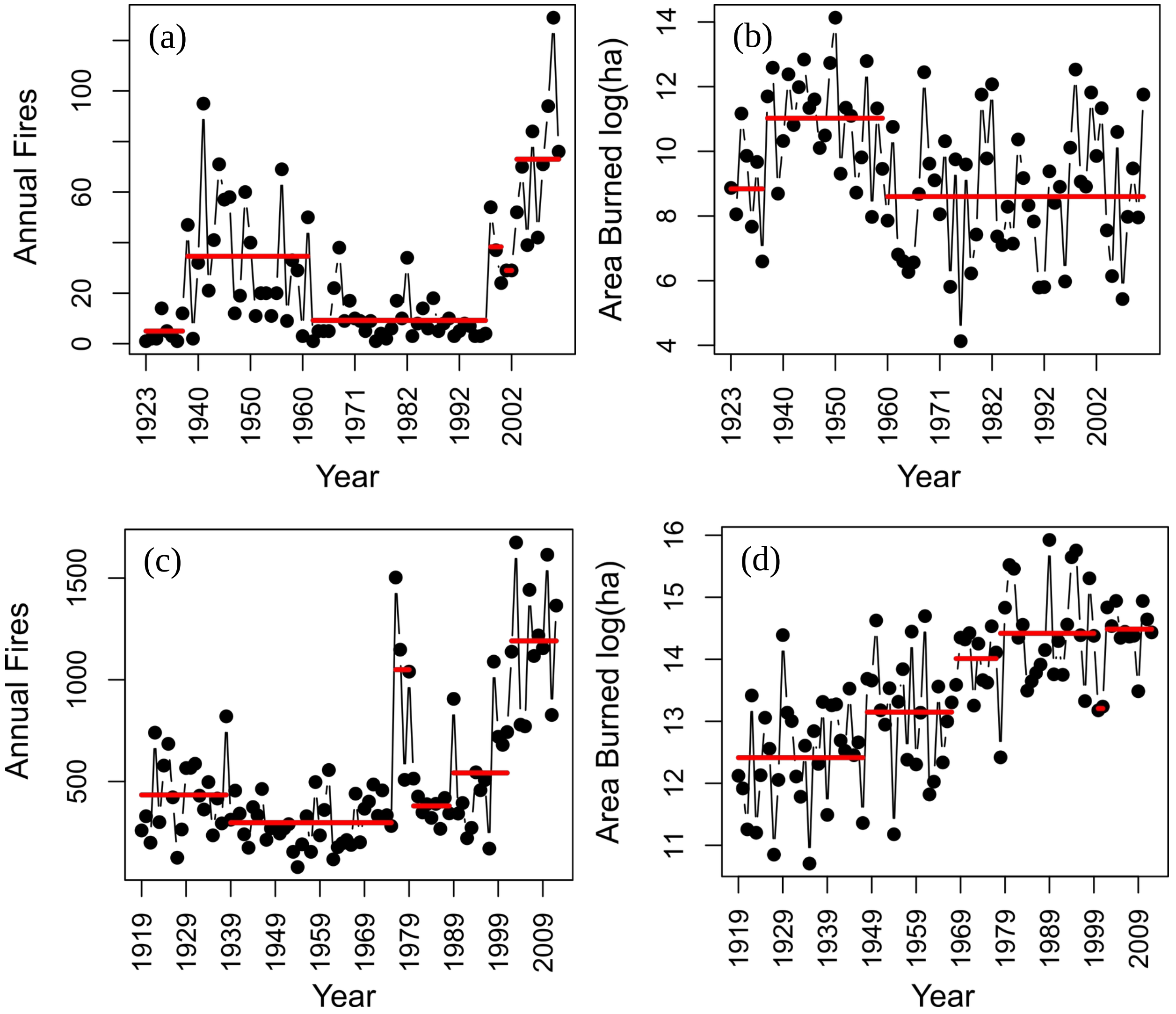

Figure 6. Fire regime change-point segmentation using the binary segmentation algorithm: (a) Alberta fire frequency by year; (b) Alberta total area burned by year; (c) Canada-wide fire frequency by year; (d) Canada-wide total area burned by year

Fire regime periods differed for the two scales. Canada-wide, the 1940s through 1970s were characterized by infrequent fires and a steadily increasing area burned, while the inverse was true for Alberta. Nationwide, the first broad shift in fire regimes occurred during the 1970s with a spike in fire frequency and area burned. Yet, area burned was flat from ~ 1980. In western

Alberta, similar to nationwide patterns, fire frequency increased rapidly beginning ~ 1990. Yet, Alberta showed little change in area burned from 1960 to 2012, despite strong variability within the period (Figure 6).

