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RESEARCH ARTICLE

A century of transformation: fire regime transitions from 1919 to 2019 in southeastern British Columbia, Canada

Jennifer N. Baron · Sarah E. Gergel · Paul F. Hessburg · Lori D. Daniels

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Abstract

Context In fire-excluded forests across western North America, recent intense wildfire seasons starkly contrast with fire regimes of the past. The last 100 years mark a transition between pre-colonial and modern era fire regimes, providing crucial context for understanding future wildfire behavior.

Objectives Using the greatest time depth of digitized fire events in Canada, we identify distinct phases of wildfire regimes from 1919 to 2019 by evaluating changes in mapped fire perimeters (> 20-ha) across the East Kootenay region (including the southern Rocky Mountain Trench), British Columbia.

Methods We detect transitions in annual number of fires, burned area, and fire size; explore the role of lightning- and human-caused fires in driving these transitions; and quantify departures from historical fire frequency at the regional level.

Results Relative to historical fire frequency, fire exclusion has created a significant fire deficit in active fire regimes, with a minimum of 1–10 fires missed across 46.4-percent of the landscape. Fire was active from 1919 to 1939 with frequent and large fire events, but the regime was already altered by a century of colonization. Fire activity decreased in 1940, coinciding with effective fire suppression influenced by a mild climatic period. In 2003, the combined effects of fire exclusion and accelerated climate change fueled a shift in fire regimes of various forest types, with increases in area burned and mean fire size driven by lightning.

Conclusions The extent of fire regime disruption warrants significant management and policy attention to alter the current trajectory and facilitate better coexistence with wildfire throughout this century.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10980-022-01506-9.

J. N. Baron (✉) · S. E. Gergel · L. D. Daniels
Department of Forest and Conservation Sciences, Faculty of Forestry, University of British Columbia, Vancouver, BC V6T 1Z4, Canada
e-mail: jenbaron@mail.ubc.ca

P. F. Hessburg
USDA-FS, Pacific Northwest Research Station, Wenatchee, WA 98801, USA

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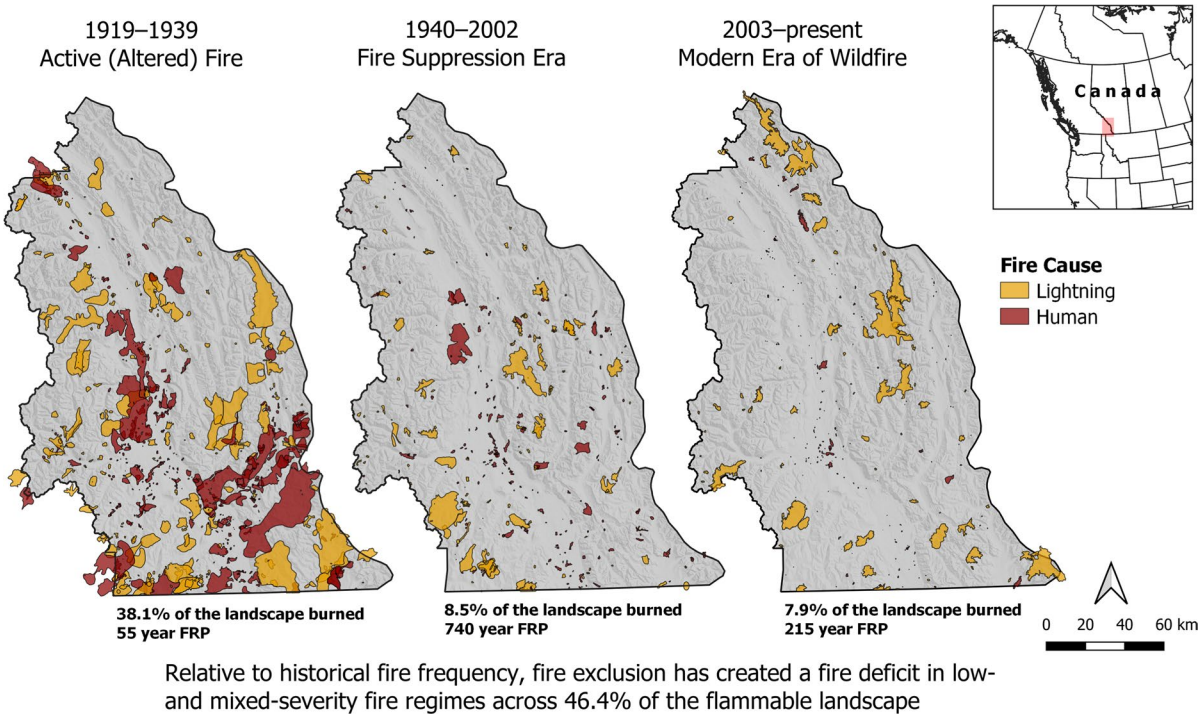
Graphical abstract



Keywords Fire suppression · Fire deficit · Fire return interval · Historical ecology · Regime shift · Indigenous fire stewardship · Mixed-severity · Reburning · Historical range and variability · Breakpoint analysis

Introduction

Around the world, large changes in fire regimes are being observed (Flannigan et al. 2009; Kelley et al. 2019). Global increases in extreme fire weather, drought, and fire season length illustrate the monumental scale of shifts in fire activity (Jolly et al. 2015; Jain et al. 2021). Wildfire activity has increased in the western North America since the mid-twentieth century (Hagmann et al. 2021), with increases in the number and size of large fires, area burned, fire severity, and length of the fire season (Dennison et al. 2014; Westerling 2016; Coops et al. 2018; Hanes et al. 2019; Coogan et al. 2020; Parks and Abatzoglou 2020). Increasingly, wildfires are exhibiting extreme fire behavior and exceeding suppression capabilities (Wotton et al. 2017). Interactions between lightning and human ignitions (Romps et al. 2014; Balch et al. 2017; Veraverbeke et al. 2017), increased forest area, forest density and woody fuels (Hessburg et al. 2019; Hagmann et al. 2021), and climatic warming (Abatzoglou and Williams 2016; Parks and Abatzoglou 2020; Higuera and Abatzoglou 2021) drive these large changes in fire behavior. Moreover, frequent, large, and intense fires threaten communities and ecosystems and conflict with core social values (Moritz et al. 2014; Coogan et al. 2019; Johnston et al. 2020).

In active fire regimes where fire suppression has been highly effective, modern (since 2000) fire events signify the advent of a wildfire era that is without a recent historical analog and is departed from precolonial (before 1850) fire regimes (Coogan et al. 2019; Higuera et al. 2021). Wildfire regimes are defined by the cumulative spatial and temporal occurrence and impacts of fire events over a given area and period of time (Pickett and White 1985; Agee 1996).

Fire *events* are characterized by their timing (start and end date), ignition source, location, size (area), shape, intensity, and severity, while fire *regimes* are characterized by the seasonality, frequency (or return interval), intensity and severity, size distributions of event and severity patches, and interactions with other disturbances (Agee 1996; Turner 2010). Modern fire events are typically described by ignition type, date, location, shape, and size, while regime shifts typically focus on the number of fires and comparisons of burned area and fire severity over specified time periods.

Multiple fire attributes must be evaluated to effectively characterize fire regimes and estimate departures from historical conditions or compare periodic fire regime shifts (Daniels et al. 2017; Hagmann et al. 2021; Hessburg et al. 2021). The past 100–150 years marks an important transition between pre-colonial and modern era fire regimes; however, this time period is not well reflected by contemporary data collection methods (e.g., remote sensing, GIS databases, fuel type classification systems) which emerged in the late-twentieth century and typically reflect modern conditions. Documentary records and research approaches from early-twentieth century (e.g., dendrochronology, fire history studies, repeat aerial and panoramic photography, Indigenous Ecological Knowledge) can expand the time depth of these characterizations and be used to quantify fire regimes departures (Safford et al. 2012; Naficy 2016; Buma et al. 2019) from the historical range and variability (HRV) (Keane et al. 2009, 2018, 2019; Hagmann et al. 2021). When integrated, these approaches can advance the understanding of fire regimes and the factors that drove their transformation into the present.

In Canada, a large fire geodatabase (Stocks et al. 2003; Canadian Forest Service 2020) documents national wildfire trends since 1980 (Parisien et al. 2006; Hanes et al. 2019) and offers opportunity for new characterizations of fire regimes and shifting dynamics (Burton et al. 2008; Burton and Boulanger 2018). Using this database, extant analyses of fire regime changes in Canada have primarily focused on large wildfire events (> 200-ha) with a limited selection of fire regime attributes, typically including number of fires and area burned (e.g., Podur et al. 2002; Stocks et al. 2003; Kasischke and Turetsky 2006; Boulanger et al. 2014). While the temporal depth of regional studies has increased by combining data sources and techniques, this has come at the cost of a more limited selection of fire regime attributes (e.g., Bergeron et al. 2004; Girardin and Mudelsee 2008; Rogeau et al. 2016; Portier et al. 2016).

