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

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

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Abstract

The past 100 years marks a transition between pre-colonial and modern era fire regimes, which provides crucial context for understanding future wildfire behavior. Using the greatest 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 forest region (including the southern Rocky Mountain Trench), British Columbia (BC). We detect transitions in annual number of fires, burned area, and fire size; explore the roles of lightning- and human-caused fires in driving these transitions; and quantify departures from historical fire frequency at the regional level. We found that, relative to historical fire frequency, fire exclusion created a significant fire deficit across 89% of the flammable landscape. Fire was active from 1919 to 1940 with frequent and large fire events, but the regime was already altered by a century of

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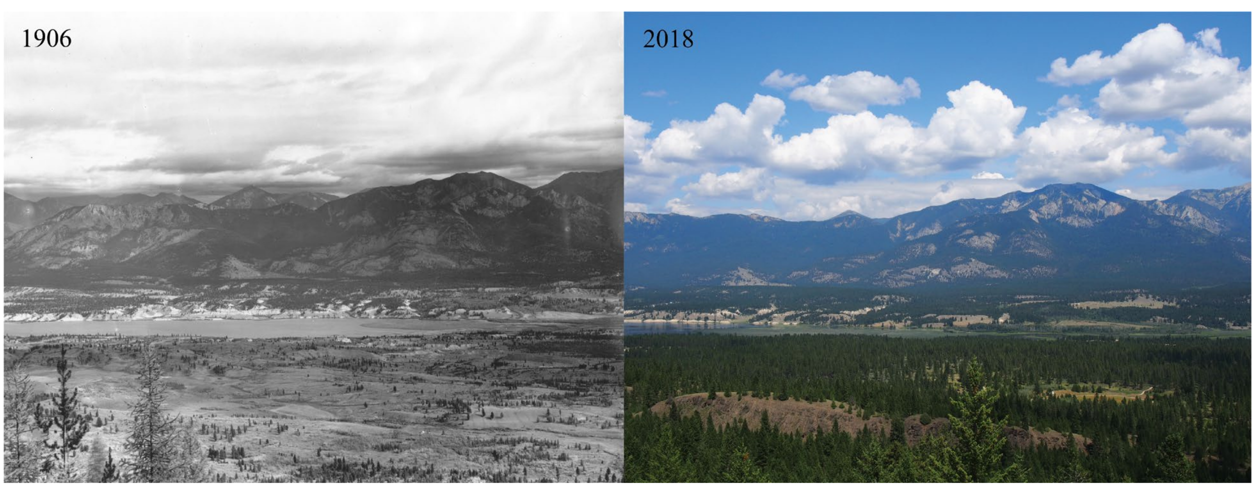
colonization. Fire activity decreased after 1940, coinciding with effective fire suppression influenced by a mild climatic period. After 2003, the combined effects of fire exclusion and accelerated climate change fueled a shift in fire regimes of various forest types, with increases in area burned and mean fire size driven by lightning. (198 Words)

Keywords: Fire suppression, fire return interval, East Kootenays, Rocky Mountain Trench, Indigenous fire stewardship, historical ecology, reburning, mixed-severity, historical range of variability, breakpoint analysis, land management, natural disturbance, landscape heterogeneity, spatial pattern of fire

Brief Summary

Wildfire in southeastern British Columbia has shifted through three phases since 1919. Fires were large and frequent from 1919–1940, small and infrequent from 1940–2003, and have become more active since 2003. Over a century of fire exclusion created a fire deficit across 89% of the landscape.

Graphical Abstract



Word Count: 5,211

1. Introduction

Wildfire activity has increased in the western North America since the mid-20th century (Hagmann *et al.* 2021), with increases in fire frequency, burned area, number and size of large fires, fire severity, frequency of lightning-caused fires, and length of the fire season (Dennison *et al.* 2014; Coops *et al.* 2018; Hanes *et al.* 2019; Coogan *et al.* 2020; Parks and Abatzoglou 2020). Increasingly, fires exhibiting extreme behavior and exceeding suppression capabilities are being driven by lightning and human ignitions (Romps *et al.* 2014; Balch *et al.* 2017; Veraverbeke *et al.* 2017), increased forest area, forest density and woody fuels (Hagmann *et al.* 2021), and climatic warming (Gillett *et al.* 2004; Abatzoglou and Williams 2016; Parks and Abatzoglou 2020; Higuera and Abatzoglou 2021; Alizadeh *et al.* 2021).