Over the 90-year period, in western Alberta, fire seasons lengthened by ~ 60 days, or two months (mean = +1.2 days/year), due to more frequent human-caused fires (mean = +9.2 fires/year) earlier and later in the season (Figure 7a). The fire season experienced a lower rate of lengthening nationwide (Figure 7b). At both scales, lightning-caused fires were concentrated in summer, while human-caused fires were concentrated in the spring and fall (Figure 7).

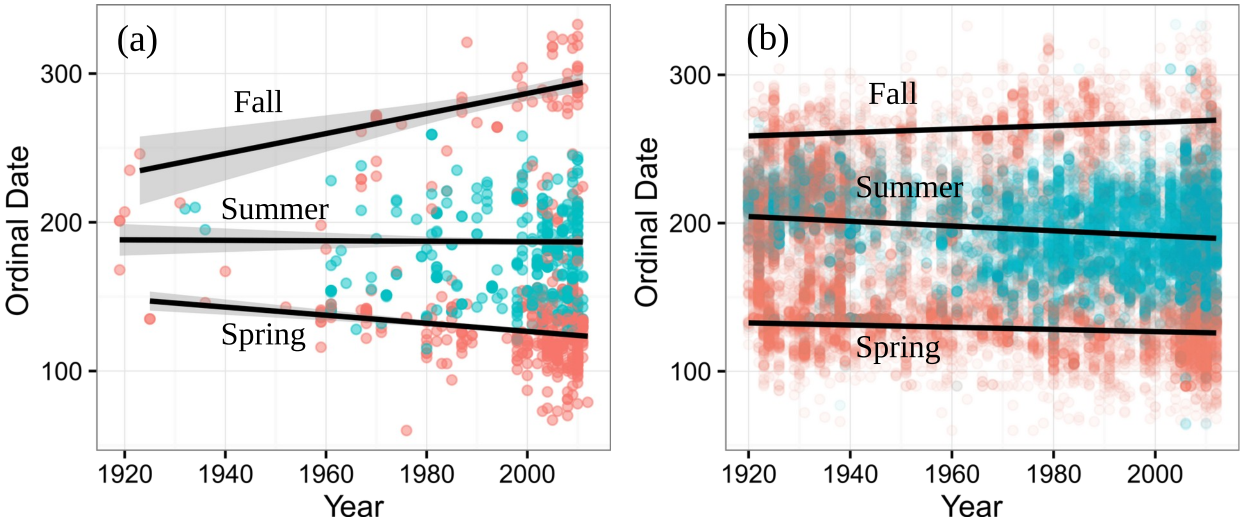

Figure 7. Fire regime patterns nationwide and western Alberta changes in seasonality with linear models and 95% confidence intervals: (a) western Alberta fire ordinal date by year and season; (b) Canada-wide ordinal date by year, season, and cause; salmon = human; aqua = lightning; linear regression with 95% confidence interval shown

Within western Alberta, the largest fire sizes and area burned occurred in the boreal, followed by the foothills and Rocky Mountain regions. Within the boreal region, the lowland mixedwood subregions experienced a greater area burned than the highland subregions. Yet, mean fire size and annual area burned declined in the boreal across the study period. Canada-wide, the log-transformed fire size distribution for fires > 2 ha showed reasonable fit with a Weibull distribution ($K\text{-}S = 0.02$; $\varpi = 1.60$; $A^2 = 27.34$; $AIC = 174679.6$; $BIC = 174696.8$), with fit improving with the right-tail second-order Anderson-Darling (AD2R) statistic due to power-law behavior at the tail. While the distribution of fire sizes nationwide showed unimodality per Hartigan's dip test ($D = 0.003$, p-value = 0.11) despite visual evidence of bimodality, fire sizes in western Alberta showed significant bimodality ($D = 0.02$, p-value = 0.002). Using a mixed Gaussian model for western Alberta fire size, the two modes centered on μ of 1.2 and 6.2 log ha, with Expectation-Maximization (EM) and Bayesian Markov Chain Monte Carlo (MCMC) algorithms each converging to these values. This implies the presence of two dominant fire regime phases in Alberta.