Furthermore, owing to improved data accuracy and availability, previous analyses focused on datasets beginning in the mid- to late- twentieth century at regional (Burton et al. 2008; Albert-Green et al. 2013; Veraverbeke et al. 2017; Campos-Ruiz 2018) and national scales (Coogan et al. 2020; Coops et al. 2018; Hanes et al. 2019). These studies generally investigated fire regime changes using a single trend line, despite multiple lines of evidence that fire regimes through the 20th century have been spatially and temporally dynamic (Naficy et al. 2015; Hessburg et al. 2019; Chavardès et al. 2021; Hagmann et al. 2021). In British Columbia (BC), provincial fire records cover 94.4 million hectares (ha) and represent the greatest time depth of digitized fire events available in Canada (BC Wildfire Service 2021a; Skakun et al. 2021). This record provides an opportunity to better understand fire regime transitions since the early 1900s at regional and landscape scales, and with a greater range of fire regime attributes including number of fires, area burned, seasonality, fire size and ignition source.

Recent record-breaking fire seasons in BC are being fueled by anthropogenic climate change (Kirchmeier-Young et al. 2017; Kirchmeier-Young et al. 2019), with fires in 2017, 2018, and 2021 burning 870,000 to 1.3 million ha per year (BC Wildfire Service 2021b, c). Accompanying the rapidly declining effectiveness of fire suppression under extreme fire weather conditions (Wotton et al. 2017), these severe fire seasons sharply contrast with 20th century fire regimes (Hanes et al. 2019; Coogan et al. 2020). In the East Kootenay forest region of southeastern BC, contemporary wildfire risk (Kirchmeier-Young et al. 2017; Johnston et al. 2020) and disrupted low- and mixed-severity fire regimes shaped by Indigenous burning (Marcoux et al. 2015; Chavardès et al. 2021; Greene 2021) incentivize an improved understanding of fire regime transitions.

Here, we analyze 20th century fire regime transitions and estimate departures from historical fire frequency, overcoming previous limitations to provide new insights at a regional scale. We map a century of historical fire perimeters for fires > 20-ha across 2.8 million ha in the East Kootenay Regional District, BC, Canada to identify and evaluate potentially distinct phases of

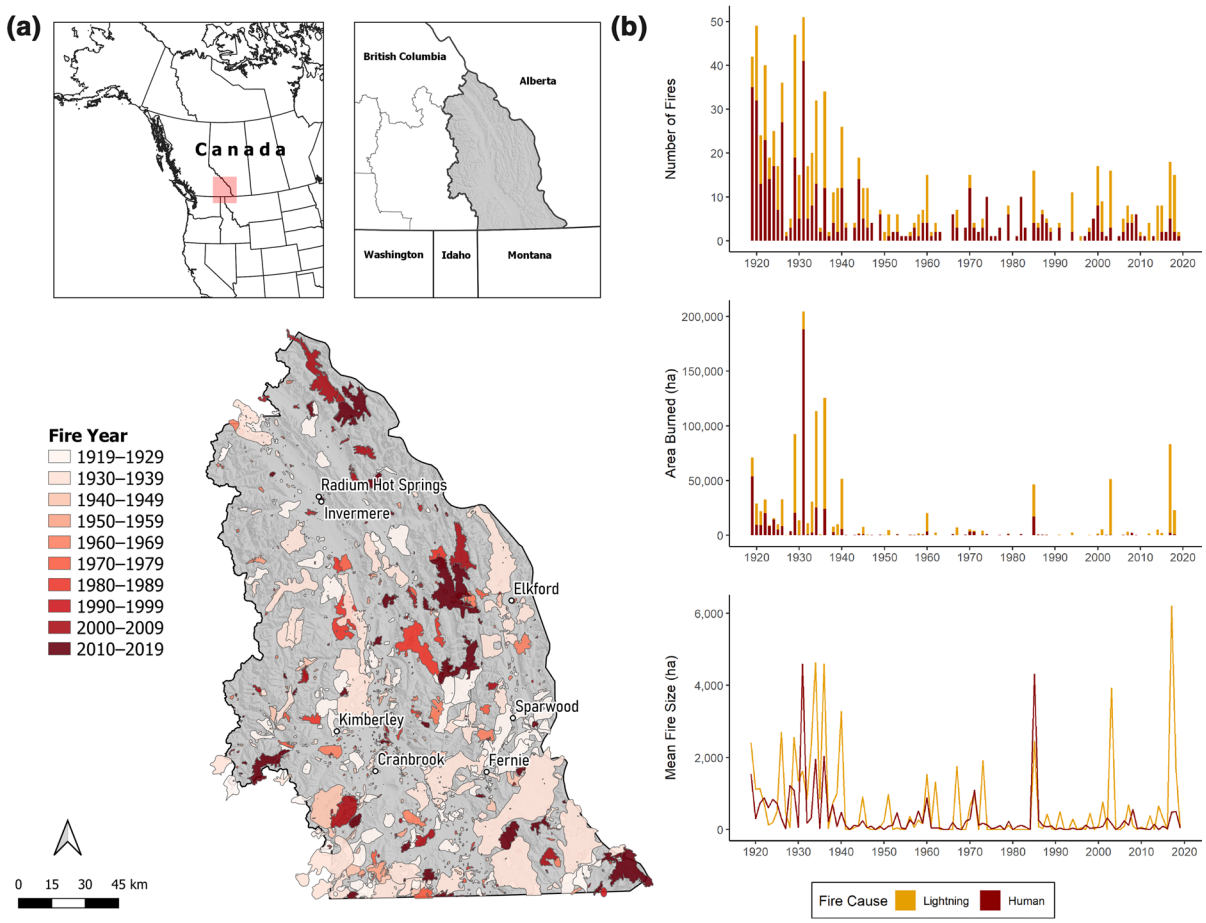


Fig. 1 **a** Historical fire perimeters in the East Kootenays, British Columbia, Canada from 1919–2019. **b** Annual number of fires, area burned (ha), and mean fire size (ha) by fire cause (lighting and human) derived from historical fire perimeter records in the East Kootenays, British Columbia, Canada from 1919–2019

wildfire regimes from 1919 to 2019. We evaluate twentieth century transitions in the annual number of fires, burned area, and fire size; explore the role of lightning- and human-caused fires in driving these transitions; and quantify departures from historical fire frequency at the regional level. We discuss our findings in the context of weather and climate, fuel availability, ignitions, land-use, and management driving variables.

Materials and methods

Study area

The East Kootenays are bisected north to south by the southern Rocky Mountain Trench (RMT), which separates the Columbia Mountains to the west from the Rocky Mountains to the east (Fig. 1). In the dry, broad, valley-bottom landform of the southern RMT (known as the Interior Douglas-Fir zone, IDF), forest stands are co-dominated by fire-tolerant Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mayr) Franco), ponderosa pine (*Pinus ponderosa* Douglas ex Lawson), and western larch (*Larix occidentalis* Nutt) (MacKillop 2018). Montane (Montane Spruce zone, MS) and subalpine (Engelmann Spruce-Subalpine Fir zone, ESSF) forests consist of hybrid spruce (*Picea engelmanni* x *glauca*), subalpine fir, (*Abies lasiocarpa* (Hook.) Nutt.), and lodgepole pine (*Pinus contorta* Douglas ex Louden) (MacKillop 2018), although mountain pine beetle (*Dendroctonus ponderosae* Hopskins) outbreaks caused widespread

mortality of mature lodgepole pine from 2002 to 2012 (Kurz et al. 2008; Walton 2013; Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2021). In mesic montane valleys adjacent to the RMT (Interior Cedar-Hemlock zone, ICH), forests of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western redcedar (*Thuja plicata* Donn ex D. Don), and grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.) occur at middle elevations (MacKillop 2018).

Climate in the region is warm (4.8–10 °C mean annual temperature) and dry (280–500 mm mean annual precipitation) at the valley floor (750–1000 m), but becomes wetter (300–750 mm) and cooler (1.6–9.5 °C) with increasing elevation (600–1400 m, Köppen-Geiger class Dfb cold, no dry season, warm summer) (Meidinger and Pojar 1991; Beck et al. 2018). Mean temperatures decrease (0.5–4.7 °C) and precipitation increases (380–900 mm) in the subalpine zone (1100–1500 m, Köppen-Geiger class Dfb cold, no dry season, cold summer) (Beck et al. 2018). At the highest elevations (1500–2300 m), mean temperatures are low (< 0 °C) and precipitation is abundant (up to 2200 mm), predominantly occurring as snow (50–70%) (Meidinger and Pojar 1991).