A further analysis reveals distinct changes in the fire size distribution over time. While previous periods showed approximately Gaussian fire size distributions without skew, fires in the Global Change period were strongly skewed toward smaller values. Bimodality of fire sizes for all years in western Alberta is comprised of two distinct components: (1) frequent large fires in 1923-1952; (2) frequent small fires in 1983-2012. The Most Recent Decade showed the second greatest K-L divergence ($D_{KL} = 0.84$, after the Pre-Suppression period ($D_{KL} = 1.05$), and greatest distance from, the fire size distribution for all years, based on the Earth Mover's Distance (EMD) or Wasserstein metric ($EMD = 5.15$). Fire regimes in Alberta thus reached a novel state in recent years.

For Canada, monthly aggregations show mean fire size and total area burned were typically largest in June, followed by July and May. Fire frequency peaked in July, followed by

June and May (Figures 8a – c). These findings are supported by daily resolution data. Given increased temporal resolution, Gaussian and splines models indicate a typical fire frequency peak between 184-185 DOY, mean fire size peak between 172-178 DOY, and area burned peak between 171-178 DOY (Figures 8d – f). The splines models shows early season spikes in fire frequency and areas burned corresponding with the ‘spring dip’ in foliar moisture content indicated in Figure 3.4c – a sharp early season increase in the frequency and size of fires (Van Wagner, 1967) – as well as a skewed fire frequency distribution. The log of mean daily fire size centers at ~ 5.5 ha, while the log of mean daily area burned centers at ~ 6.5 ha. The log of daily fire frequency shows a negative exponential distribution with a large λ value (Figures 8g – i). This matches the typical model for the probability distribution of time-since-event for Poisson processes, such as the probability of fire events, as in LANDIS-II (Sturtevant et al., 2009; Yang et al., 2004).

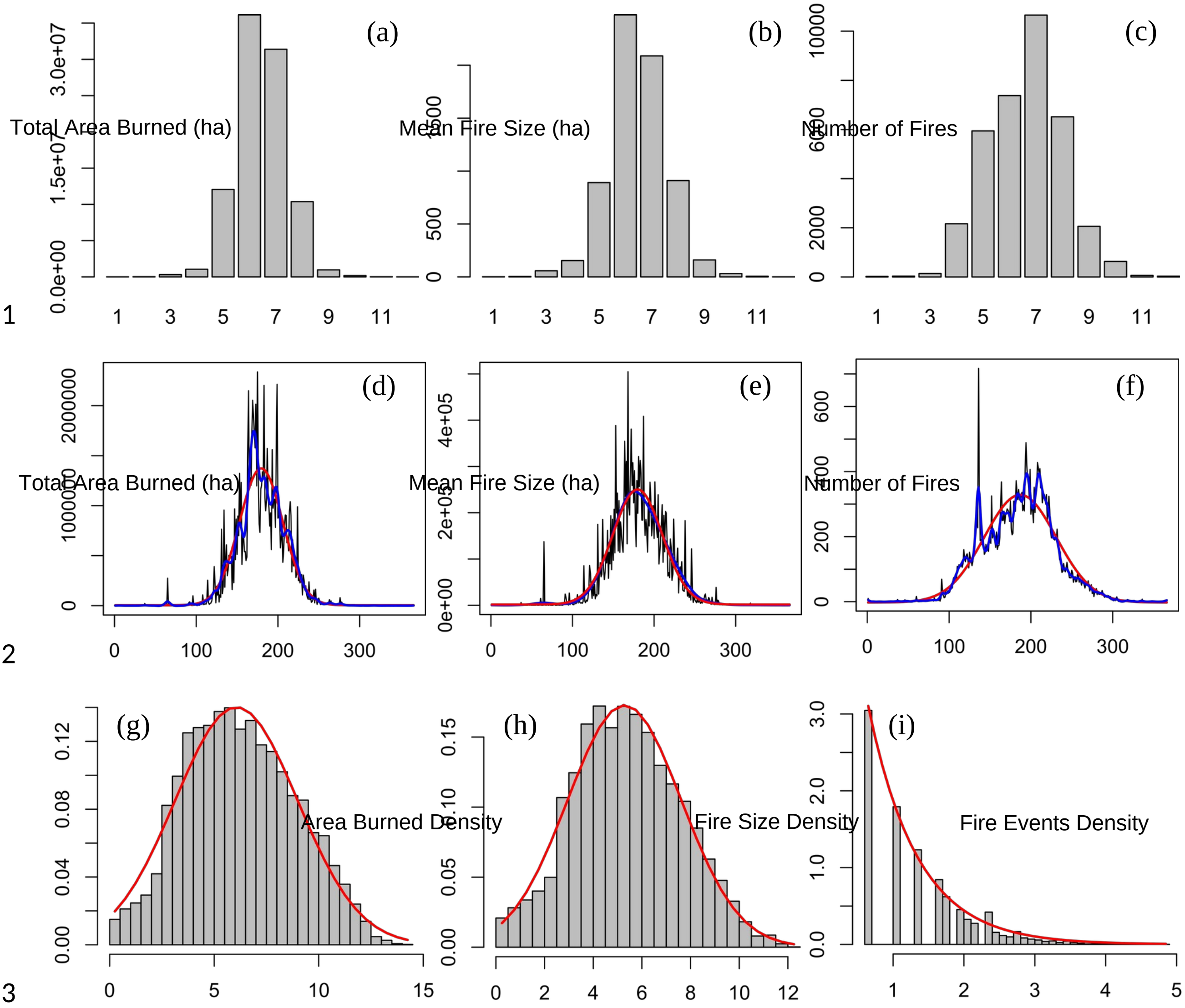

Figure 8. Monthly and daily patterns of fire frequency, mean fire size, and total area burned Canada-wide: (a) total area burned by month; (b) mean fire size by month; (c) fire frequency by month; (d) total area burned by ordinal date; (e) mean fire size by ordinal date; (f) fire frequency by ordinal date; (g) log of daily area burned; (h) log of daily mean fire size; (i) log of daily fire frequency; recorded fire detection dates are used to calculate DOY values; blue and red lines in (d-f) are cubic splines and a Gaussian distribution fit, respectively, while the red line in (i) is an exponential distribution fit

Discussion

The distribution of fire sizes follows well-documented power-law behavior common to self-organizing systems (Malamud et al., 1998; Reed and McKelvey, 2002), showing a heavy-tailed distribution. Previous theoretical work suggested that fire size distributions should fit a truncated Pareto distribution (Strauss et al., 1989). However, an empirical study of the boreal mixedwood region of Alberta, using the former Large Fire Database for 1980-1998, showed optimal model fit with a truncated exponential distribution (Cumming, 2001). The above results suggest that the use of the AD2R goodness-of-fit statistic yields reasonable model fit with a Weibull distribution for the logarithm of fire sizes.

The results illustrate that western Alberta experienced a sharp rise in human-caused fires and area burned since 1990. This rise in human-caused fires likely combined with warming to facilitate lengthening fire seasons in both early spring and late fall (spring mean = +0.26 days/year; fall mean = +0.67 days/year; $R^2 = 0.83$; $p < 0.001$), in agreement with previous observations (Kasischke and Turetsky, 2006; Stocks et al., 2002). The combined lengthening of fire seasons by 0.93 days/year is approximately five times faster than the Canada-wide average of 0.2 days/year (spring mean = +0.07 days/year; fall mean = +0.13 days/year; $R^2 = 0.57$; $p < 0.001$). This difference in fire season lengthening rates is likely attributable to rapidly increasing human activity in western Alberta, as well as data sparsity in early years. From the 1970s to the 2000s, human-caused fires accounted for a growing proportion of both annual fires (+9.8%) and area burned (+38.9%) for fires of known cause.

While the majority of area burned continues to be produced by lightning-caused fires nationally, this work observed a southern boreal shift to human-driven regimes characterized by more frequent, smaller fires near human activity earlier and later in the year. Climatic warming and a growing human presence are combining to create longer fire seasons, known to have challenged managers in recent years (Tymstra et al., 2007). Fire frequency, area burned, and mean fire size were greatest in spring for all regions, representing 51% of fires and 63% of area burned, except the Rocky Mountain region, where fire frequency and size are greatest in summer due to temperature constraints. The largest fires occurred in May, consistent with a ‘spring dip’ in foliar moisture content. Although this episodic decline in foliar moisture content remains under investigation (Jolly et al., 2014), it is an important physiological phenomenon in these forests (Alexander, 2010; Finney et al., 2013; Jolly et al., 2014; Little, 1970). Spring dip typically corresponds to intense crown fire activity, producing the largest and most severe fires of the fire season, which these data support.

Boreal fire regimes appear to be tracking a northward shift of boreal climatic conditions (Koven, 2013), reducing the size and severity of fires in western Alberta, as southern boreal ecosystems transition to Anthropocene fire regimes. Data from southeastern Canada indicate that the in-migration of temperate species into the southeastern reaches of the American boreal is already underway (Fisichelli et al., 2014). Fisichelli *et al.* (2014) proposes that the reduced size of boreal fires, despite warming, is attributable to four key factors: (1) reduced surface fuel loads from frequent small human-caused fires; (2) increased fire suppression; (3) reduced crown fuels and/or forest fragmentation due to extractive industry activities; (4) a northward shift of boreal climatic conditions, evidenced by changing wildfire patterns and climate-analogue vectors (Koven, 2013).