For millennia, fire regimes in the East Kootenays were linked to climate through warm and dry conditions and droughts caused by large-scale atmospheric circulation patterns (i.e., Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation, El Niño–Southern Oscillation) (Daniels et al. 2007, 2011). Fire history reconstructions reveal that pre-colonial (1200–1850) fire regimes were low-severity (5–20 year fire return interval, FRI) in valley bottoms (IDF zone), mixed-severity (20–80 year FRI) in montane and lower subalpine forests (MS, ICH zones), and high-severity (80–300 year FRI) at upper elevations (ESSF zone), with increasing fire severity and decreasing frequency further upslope (Marcoux et al. 2013, 2015; Hessburg et al. 2019; Chavardès et al. 2021; Greene 2021). Episodic insect outbreaks were common and intermixed with fire events, maintaining patch-to-landscape level heterogeneity (Burton and Boulanger 2018; Hessburg et al. 2019).

Prior to colonization, frequent fire regimes were maintained with low- to moderate-severity surface fires from lightning ignitions and Indigenous cultural burning (Lake and Christianson 2019; Hoffman et al. 2022). The traditional territory of the Ktunaxa Nation spans 70,000 km^2 of southeastern BC and includes parts of Alberta, Montana, Washington, and Idaho, where they have stewarded the land for over 10,000 years (Choquette 1996; Ktunaxa Nation 2022). Grasslands are essential to the Ktunaxa way of life and were traditionally maintained through frequent surface fires set in the fall to reduce forest encroachment on fire-cultivated tracts, maintain travel corridors, and influence the movement of and foraging conditions for hunted animals including elk, deer, and bear (Smith 1984; Munson 2006). Fire was also used to produce foods and medicines including wild tobacco, a regionally cultivated ceremonial plant with important spiritual and cultural value (Smith 1984; Mah 2000; Munson 2006). Indigenous fire stewardship was systematically discouraged during the late 19th-century, driven by colonial policies (e.g., Indian Act, Indian Reserves and Residential Schools), which sought to weaken and eliminate Indigenous cultures (Copes-Gerbitz et al. 2022). Dendrochronological evidence indicates a disruption in fire frequency after 1940, which is attributed to the displacement of Indigenous peoples onto reserves, colonial fire exclusion policies, and a period of cool and wet climate (Daniels et al. 2011; Chavardès and Daniels 2016; Greene 2021).

*Historical fire p*erimeters

We used the BC Wildfire Service (BCWS) Historical Fire Perimeters GIS database, which documents fire events on provincial crown land since 1919 and is updated annually (BC Wildfire Service 2021a, https://catalogue.data.gov.bc.ca/dataset/fire-perimeters-historical). Fire events from 1919 to 2019 were compiled from administrative fire suppression records, forest inventories, and via other remotely sensed data (Taylor et al. 2006). Polygons representing the perimeters of individual fire events include information such as fire cause, size (ha), source data (e.g., satellite, historical records, field survey) and survey method (e.g., aerial sketch mapping, buffered point, GPS digitization, see Skakun et al. 2021) used to spatially represent the event. Fire perimeters in this dataset (pre- and post-2000) generally include the total area of fire events across a range of fire severities (high-, low-,

unburned) and do not exclude areas of fire refugia, water, rock, or bare ground.

Features of fire events before 2000 were obtained from the Pacific Forestry Centre (Victoria, BC) which archives the BC Natural Disturbance Database; a project that digitized and georeferenced historical hardcopy fire maps (Taylor et al. 2006). Features of fire events after 2000 were collected using GPS, satellite, drone, and low altitude fixed-wing aircraft observations and obtained from the BCWS and Forest Analysis and Inventory Branch (BC Wildfire Service 2021a). The BCWS records and manages fires on provincial lands, while National Parks fall under federal jurisdiction and are managed by Parks Canada. We supplemented the BCWS Historical Fire Perimeters dataset with 9 other wildfire events within the borders of Kootenay National Park obtained from the Canadian National Fire Database (CNFDB; Canadian Forest Service 2020, https://cwfis.cfs.nrcan.gc.ca/ha/nfdb). In total, we included fire events intersecting or completely included in the East Kootenay study domain to ensure inclusion of all events influencing the region over the period of record. Further, we included all fires > 20-ha in size in our analyses (n = 920) because historical fires < 20-ha were not digitized by Taylor et al. (2006). Given our aim of investigating regional fire patterns over 2.8 million ha, we consider 20-ha to be a sufficiently small minimum mapping unit. We evaluated fires caused by lightning (n = 416) or human (n = 504) ignitions.

Transitions in fire regime attributes

We used breakpoint analysis to identify phase transitions in three annual fire regime attributes: number of fires, area burned (ha), and mean fire size (ha) (Fig. 1). Breakpoints are statistically derived variations in time series data which may be used to identify important temporal transitions in the value of an attribute (Aminikhanghahi and Cook 2017). We used the *strucchange* package (Zeileis et al. 2002) in R (version 4.0.5) statistical software (R Core Team 2021) to conduct change-point detection using segmented (parametric) linear regression models. Following the procedures of Zeileis et al. (2003, 2005) we used the ordinary least squares (OLS-based) CUSUM process to verify structural change in the model and the Bayesian information criterion (BIC) to determine the most parsimonious breakpoint number. We selected this particular procedure after evaluating several parametric and non-parametric modelling approaches for trend and change-point detection (e.g., Mann–Kendall, modified Mann–Kendall, Cox-Stuart, Pettitt's test, Buishand tests, standard normal homogeneity test, structural change, breaks for additive seasonal and trend, hierarchical divisive and agglomerative tests) to optimize statistical power and minimize type I error probability (Militino et al. 2020).

We evaluated model assumptions following methods of Zeileis et al. (2003, 2005) and Militino et al. (2020). Pertinent to timeseries data, if there is strong temporal autocorrelation then the assumption of independence is violated, resulting in poor performance of trend and changepoint detection methods (Militino et al. 2020). We assessed and did not find strong temporal autocorrelation at any lag (lags 1–15) in the annual timeseries. Assumptions of normality, heterogeneity, and linearity were assessed using normal Q-Q plots and plots of residuals against fitted values following Zuur et al. (2009). The leverage of influential points was assessed using Cook's distance, a measure that describes the impact of individual observations on the fitted model (Zuur et al. 2009). To explore the relationship between fire attribute transitions and fire cause, we conducted breakpoint analyses on all ignitions (lightning + human), lightning ignitions, and human ignitions. To explore the influence of fire cause, we calculated the relative proportion of fires and burned area associated with lightning and human ignitions.

Mapping departures from historical fire frequency

To locate and quantify departures from historical fire frequency, we mapped historical fire frequency, time since a fire event, the number of fire events since 1919 (burns and reburns), and fire regime interval departure (FRID).

Using the georeferenced historical fire perimeters dataset, we used a geographical information system (GIS; ESRI Inc. 2021) to derive a 30-m raster containing the year of the most recent fire event, and then determined time since fire (since 2019) for each pixel. We selected the flammable landscape (excluding areas of rock, water, and ice or permanent snowpack) using the BCWS Fire Fuel Types dataset (BC

Wildfire Service 2021d), which classifies fuel types from the Canadian Forest Fire Behavior Prediction System (FBP) based on BC Vegetation Resource Inventory (VRI) polygon data (Perrakis et al. 2018). We quantified reburns by identifying overlapping fire events using the "Count Overlapping Features" tool (ESRI Inc. 2021) and deriving a 30-m raster which identified the number of fire events in each pixel. We calculated the area and percent cover for each decade (time since fire) and number of burns (reburns) using the *landscapemetrics* package in R (Hesselbarth et al. 2019). We calculated the percentage of the flammable landscape that did not burn (unburned) and the fire rotation period (FRP; the time necessary for fire to burn the equivalent of the total area, Agee 1996) for the phases identified through breakpoint analysis.

To map historical fire frequency to biophysical domains, the BC provincial Biogeoclimatic Ecosystem Classification (BEC) shapefile was combined in a GIS with fire history data from the region. BEC subzones, which are grouped based on climatic, topographic, and vegetation characteristics, provided useful biophysical divisions for partitioning fire frequency results and later extrapolating those results to a broader geographic area (Province of British Columbia 2022). A network of 11 dendrochronology

Table 1 Summary of dendrochronology and fire history studies used to estimate historical fire return intervals (FRIs) in the East Kootenay Regional District, British Columbia, Canada (adapted from Chavardès et al. 2021)

Location of study area centroid		Elevation (masl)	Biogeoclimatic zone[1]	Number of plots (n)	Composite fire record (calendar yrs)	Plot-level mean (range) fire intervals (yrs)	Last fire (calendar yr)	Citation
49°34'N	117°10'W	600–1725	ICH, ESSF	18	1665–2009	52 (14–149)	1927	Nesbitt (2010)
49°13'N	116°45'W	595–1690	ICH, ESSF	45	1407–2009	33 (3–128)	1926	Greene and Daniels (2017)
49°28'N	115°32'W	738–1169	IDF	20	1192–2013	12 (7–15)	1965	Greene (2021)
50°01'N	116°05'W	930–1600	MS	10	1353–2005	37 (2–202)	1937	Daniels and Gray (2007) and Daniels et al. (2007)
49°34'N	115°46'W	940–1000	IDF	2	1522–2003	21 (3–236)	1891	Nesbitt and Daniels (2009)
49°25'N	115°40'W	1080–1980	IDF, MS, ESSF	22	1510–2007	35 (4–148)	1957	Marcoux et al. (2013), (2015) and Villemaire-Côté (2014)
50°10'N	115°47'W	1100–1555	MS	20	1431–2006	57 (4–232)	2003	Cochrane (2007)
50°48'N	115°58'W	1100–1330	MS	43	1693–2009	26 (5–57)	1926	Kubian (2013)

[1]*ICH* Interior Cedar-Hemlock, *IDF* Interior Douglas-Fir, *ESSF* Engelmann Spruce-Subalpine Fir, *MS* Montane Spruce

Table 2 Fire regime attributes during 3 distinct phases of fire activity: (i) active but altered fire from 1919–1939, (ii) a fire suppression era from 1940–2002, (iii) the modern era of wildfire from 2003–present (see Fig. 3)

Time period	Number of fires	Area burned (ha)	Mean fire size (ha)	[1]Percent unburned (%)	[2]FRP (years)
1919–1939	503	837,571	1237	61.9	55
1940–2002	314	187,188	281	91.5	740
2003–2019	103	173,698	709	92.1	215

[1] Percent of the flammable landscape that did not experience a fire event

[2] Fire rotation period

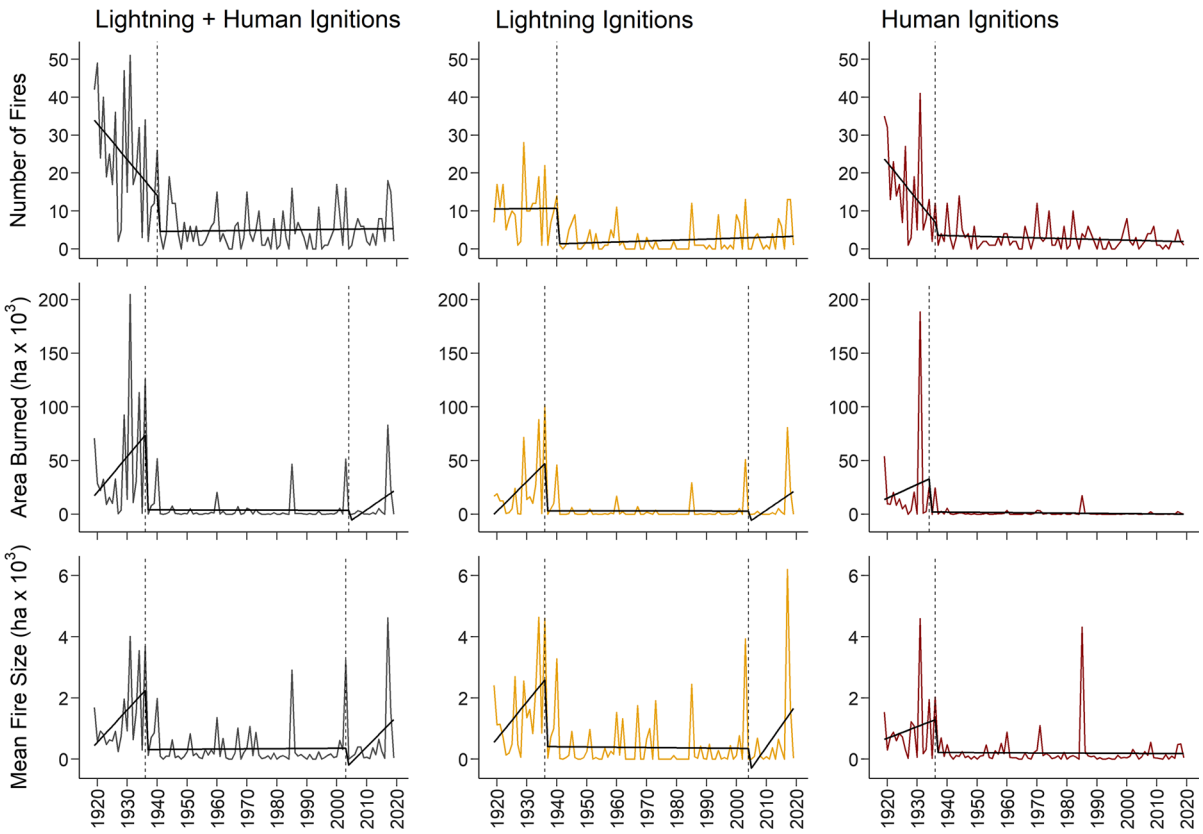


Fig. 2 Breakpoints (dashed lines) and model predictions (black lines) for annual number of fires, area burned (ha), and mean fire size (ha) by fire cause in the East Kootenays, British Columbia, Canada from 1919–2019 (see Table 3)

and fire history studies were supplemented with values from east of the continental divide in Alberta (Rogeau et al. 2016; Rogeau and Armstrong 2017) to assign a historical FRI to each BEC subzone. The 11 studies comprised 180 plots, recording 822 years of fire history across 4 distinct BEC zones (IDF, ICH, MS, ESSF zones), and reflecting conditions on elevation gradients ranging from 600–1980 masl (Table 1, see Chavardès et al. 2021).

We calculated and mapped FRID, which represents the number of missed fire return intervals, by dividing the current FRI (i.e., time since fire) by the historical FRI (Davis et al. 2010). Values between 0–1 indicate no fire deficit; values ≥ 1 indicate the number of fires missed (e.g., 25 year historical FRI, 100-year current FRI, FRID = 4 fires missed). In high-severity fire regimes (historical FRI > 100 years),where time since fire exceeds 100 years (the temporal limit of our dataset), FRID values were represented as 1 (i.e., no departure detectable).

Results

Over the past century, 920 fires (> 20-ha) burned 1.2 million ha, with a mean size of 1,300 ha (range: 20–68,000 ha) (Fig. 1, Table 2). We detected two significant breakpoints in the fire record marking phase transitions in wildfire activity (Fig. 2, Table 3). Wildfires were active between 1919 and 1939, when 503 fires burned 838,000 ha with a mean size of 1,237 ha, leaving 61.9-percent of the landscape unburned. Wildfire activity (lighting + human ignitions) decreased after 1940, when 314 fires burned 187,000 ha with a mean fire size of 281 ha, leaving 91.5-percent of the landscape unburned. In 2003, a third lightning-driven phase transition occurred, after which 103 fires burned 174,000 ha with a mean fire size of 709 ha, leaving 92.1-percent of the landscape unburned (Figs. 2, 3, Table 2).

Table 3 Phase transitions shown by fire cause (lightning and human) for number of fires, area burned, and mean fire size records from 1919–2019 (see Fig. 2)

Metric	Fire cause	Time period (estimate)	95% CI (lower)	95% CI (upper)	Slope	Intercept	p-value
Number of fires	Lightning + Human	1919–1939	1939	1946	-9.44×10^{-1}	1.85×10^{3}	[a]
		1940–2019			9.49×10^{-3}	-1.38×10^{1}	$\mathbf{6.76\times10^{-4}}$
	Lightning	1919–1939	1938	1947	3.78×10^{1}	-7.18×10^{4}	[a]
		1940–2019			-4.90×10^{-1}	1.17×10^{3}	9.08×10^{-1}
	Human	1919–1935	1935	1945	-9.81×10^{1}	1.91×10^{3}	[a]
		1936–2019			-2.01×10^{-2}	4.26×10^{1}	$\mathbf{1.10\times10^{-4}}$
Area burned (ha)	Lightning + Human	1919–1935	1935	1952	3.32×10^{3}	-6.34×10^{6}	[a]
		1936–2003			-6.19	1.60×10^{4}	$\mathbf{4.68\times10^{-3}}$
		2004–2019	1956	2005	1.92×10^{3}	-3.86×10^{6}	4.60×10^{-1}
	Lightning	1919–1935			2.77×10^{3}	-5.31×10^{6}	[a]
		1936–2003	1935	1950	-2.27	7.42×10^{3}	$\mathbf{1.94\times10^{-4}}$
		2004–2019	1959	2005	1.91×10^{3}	-3.84×10^{6}	4.65×10^{-1}
	Human	1919–1933	NA	NA	1.26×10^{3}	-2.41×10^{6}	[a]
		1934–2019			-2.35×10^{1}	4.74×10^{4}	1.97×10^{-1}
Mean fire size (ha)	Lightning + Human	1919–1935	1935	1945	1.05×10^{2}	-2.02×10^{5}	[a]
		1936–2002			6.37×10^{-1}	-9.16×10^{2}	$\mathbf{4.81\times10^{-3}}$
		2003–2019	1953	2004	9.97×10^{1}	-1.99×10^{5}	9.17×10^{-1}
	Lightning	1919–1935	1935	1946	1.20×10^{2}	-2.29×10^{5}	[a]
		1936–2003			-8.81×10^{-1}	2.12×10^{3}	$\mathbf{1.01\times10^{-2}}$
		2004–2019	1954	2005	1.40×10^{2}	-2.80×10^{5}	7.92×10^{-1}
	Human	1919–1935	1935	1958	3.78×10^{1}	-7.18×10^{4}	[a]
		1936–2019			-4.90×10^{-1}	1.17×10^{3}	1.96×10^{-1}