A recent study shows demographic ageing for the region (Zhang et al., 2015), which may further reduce surface fuels prior to gap formation and understory reinitiation. Previous studies argue little effect of fire suppression on fire regimes in boreal and subalpine systems, as fuel moisture shows greater importance than fuel load in models, while neither fire frequency nor crown-fire potential were correlated with stand age (Johnson et al., 2001). Nevertheless, a shift toward more frequent and smaller fires is evident for fire suppression regions (Kasischke and Stocks, 2000). Subsequent analyses of Ontario and Alberta provide contrasting views on the effectiveness of fire suppression in Canada (Bridge et al., 2005; Cumming, 2005).

The increasing extent and magnitude of industrial activity, recreational usage, and road network expansion in formerly remote areas are combining with record temperature anomalies (Kamae et al., 2014) to produce frequent ignitions and small fires around areas of human activity. Harvest operations are widespread in these forests, reducing canopy fuels while providing new ignition sources. A temporal lag of large fires following periodic pulses in pest populations (Kurz et al., 2008) may amplify fuel conditions, fire regimes, and forest transition rates. Increasingly warm and wet conditions may favor deciduous species in the southern boreal (Terrier et al., 2012), producing a negative climatic feedback through increased summer albedo (Amiro et al., 2006) while reducing the rate of fire spread (Dash et al., 2016).

An increase in fire suppression corresponds to an increasing human presence in previously remote forested regions, related to a 619% increase in Alberta's population during the 1921-2011 period (Statistics Canada, 2011) and economic-related extractive industry activity (Cross and Bowlby, 2006). The advent of fire suppression is indicated in the historical record by reduced fire activity in the mid-20th century, following the 1950 Chinchaga wildfire in northwestern BC and western Alberta, the largest recorded wildfire in North American history. The disturbance legacy of this large fire is evident in the fire data, with few fires in its recovery zone since, while surrounding boreal areas have burned frequently. This may partially explain the observed decline in mean fire size, but it does not explain the accelerated decline in recent decades. The mean area burned by fires followed a similar trend, only rising in 1998 at the beginning of an exponential-like increase in fire frequency, as described for other regions of the boreal (Kasischke and Turetsky, 2006; Kelly et al., 2013). Research for Alberta, conducted parallel to this work, selected a similar fire exclusion period start date of 1948, chosen for its correspondence with the establishment of the Eastern Rockies Forest Conservation Board. This work also shows a general lengthening of fire rotation periods compared to historical burn rates (Rogeau, 2016).

While one may infer that increased fire detection by satellites in recent decades (e.g., Landsat and MODIS) explains the observed rapid increase in fire frequency, decrease in fire size, and increase in latitude of large lightning-caused fires during this period, an analysis of the reported detection source rejects this hypothesis. Recent studies elsewhere in the boreal have shown the effect of human activity on fire frequency (Gaglioti et al., 2016). While disturbance detection source or instrument (spaceborne remote sensing versus traditional air and ground methods) shows a statistically significant relationship for fire size ($p < 0.001$) and latitude ($p < 0.001$), it is not enough to explain recent fire regime changes.

Mean decadal fire frequency and area burned show little change due to inclusion of spaceborne remote sensing over the past three decades (Figures 9a and 9b). Only mean fire latitude and size were significantly impacted by detection source (Figures 9d and 9c), with the effect greater for median values; an ANOVA indicates that latitude was more strongly affected than fire size (p = 7.39e-05; p < 2e-16). Since the 1970s, spaceborne detection methods appear to have substituted for traditional methods in northern regions. The mean decadal latitude of lightning-caused fires > 200 ha peaked in the 1970s, prior to broad use of spaceborne monitoring. Large lightning-caused fires were 2 degrees further north on average than fires ⊣| 200 ha, with a maximum of 5.3 degrees higher in the 1970s (WGS84 coordinates).