Confidence intervals around breakpoints are presented for the lower limit of the time period

[a]reference period; p-values indicate whether the slope is significantly different from the reference period (bold values indicate statistical significance at $\alpha = 0.05$)

Fire regime phase transitions

We detected significant changes in the number of fires, burned area, and mean fire size since 1919, with transitions in 1940 (range: 1936–1940) and again in 2003 (range: 2003–2004) (Fig. 2, Table 3). When separated by fire cause, phase transitions occurred in 1940 (range: 1936–1940) and 2004 for lightning-caused fires, and 1936 (range: 1934–1936) for human-caused fires (Fig. 2, Table 3). Most fire events were associated with human-ignitions (55-percent), while lightning-caused fires were responsible for the most area burned (61.5-percent) (Table 4).

Annual number of fires was initially high and decreased from 1919 to 1939 at a rate of about 1 fire per year (Fig. 2, Table 3). Between 1940 and 2019, the number of fires was low, and the rate of change decreased significantly to 0.01 fires per year ($p = 6.76\times10^{-4}$). The number of human-caused fires declined from 1919 to 1935, sharply decreased in 1936, and remained low until 2019 ($p = 1.10\times10^{-4}$). The relative importance of lightning ignitions also shifted over time, with the lowest frequency of lightning ignitions occurring in the 1970s (15.2-percent) and 1980s (27.3-percent) (Table 4). Lightning-caused fires increased to > 50-percent relative abundance in the 1930s, 1950s, and 2000s, and up to 80-percent in the 2010s (Table 4).

Area burned was initially low and increased between 1919 and 1935 at a rate of 3,320 ha • yr $^{-1}$ (Fig. 2, Table 3). Area burned subsequently decreased and remained low from 1936 to 2003, declining at a rate of -6.2 ha yr $^{-1}$ ($p = 4.68\times10^{-3}$). From 2004 to 2019, burned area increased once again at a rate of 1,920 ha yr $^{-1}$. Phase transitions in burned area were detected in 1936 and 2004 for lightning-caused fires,

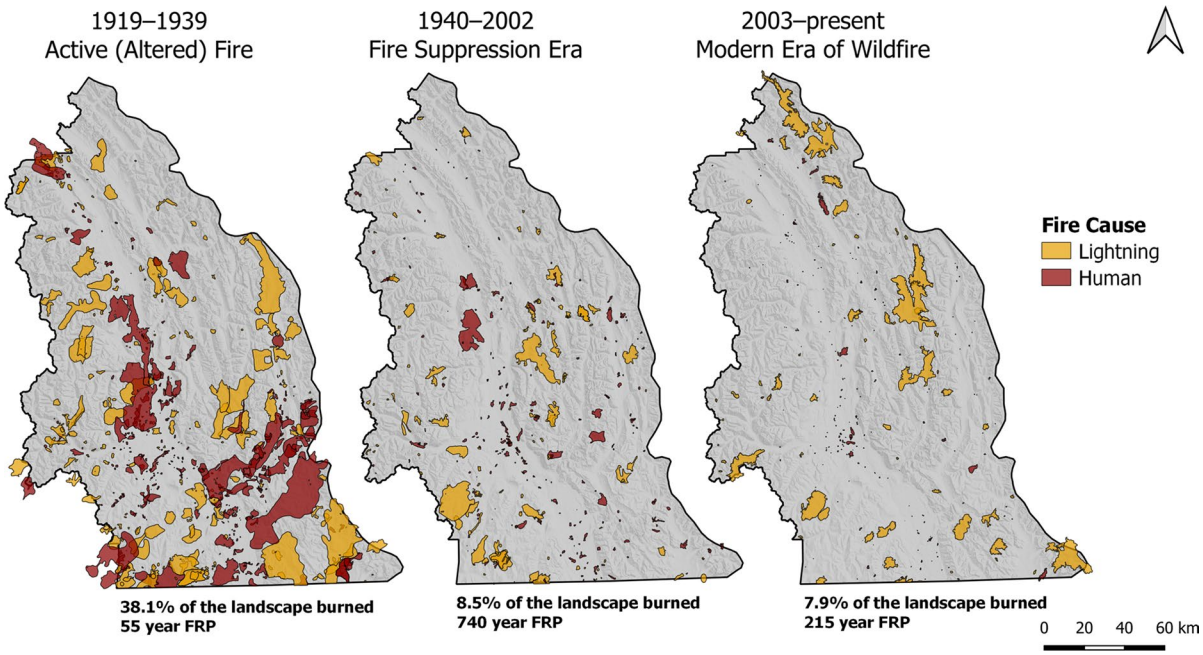


Fig. 3 Using breakpoint analysis, we identify three distinct phases of fire activity: (i) active but altered fire from 1919–1939, (ii) a fire suppression era from 1940–2002, (iii) the modern era of wildfire from 2003–present

Table 4 Number of fires, area burned, and mean fire size (1919–2019) summarized by decade and fire cause

Year	Number of fires			Area burned (ha)			Mean fire size (ha)		
	L + H[1]	L	H	L + H	L	H	L + H	L	H
1919–1929	306	115 (38%)	191	319,225	164,813 (52%)	154,412	875	1095	754
1930–1939	197	104 (53%)	93	518,346	273,165 (53%)	245,181	1636	1802	1019
1940–1949	88	38 (41%)	50	63,653	53,568 (84%)	10,085	317	643	163
1950–1959	37	21 (63%)	16	11,182	7848 (76%)	3335	240	306	210
1960–1969	39	18 (46%)	21	32,398	26,620 (82%)	5778	363	1185	214
1970–1979	49	8 (15%)	41	17,741	7066 (36%)	10,675	295	926	249
1980–1989	49	16 (27%)	33	50,614	29,913 (59%)	20,701	373	603	643
1990–1999	25	12 (43%)	13	4289	3609 (83%)	680	81	321	60
2000–2009	69	38 (57%)	31	65665	60,670 (93%)	4994	534	948	189
2010–2019	61	46 (80%)	15	115,344	111,404 (97%)	3940	774	1337	171

[1]L + H: lightning and human caused ignitions

L lightning only; *H* human only

and 1934 for human-caused fires (Fig. 2, Table 3). Area burned by lightning ignitions increased from 1919 to 1935, then decreased in 1936 and plateaued until 2003 ($p = 1.94 \times 10^{-4}$). Thereafter, area burned by lightning increased until 2019. Lightning-caused fires accounted for > 50-percent of all burned area in all decades except for the 1970s (36.4-percent), with the greatest relative burned area occurring in the 2000s (93-percent) and 2010s (96.8-percent, Table 4).

Mean fire size was initially low and increased from 1919 to 1935 at a rate of 105 ha yr $^{-1}$ (Fig. 2, Table 3). Mean fire size subsequently decreased and remained low from 1936 to 2002, increasing at a rate of 0.64 ha yr $^{-1}$ ($p = 4.81 \times 10^{-3}$). Finally, from 2003 to 2019, mean fire size increased at a rate of 99.7 ha yr $^{-1}$. Phase transitions in mean fire size were detected in 1936 and 2004 for lightning-caused fires, and 1936 for human-caused fires (Fig. 2, Table 3). Mean lightning fire size increased significantly from

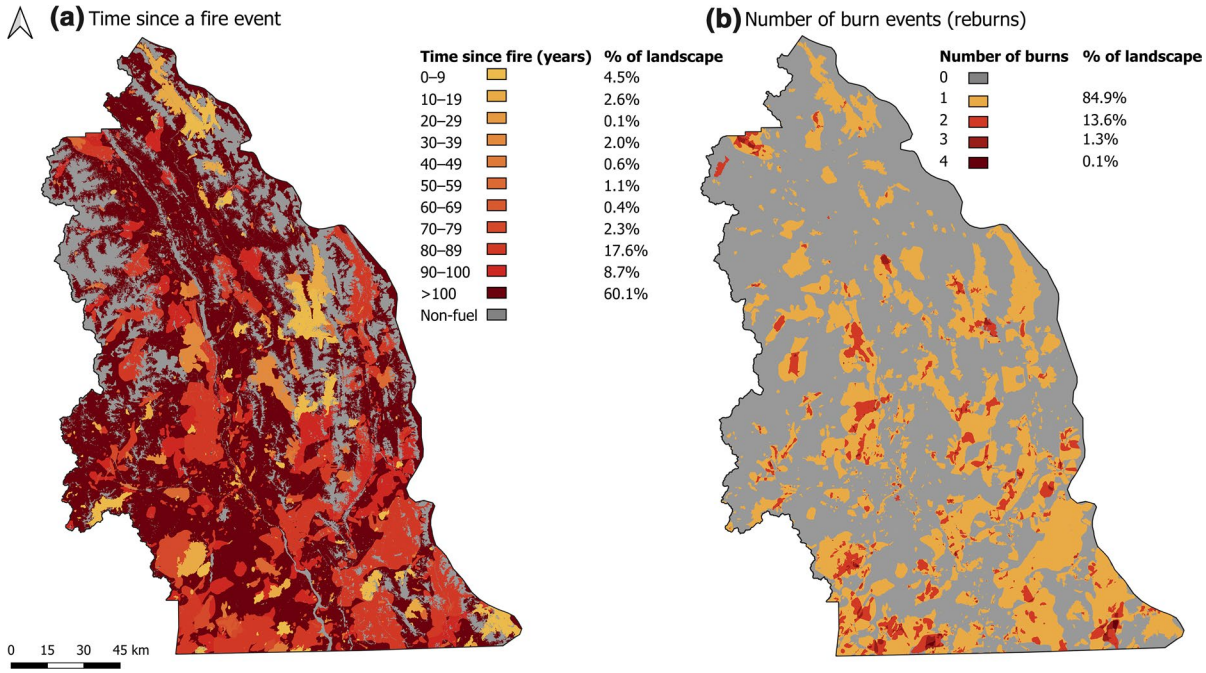


Fig. 4 **a** Time since a fire event (years) and **b** number of burn events since 1919 (reburns) derived from historical fire perimeter records in the East Kootenays, British Columbia, Canada from 1919–2019. The majority of the flammable landscape (89-percent) has not experienced a fire event since 1959

1919 to 1935, decreased in 1936, and plateaued until 2003 ($p = 1.01 \times 10^{-2}$), after which time it increased until 2019 (Fig. 2, Table 3).

Fire regime interval departure reveals significant fire deficits

Most of the flammable landscape (60.1-percent, 1,321,477 ha) has not burned or reburned in the past 100 years (Fig. 4). From 1919 to 1939, 38.1-percent of the flammable landscape burned (55 year FRP, Fig. 3); from 1940 to 2002, 8.5-percent of the flammable landscape burned (740 year FRP, Fig. 3); from 2003 to 2019, 7.9-percent of the flammable landscape burned (215 year FRP, Fig. 3). Of the 39.9-percent (878,522 ha) of the landscape that burned in the past century, 26.3-percent last burned between 1919 and 1939, 6.7-percent last burned between 1940 and 2002, and 6.9-percent last burned between 2003 and 2019 (Fig. 4). Thus, 89-percent of the flammable landscape has not experienced a fire event since 1959. Most pixels only burned once over the past century (84.9-percent of burned area, 833,975 ha). Of the landscape that burned, 15.1-percent experienced reburns (> 1 fire events); 13.6-percent burned twice (133,738 ha), 1.3-percent burned three times (13,143 ha), and 0.1-percent burned four times (1,304 ha) (Fig. 4).

Historically low- and mixed-severity fire regimes are in a deficit, with FRID ranging from 1 to 10 fires missed since 1919 across 46.4-percent of the flammable landscape (Fig. 5, Table 5). The fire deficit is greatest in low-severity fire regimes, with FRID ranging from 6–10 fires missed. However, fire regime departure is also evident in mixed-severity fire regimes, with FRID ranging from 1–6 fires missed (Fig. 5, Table 5). The remaining 53.6-percent of the landscape (FRID 0–1) occurs predominantly in high-severity fire regimes where historical fire frequency exceeds 100 years.

Discussion

Wildfire activity in fire-excluded forests has been increasing across Canada and western North America since the 1980s (Dennison et al. 2014; Coops et al. 2018; Hanes et al. 2019; Coogan et al. 2020; Parks and Abatzoglou 2020; Hagmann et al. 2021). Here we

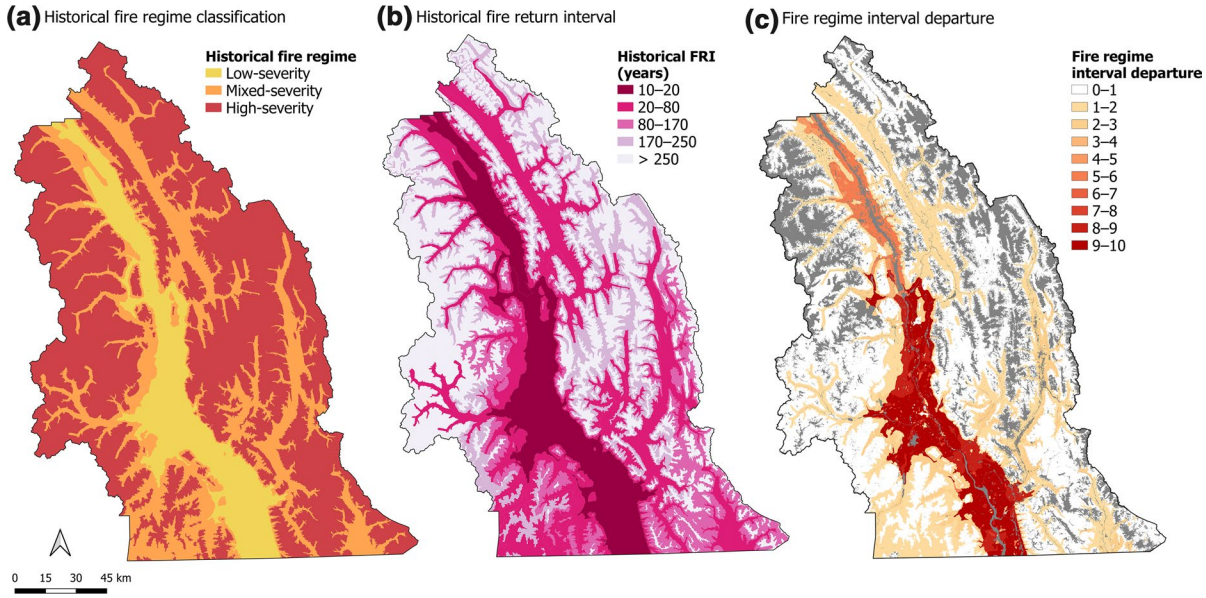


Fig. 5 **a** Historical fire regime classification and **b** historical fire return interval (FRI), derived from fire history reconstructions in the East Kootenays, British Columbia, Canada (see Table 1). **c** Fire regime interval departure (FRID) for the flammable landscape (non-fuel shown in grey), calculated as the current (1919–2019) FRI divided by the historical (1200–1850) FRI (see Table 5). Values between 0–1 indicate no fire deficit; values ≥ 1 indicate the number of fires missed. 46.4-percent of the flammable landscape is in a fire deficit, missing between 1 and 10 fires since 1919

Table 5 Fire regime interval departure (FRID, the number of fire return intervals missed) for the flammable landscape (see Fig. 5)

Fire regimeinterval deficit	% of flammable landscape
0–1	53.6
1–2	23.3
2–3	6.9
3–4	0.3
4–5	0.5
5–6	2.8
6–7	0.1
7–8	0.1
8–9	2.9
9–10	9.5

Values between 0–1 indicate no fire deficit detected; values ≥ 1 indicate the number of fires missed

build on the finding of spatially complex fire regimes in BC (Meyn et al. 2010a) using additional fire regime attributes (number of fires, area burned, mean fire size, and ignition source) and contribute greater time depth in analyses, identifying and defining three distinct phases of fire activity since 1919. Notably, we identify a recent fire regime shift in 2003, confirming that lightning-driven fire activity is increasing in southeastern BC. Further, we link multiple lines of evidence, connecting 20th century fire records and dendrochronological fire history reconstructions (Table 1) to conclude that 46.4-percent of the flammable landscape is in a fire deficit and is departed from pre-colonial fire frequency. Finally, in addition to weather and climate, we consider and discuss the role of fuel, ignition sources, land-use, and management driving variables, which were dynamic throughout the 20th century.