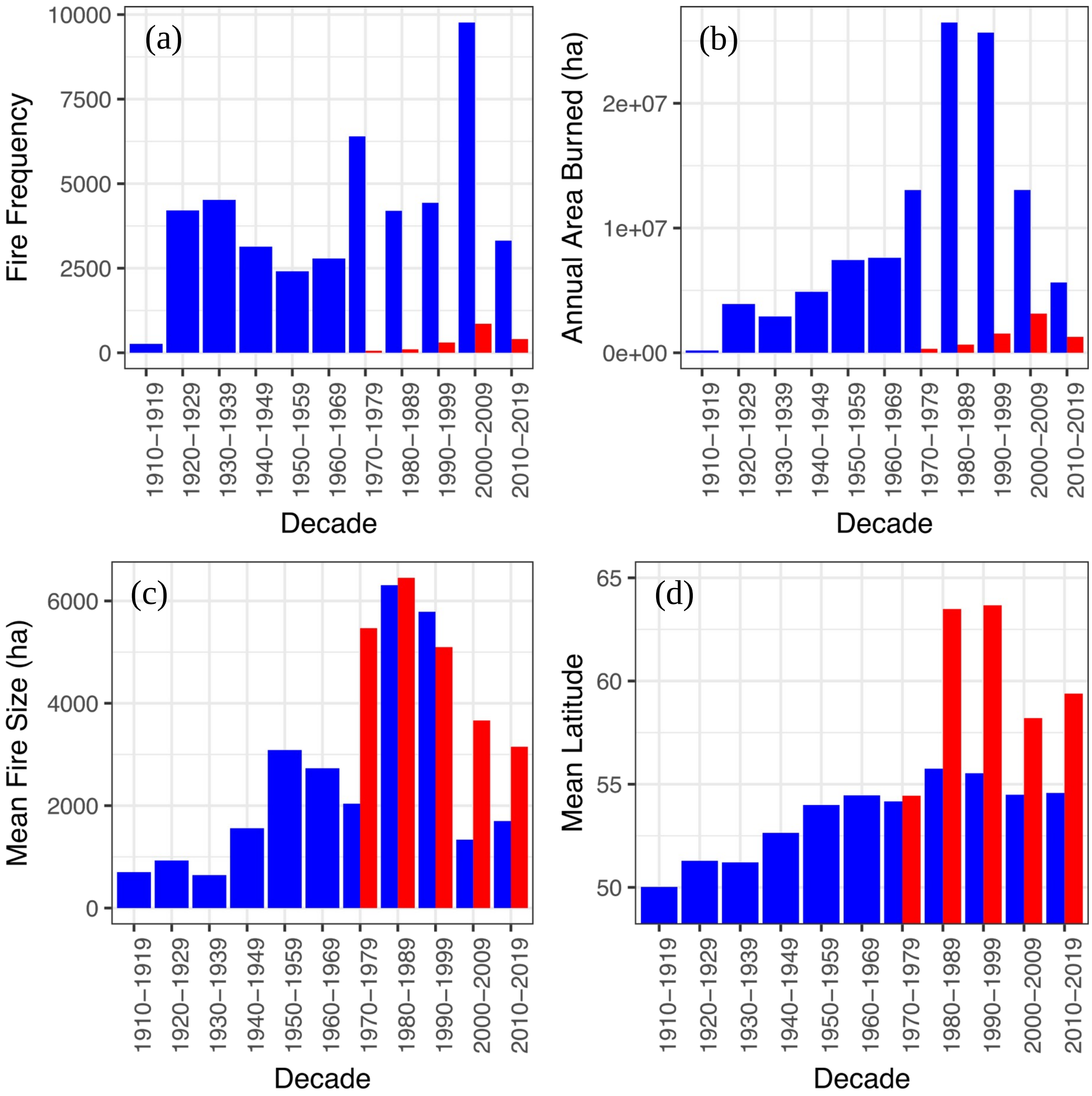

Figure 9. Fire statistics by reported detection source Canada-wide: (a) fire frequency by decade; (b) area burned by decade; (c) mean fire size by decade; (d) mean fire latitude by decade in WGS84 (decimal degrees) coordinates; blue = traditional detection source; red = modern remote sensing instruments

Thus, the contribution of spaceborne instruments to observed fire patterns remains small relative to traditional methods. In the 2000s, spaceborne monitoring was used to detect less than 9% of recorded fires in Canada, despite reliable Landsat and MODIS coverage for the period (Fensholt and Proud, 2012; Wulder et al., 2016). Even though spaceborne detection methods produced a mean fire size twice that of traditional sources during the past decade, likely due to the a combination of the coarse resolution of the MODIS hotspot product (Hantson et al., 2013) and increased coverage in the north, the combined mean fire size sharply declined from 1990 onward. Furthermore, a rapid increase in the frequency of small human-caused fires in recent decades may drive the mean fire latitude southward toward population centers. While this is evident for fires of all sizes, large lightning-caused fires > 200 ha representative of classical boreal fire regimes generally increased in latitude over the past 90 years, indicative of high-latitude warming and an increased human presence in the north; disentangling these two factors, as well as the inherent sampling bias of non-satellite detection methods, presents an opportunity for future research. Nonetheless, a poleward shift of boreal fire regimes may correspond to a northward migration of boreal forests under warming (D’Orangeville et al., 2016; Koven, 2013). Further research leveraging the Landsat and/or AVHRR record is required to confirm this dynamic.