Between 1919 and 1939 the fire regime was active, with large fires still contributing to substantial burned area; however, fire regimes were already altered by a century of colonization and land-use (Hessburg et al. 2019; Greene 2021). Wildfire activity decreased significantly after 1940 and remained low until 2003, coinciding with active fire suppression and a period of relatively cool and moist climate (Morgan et al. 2008; Daniels et al. 2011; Chavardès et al. 2021). The legacy of fire suppression combined with accelerating climatic changes fueled a significant shift in fire

activity after 2003, marked by increased burned area and mean fire size. Prior to this time, human ignitions were an important driver of wildfire activity, with the greatest relative impacts occurring in the 1920s, 1970s and 1980s. The decrease in fires we noted in 1940 was correlated with a decrease in human and lightning ignitions; however, the recent increase since 2003 in burned area and mean fire size was driven by lightning ignitions.

Twentieth century fire regimes reveal a significant fire deficit

When compared to pre-colonial (1200–1850) fire regimes, contemporary fire regimes reveal a significant fire deficit. Only 39.9-percent of this landscape burned in the past century, 26.2-percent of which last burned between 1919 and 1939 (Fig. 4). Of the patches that burned, only 15.1-percent of that area experienced multiple fire events. This stands in marked contrast to the historical fire ecology of these forests. Under conservative estimates of historical fire frequency, forests in the East Kootenays would have burned between 1 and 10 times in the past century, depending on the forest type (Fig. 5). Instead, we find that a minimum of 46.4-percent of the flammable landscape is in a fire deficit. Dry, low elevation forests in the southern RMT experience the largest fire deficit, missing 6–10 fires, due both to the pre-colonial frequency of low-severity surface fire and the extremely effective exclusion of fire over the past century (Figs. 3, 4). Mid-montane and lower subalpine forests are also departed, missing 1–6 fires, and have lost active fire from historically mixed-severity fire regimes.

Given that FRID values were determined using 100 years of fire history, and fire exclusion may exceed 100 years some of in these forests (Greene 2021), these values represent absolute minimum estimates of fire regime departure. The remaining 53.6-percent of the flammable landscape that we are unable to detect a fire deficit in (FRID 0–1) occurs predominantly in subalpine forests with high-severity fire regimes, where historical mean FRIs often exceed 100 years. However, the mean FRI is a central tendency measure that typically includes a broad range of fire return intervals, varying between 5–10 years to intervals that range from 150–200 years for specific patches. In subalpine forests, more frequent fires once pockmarked the landscape to create stabilizing feedbacks. Work by Hessburg et al. (2019) showed that in 5 different US provinces, similar cold forests showed evidence of 25- to 40-percent non-forest and early seral conditions, deriving from this variability in fire frequency. Our approach was not designed to address fire deficits in high-severity fire regimes due to the absence of spatially explicit fire history data prior to 1919. In this light, we expect that we are underestimating FRID of subalpine forests to an unknown degree.

On balance, we found that nearly half of the evaluated landscape was departed from its historical fire frequency and is in a fire deficit which persists across a range of forest types and elevational gradients. The scale of this departure presents a fundamental challenge for modern wildfire management and contemporary fire risk management (Johnston et al. 2020). Wildfires are currently managing the western North American landscape under some of the most extreme fire weather conditions (North et al. 2015). This will continue in accelerating fashion until a more appropriate form of fire is intentionally returned to the landscape.

Through science-based management interventions, we can facilitate re-entry of fire to the ecosystem and maintain its stabilizing feedbacks to the broader landscape (Hessburg et al. 2021). Managing fuels, protecting people and infrastructure, and restoring an active and more benign fire regime will require broadly applied thinning and fuel reduction, prescribed and cultural burning, and managed wildfire treatments (North et al. 2021; Prichard et al. 2021). Integrated landscape planning will be needed to address both the effects of inaction (i.e., continued fire suppression) and of actions taken to return fire as a stabilizing ecosystem process (Hessburg et al. 2021).

Three distinct phases of fire activity from 1919–2019

An active but altered fire regime: 1919–1939

In the early 20th century, fires were frequent and large with 38.1-percent of the flammable landscape experiencing a fire event (55 year FRP, Fig. 3). Of the 10 largest events in the record (all > 20,000-ha in size), 9 occurred between 1919 and 1939. Although fires occurred abundantly during droughts and a warm phase of the Pacific Decadal Oscillation (PDO)

from 1925 to 1945 (Morgan et al. 2008; Daniels et al. 2011), they were markedly different from pre-colonial fire regimes, having already been altered by a century of colonial land-uses (Hessburg et al. 2019; Greene 2021).

While large portions of the landscape were burning, development and changes in land-use resulted in altered fuel structures that differed from pre-colonial landscapes, increasing fire severity and fire effects. For example, widespread 19th-century land clearing by colonists for homesteads and agricultural use eliminated many grassland and meadow areas that had formerly functioned as "conveyor belts", spreading early 20th century fires from lowland valleys to mid- and upper elevation forests (Hessburg and Agee 2003; Hessburg et al. 2005, 2019). In the 1920s and 30s, residual slash from early logging combined with persistent drought to produce large and uncontrollable wildfires (Dombeck et al. 2004).

Human ignitions coupled with lightning from late-summer thunderstorms (Agee 1996; Wierzchowski et al. 2002) drove high levels of fire activity. In the early twentieth century, the source of human ignitions shifted from pre-colonial, low-severity, Indigenous cultural burning (Lewis et al. 2018; Lake and Christianson 2019; Greene 2021) to intentional and unintentional ignitions of varying severity set by Euro-Canadian colonists. Unintentional human ignitions often resulted from sparks created by rail cars of the Canadian Pacific Railway and campfires of settlers moving along recently established trails and travel corridors (Parminter 1981; Dombeck et al. 2004; Pogue 2017). Intentional or accidental settler ignitions associated with resource extraction (e.g., hillslope burning to expose mineral or precious metal veins, loggers using yarding machinery and locomotives to convey logs to sawmills) were also common during this period, contributing to the large fires of the era (Parminter 1981; Drushka 1998). As repeat low-severity Indigenous burning was replaced by incidental settler ignitions, large portions of the landscape burned, but the Indigenous land stewardship and governance systems that targeted ecological and cultural objectives were lost (Copes-Gerbitz et al. 2022).

Fire suppression era: 1940–2003

Beginning in the early 1940s, wildfire activity rapidly declined with a 79-percent decrease in annual number of fires, 93-percent decrease in area burned, and 77-percent decrease in mean fire size (Fig. 1, Table 2). From 1940 to 2002, only 8.5-percent of the flammable landscape burned, with a 740 year FRP already revealing a severe fire deficit (Fig. 3). A disruption in fire frequency is also observed in dendrochronological and fire history records after 1940, which is attributed to variations in the Earth climate, the elimination of Indigenous cultural burning (Lake and Christianson 2019), and fire exclusion by various means (Marcoux et al. 2015; Chavardès et al. 2018, 2021; Greene 2021). Low temperatures and high precipitation, a cool PDO phase from 1946–1976, and the absence of extreme fire weather conditions in the mid-twentieth century (Morgan et al. 2008; Meyn et al. 2010b, 2013; Daniels et al. 2011; Chavardès et al. 2021) supported a growing fire suppression program.

Following WWII, several technologies were adopted to fight the war on wildfire, with the integration of military incident command systems (Dague and Hirami 2015) and technology (e.g., aerial imagery, heavy machinery, chainsaws, and an aerial attack fleet) (Dombeck et al. 2004; Copes-Gerbitz et al. 2022). The cool and wet conditions of the 1940s and 1950s (Appendix A; Morgan et al. 2008; Meyn et al. 2013) provided time for newly augmented fire suppression systems and technology to develop, as personnel and equipment became widely integrated. As the climate began to shift to warmer conditions with anthropogenic climate change and a warm PDO phase beginning in 1977 (Appendix A; Morgan et al. 2008; Daniels et al. 2011), a potential increase in wildfire activity was met by additional advances in wildland fire science and technology (e.g., Canadian Forest Fire Danger Rating System, Fire Weather Index System) which kept wildfire activity low (Stocks et al. 1989; Coogan et al. 2021). Notable fire seasons with large fire events escaping suppression became relatively rare and only occurred under extreme fire weather conditions (Appendix A; Aikenhead 1985).

While burning was excluded from fire-adapted forests for over a century, land-use practices became increasingly industrialized. Forests were harvested

for their large, old, fire-tolerant trees and regenerated (as Douglas-fir) or were intentionally replanted (as lodgepole pine) as high-density monocultures, of preferred commercial species, and at large spatial scales (McWilliams and McWilliams 2009; Marcoux et al. 2015). These management decisions resulted in increased fuel connectivity, physiognomic and forest successional heterogeneity (Hessburg et al. 2015, 2019; Greene 2021; Hagmann et al. 2021). The absence of historically frequent surface fires drove fuel accumulation in dry pine, interior Douglas-fir, and western larch forests, as grasslands and meadows, sparse woodlands, and forests systematically filled in with fire-intolerant trees, creating abundant fuel ladders (Hessburg et al. 2019; Greene 2021). These transitions created hazardous conditions conducive to high-severity crown fire-driven events (Stockdale et al. 2019; Hagmann et al. 2021).

The modern era of wildfire: 2003–present

In 2003, an exceptional fire season (the "2003 Firestorm") threatened many communities and exceeded suppression capabilities (Filmon 2004). We identified a phase transition in fire activity in 2003, after which point burned area and mean fire size increased significantly (Fig. 2, Table 3). Confidence intervals (CIs) around the timing of this breakpoint are large at the lower end of the estimate (Table 3), but the upper end of the CI (2005) for burned area and fire size suggest that this was an important shift. The 2003 fire season was widely regarded as a harbinger of the dangers to come, with record-breaking 2017, 2018, and 2021 fire seasons (Abbott and Chapman 2018; BC Wildfire Service 2021b) confirming that extreme fire years continue to increase in frequency.

Since 2003, the annual number of fires increased by 29-percent, while burned area increased by 265-percent, and mean fire size by 152-percent (Fig. 1, Table 2). The FRP decreased to 215 years but remains clearly departed from pre-management era fire frequency (Fig. 3, Table 2). These levels of fire activity are still lower than those of the early 20th-century, and under low to moderate fire weather conditions (the most numerous days), wildfire suppression still remains highly effective (BC Wildfire Service 2021e). Increasingly, when fires escape suppression, they exhibit dangerous fire behavior, occurring under the most extreme fire weather conditions that are influenced by climate change (Wang et al. 2015; Parks and Abatzoglou 2020; Zhuang et al. 2021). Decreasing summer precipitation, prolonged extreme temperatures, and drought clearly enabled recent extreme fire seasons in 2017, 2018, and 2021 (Holden et al. 2018; Kirchmeier-Young et al. 2019; Higuera and Abatzoglou 2021).

The continued growth of the wildland-urban interface (WUI) into highly fire-prone environments further increases the potential for human ignitions in hazardous fuels (Balch et al. 2017) and the likelihood that fires will be suppressed to protect values at risk (Camp 2016; Parisien 2016; Johnston and Flannigan 2018). Patterns of aggressive fire suppression are evident in the southern RMT of the East Kootenays (Fig. 3), where population density is high and ignitions are quickly suppressed, re-enforcing the greatest fire deficit (Fig. 5). The combination of climate change, fuel accumulation, WUI exposure, and a century of colonial land-uses has created a volatile environment for high severity fires that now threaten human communities and other ecological and social values.

Increasing importance of lightning ignitions

Lightning is a major driver of fire activity in the East Kootenays. In southeastern BC, lightning discharges are 28 times more likely to cause a fire event with 2.3–2.6 times higher fire severity rating compared to southwestern Alberta (Wierzchowski et al. 2002). Notably, the relative importance of lightning ignitions is also increasing. Lightning ignitions drove the 2003 shift in wildfire activity (Fig. 2, Table 3) and were responsible for 80-percent of the total fire events and 97-percent of burned area since 2010, compared to 28- and 52-percent, respectively, in the 1920s (Table 4). Increases in lightning-caused fires in western Canada were also found by Hanes et al. (2019) and Coogan et al. (2020). While using a similar dataset over a longer time period, our findings may have benefited from increased report efficiency, as lightning detection systems have improved over time. However, recent research also suggests that climate change is increasing the frequency of lightning discharges and lightning-caused fires in the Pacific Northwest (Romps et al. 2014; Veraverbeke et al. 2017) which are favored by increased frequency of dry convective storms (Rorig and Ferguson 1999).

Human factors related to management and suppression likely contribute to patterns in lightning ignitions and escaped wildfires as well. The success of public messaging initiatives (e.g., fire prevention) beginning in the early 20th-century may in-part explain the progressive decline in importance of human ignitions. Compared to human ignitions, which are concentrated close to infrastructure, travel routes, and resources (Balch et al. 2017), lightning ignitions occur as clusters, often in remote locations where suppression can be logistically difficult (Wierzchowski et al. 2002; Podur and Wotton 2010; Blouin et al. 2016). In severe wildfire seasons when suppression resources may become limited, suppression of lightning-caused fires in the backcountry is often deferred in favor of suppressing those that threaten human communities and WUI in the front country (Podur and Wotton 2010). These trends may partially explain the greater size and area burned by lightning-caused fires since 2003.

Fire perimeters illustrate where fire suppression failed

Observations of fire events during an era of intensive land-use and resource management show us where fire suppression was unsuccessful at meeting its intended goals. In BC, the BCWS has successfully suppressed 94-percent of all wildfires before they reached 4-ha in size (the definition for initial attack success) by 10-am the morning after detection (the 10-AM Rule; BC Wildfire Service 2012, 2021b). By only analyzing fires > 20-ha in size (i.e., those that escape initial attack), we find strong evidence of a shift in wildfire regimes even under the influence of extremely effective fire suppression. These findings begin to quantify the extent to which East Kootenay fire regimes have been disrupted.

Limitations and future work

The wildfire perimeters dataset, while representing a long, spatially explicit record of wildfire in Canada, is neither exhaustive nor without error. Small fires have not been mapped (Taylor et al. 2006) and the accuracy of fire perimeters likely varies over time due to differing mapping techniques (see Skakun et al. 2021). For example, historical fire perimeters frequently overestimate burned area by not excluding unburned and unburnable (e.g., water, rock, bare ground) areas within fire (Andison 2012; Meddens et al. 2016; Skakun et al. 2021). Furthermore, while it is often assumed that large historical fires are generally recorded (even if fire perimeter accuracy is variable), small and remote historical fire events are often missing from records. This dataset contains the only digital record of fire events prior to 1950. Although the completeness of this period of record (1919–1950) cannot be independently verified, the sum of annual area burned agrees with provincial estimates for the same time period (Taylor et al. 2006). Further, although spatial accuracy of fire perimeters may be variable, records for the East Kootenay region are reported as being geographically complete (Taylor et al. 2006). However, integrating smaller fire events into the larger datasets remains an important goal because these fires are by far the most numerous (Moritz et al. 2011; Perry et al. 2011) and they are influential to fire flow on the landscape (Hessburg et al. 2019).

In addition to the fire regime attributes considered (fire frequency, burned area, fire size, ignition source), fire severity is another key dimension that is critically departed on the modern landscape (Hessburg et al. 2019, 2021). We find that while modern fire activity is increasing, recent increases in large high-severity fire events do not emulate the conditions of pre-colonial landscapes maintained by frequent low-severity surface fires (Parks and Abatzoglou 2020; Hagmann et al. 2021). Although we were not able to quantify fire severity transitions in this study, it remains an important attribute to characterize fire regime departures. Additional fire regime attributes (e.g., seasonality, duration) are also vital to quantifying the extent to which fire regimes have shifted (Hessburg et al. 2021); however, many of these attributes are not available for landscapes prior to 1980.

Conclusions

Using a century of historical fire perimeter data and several fire regime attributes, we find that modern fire regimes in the East Kootenays are significantly departed from pre-colonial fire regimes, transitioning through three distinct phases to the present. Fire was active from 1919 to 1939, with frequent, large fire events across the landscape, but altered from

historical regimes by a century of colonial land-use and the loss of Indigenous burning. Fire activity decreased after 1940 and remained low—coinciding with a new period of active and effective fire suppression facilitated by a coincident period of cool and moist climate. In 2003, the combined effects of fire suppression and accelerating climate change fueled another shift in wildfire activity, with increases in burned area and mean fire size driven by lightning ignitions. As a result of these changes, low- and mixed-severity fire regimes (46.4-percent of the flammable landscape) are in a fire deficit, missing between 1 and 10 fires since 1919.

Our findings begin to quantify the extent to which East Kootenay fire regimes have been disrupted. Additional research is needed to identify where surface and canopy fuels have most accumulated, the effects of fire exclusion on subalpine and non-forest areas, how future fire will behave in response to these accumulated fuels, where fuel treatments, prescribed fire, and other restorative or adaptive treatments are most appropriate, and how climate warming will influence the need for and efficacy of fuel treatments. The policies that drove transitions in fire regimes reflect the perspectives and values of the era, a phenomenon that remains true in every time period. The extent of fire regime disruption warrants significant management and policy attention, reflecting on decisions and actions that can alter the current trajectory, and facilitate better co-existence with wildfire throughout this century as the climate steadily warms.

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Author contributions JNB, SEG, PFH, and LDD: conceived and designed the study. JNB: analyzed the data, interpreted the results, and drafted the initial manuscript. SEG, PFH, and LDD: contributed to several manuscript revisions.

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Data availability The data used in this manuscript are publicly available through DataBC and can be accessed at https://catalogue.data.gov.bc.ca/dataset/fire-perimeters-historical.

Code availability The R code used in this research is available upon request.

Declarations

Conflict of interest The authors declare no conflicts of interest.

Ethical approval Not applicable.

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