While the inclusion of satellite disturbance detection data in recent decades should increase the apparent area burned, the opposite is observed across regional and national scales. At its peak prior to the current decade, in the 2000-2009 decade, spaceborne observations represented 8% of fire observations and 19.4% of the total area burned; omitting these observations leaves observed patterns generally intact. At its latitudinal peak in the 1990-1999 decade, spaceborne observations were 14% further northward on average compared to traditional detection methods.

For western Alberta, where recent changes to fire regimes are greater than national patterns, the detection source of fire observations shows no effect. According to the National Fire Database, none of the fires in western Alberta were sourced from modern remote sensing instruments. Hence, the analysis and related conclusions at the national and regional scales remain valid. At the national scale, while the subtraction of remote sensing detected fires would further increase FRP (reduce the rate of burning) during the Most Recent Decade, such large fires were often drawn on a map by hand in previous decades. Absent additional information, I estimate the historical fire size detection threshold at > 40 ha for western Alberta, based on strong correspondence to a gamma fire size distribution at this threshold ($K\text{-}S = 0.028$ $\overline{\varpi} = 0.231$; $A^2 = 1.621$). Individual fire sizes between periods do not significantly differ in mean, but do significantly differ in variance ($t = 0.750$, p-value = 0.454; $F = 301.180$, p-value < 2.2e-16).

Despite declines in fire size, latitude, and area burned for lightning-caused fires Canada-wide between the 1990s and 2000s reported here (mean = -422 ha/year; mean = -15.6 km/year; mean = -744,674 ha/year), a recent analysis of long-term warming suggests that these changes are not climatic (Karl et al., 2015). Results for western Alberta show a regime shift toward human-dominated fires in recent decades. By the 2000s, human-caused fires accounted for 58.1% of fires and 70.8% of area burned in western Alberta, surpassing the millennia-old dominance of large lightning-caused fires. These findings contrast with Canada-wide changes during the same period, where human-caused fires declined in contribution to the area burned from 9% to 6%.

While human activity has long played a role in fire regimes in the boreal (Bowman et al., 2011), Anthropocene conditions have recently combined to produce fire regimes without historical analogue along the southern boreal. By analyzing fires > 200 ha before the 2000s, due to limitations in the former national fire database, previous studies (Kasischke and Turetsky, 2006; Stocks et al., 2002) were unable to detect this regime shift. Fires < 200 ha in size represent 46.6% of fires in western Alberta (0.6% of area burned) and 59.3% of fires Canada-wide (0.9% of area burned). Thus, while large fires continue to explain the area burned, they fail to explain variation in fire frequency. As was shown, large recent changes to fire frequency are not explained by the inclusion of spaceborne detection methods.

Our results for western Alberta contrast to previous studies suggesting that lightning maintains a dominant role in annual area burned throughout the North American boreal (Kasischke and Turetsky, 2006; Stocks et al., 2002). Here, more effective fire suppression (Cumming, 2005) appears overwhelmed by a combination of warming and increased human activity, beginning at an inflection point ~1970. At higher latitudes and elevation in Canada, warming has been shown to increase biomass production (D'Orangeville et al., 2016; Hantson et al., 2015), partially explaining an increased area burned here under the assumption of fuel limitations.

An increased annual rate of fire frequency since 1980 corresponds with population growth and increased economic activity in Alberta (Statistics Canada, 2011) combined with rapid warming (Karl et al., 2015). Regional and national warming is evidenced by IPCC findings (Intergovernmental Panel on Climate Change, 2014), previous fire regime analyses (Tymstra et al., 2007; Wotton and Flannigan, 1993), and indirectly by aforementioned observed changes to fire regimes Canada-wide. Human activity may explain most of the increase in the frequency of small fires near roads and surface water, while warming also increases the frequency of lightning strikes and severity of fire weather conditions (Krawchuk et al., 2009).

Although mean annual fire size and area burned declined in western Alberta over the past decade, the effects of warming on burning appear to have been amplified, rather than attenuated, by human activity. The data do not appear to support a previously reported non-linear U-shaped relationship between human activity and the frequency of fire ignitions (Parisien et al., 2012; Syphard et al., 2007). Due to the relative remoteness of Alberta's burnable land and small urban areas (compared to populous regions, such as California), there appears to be an approximately linear, rather than a U-shaped, distribution between fire frequency, area burned, and human activity. Our results for western Alberta appear similar to findings for the Alaska boreal (Gaglioti et al., 2016). Successful fire suppression efforts (Cumming, 2005) may partially account for the decline in mean fire size nationally and in Alberta, as well as a declining national annual area burned, despite warmer conditions with more frequent human-caused ignitions. High-frequency small fires and extractive activities have likely also reduced forest fuels, which may together explain an observed demographic shift in these forests (Zhang et al., 2015).

These patterns differ from other recent studies in the North American boreal including Alaska (Kasischke and Turetsky, 2006; Stocks et al., 2002), which show a rapid rise in mean fire size and annual area burned, based on analyses of previous historical fire database versions. The results presented herein contradict both of these notions across regional and national scales, showing greater agreement with paleoreconstructions from Alaska (Kelly et al., 2013), studies on the relationship between human activity and fire frequency in the Alaskan boreal (Gaglioti et al., 2016), and recent analyses indicating the presence of negative wildfire feedback mechanisms in the North American boreal (Héon et al., 2014; Rogers et al., 2015).

Future studies should assess whether these trends are prominent across North America and northern forests globally. A coupled climatic-human activity dynamic appears to explain the observed changes in fire distribution. This is supported by a recent study showing a global human-driven reduction in burned area (Andela et al., 2017). Studies should seek to better delineate the causes of these patterns in terms of the precise roles of climatic, human, and forest fuels mechanisms responsible. Of primary interest is the unexplained inflection point observed around 1990, for both western Alberta and Canada, related to a rapid increase in fire frequency, reduction in mean fire size, and reduction in area burned, despite warming. This poorly understood inflection point appears to explain many observed dynamics. While historical landcover and demographic change undoubtedly also play a critical role in explaining variations in fire patterns, a dearth of detailed historical maps makes it difficult to assess, with remote sensing records absent earlier than a few decades into the past. Future studies should investigate the coupling of climatic change and human activity to better understand present and future conditions, until more precise maps of landcover history are available.

Results indicate that the application of historical climate-fire correlations to general circulation model projections, absent anthropogenic trajectories, carries diminished predictive power in the Anthropocene. Short-term boreal ecological forecasts should include spatially explicit dynamics of human-caused ignitions, fire suppression, and structural-demographic changes to forest fuels related to increasing human activity. Long-term forecasts should further include compositional change impacts on fuel conditions (Terrier et al., 2012), as well as coupled climate feedbacks (Amiro et al., 2006).

These requirements may motivate the development of new terrestrial biosphere models incorporating disturbance, succession, and energy partitioning processes, similar to recent hybrid models (Bond-Lamberty et al., 2005; Scheller et al., 2007). The anthropogenically focused Community Earth System Model (CESM1) revisions (Li et al., 2013) and Human-Earth System Fire (HESFire) model (Le Page et al., 2015) represent such an approach, as do Eulerian grid-based models such as WRF-Fire (Coen et al., 2012) and HIGRAD/FIRETEC (Colman and Linn, 2007).

Limitations

This research relies on the best available fire history data for Canada (Burton et al., 2008; Parisien et al., 2006; Stocks et al., 2002). Yet, the data contain known sampling biases toward lower latitudes, larger fires of longer duration, and years subsequent to ~ 1960, particularly for data on fire seasonality and cause. Thus, one would expect the data to show diminished mean fire size and increased area burned, fire frequency, and mean fire latitude until the 1970s, when the remote sensing record began with Landsat MSS. Yet, changes observed since the 1980s appear robust to these sampling biases, given an increased satellite record. For improved estimates of parameter uncertainty or model error, future studies may rely on hierarchical Bayesian modeling with climate and anthropogenic data. While modern spaceborne imaging systems such as Planet Doves (Hand, 2015) and deep learning techniques (LeCun et al., 2015) are poised to alleviate sampling biases in historical fire maps over time by improving spatiotemporal resolution and detection accuracy, the temporal depth of this remote sensing record remains limited, while the substantial size of the data and neural networks remain cumbersome. Thus, early field observations, airborne mapping, and paleorecords will remain indispensable for understanding historical fire regimes.

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