This modern era of wildfire contrasts sharply with fire regimes of the past, threatening more frequent, larger, and more intense fire events that threaten communities, ecosystems, and social values (Coogan *et al.* 2019). A fire regime describes the spatial and temporal occurrence and impacts of active wildfires within a given area and period (Hanes *et al.* 2019; Coogan *et al.* 2021). Attributes of fire regimes include fire frequency, burned area, fire size, intensity, severity, duration, seasonality, and spatial distribution. Multiple fire regime attributes must be evaluated to effectively characterize fire regimes and estimate departures from native or active fire regimes (Daniels *et al.* 2017; Hagmann *et al.* 2021, Hessburg *et al*. 2021).

The past 100 years marks a significant transition between historical and modern fire regimes. Knowledge of this transition provides crucial context for fire regimes of the future. Continuous sources of fire data from the early 20th-century (*e.g.,* documentary records, dendrochronology, fire history studies, repeat aerial and panoramic photography, Indigenous ecological knowledge) can be used to quantify fire regimes departures (Safford *et al.* 2012; Buma *et al.* 2019; Coogan *et* *al.* 2021) from the historical range of variability (HRV)—a range of responses and conditions of a resilient ecosystem under past disturbances and stressors (Keane *et al.* 2009, 2018, 2019; Hagmann *et al.* 2021). When used in tandem, historical and contemporary approaches can advance the understanding of fire regimes and the factors that drove their transformation into the present.

Analyses of fire regime changes in Canada have historically focused on large fire events (>200-ha) and a limited selection of fire regime attributes—commonly, the number of fires and area burned (Podur *et al.* 2002; Stocks *et al.* 2002; Kasischke and Turetsky 2006). While regional studies have combined data sources and techniques to increase temporal depth, this has come at the cost of observing trends among numerous fire regime attributes (Bergeron *et al.* 2004; Girardin and Mudelsee 2008; Rogeau *et al.* 2016; Portier *et al.* 2016).

Although recent research has improved the accuracy of historical area burned estimates (Skakun *et al.* 2021) and the number of fire attributes considered (Meyn, Schmidtlein, *et al.* 2010; Meyn, Taylor, *et al.* 2010), analyses generally focus on datasets beginning in the mid- to late- 20th century at regional (Burton *et al.* 2008; Albert-Green *et al.* 2013; Veraverbeke *et al.* 2017; Campos-Ruiz 2018) and national (Coogan et al., 2020; Coops et al., 2018; Hanes et al., 2019) scales. Further, these studies generally investigate fire regimes changes after a single impress of fire, despite multiple lines of evidence that fire regimes through the 20th century have been spatially and temporally dynamic (Naficy *et al.* 2015; Naficy 2016; Hessburg *et al.* 2019; Greene 2021; Hagmann *et al.* 2021).

In British Columbia (BC), Canada, record-breaking fire seasons in 2017 and 2018 fueled by anthropogenic climate change (Kirchmeier-Young *et al.* 2017; Kirchmeier-Young *et al.* 2019) burned over 1.2 million ha in both years (Wang and Strong 2019). These increasingly severe and frequent fire seasons contrast 20th century fire regimes (Hanes *et al.* 2019; Coogan *et al.* 2020), as fire suppression effectiveness rapidly declines under extreme fire weather conditions (Wotton *et al.* 2017). Provincial fire perimeter records in BC cover 94.4 million ha and represent the greatest time depth of digitized fire events in Canada (BC Wildfire Service 2021a; Skakun *et al.* 2021), providing an opportunity to understand 20th century fire regime transitions at regional and landscape scales.

In the East Kootenay forest region of southeastern BC, a disrupted low- and mixed-severity Indigenous fire regime (Da Silva 2009; Marcoux *et al.* 2015; Chavardès and Daniels 2016; Greene 2021) and contemporary wildfire risk (Kirchmeier-Young *et al.* 2017; Johnston *et al.* 2020) create incentive to understand wildfire transitions over the past century. Here, we map a century of historical fire perimeters (>20 ha) across 2.8 million ha in the East Kootenay Regional District, BC, Canada (Fig. 1), to identify and evaluate distinct phases of wildfire regimes from 1919 to 2019. Specifically, we detect 20th-century transitions in the annual number of fires, burned area, and fire size; explore the roles 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, ignition, land-use and management driving variables.

2. Materials and methods

2.1 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, 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 and subalpine 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 pine from 2002–2012 (Walton 2013; Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2021). In mesic montane valleys adjacent to the RMT, 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) in the valley bottom (750–1000 m), but becomes slightly 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). 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), temperatures are lowest (< 0°C) and precipitation is abundant (up to 2200 mm), predominantly occurring as snow (50–70%) (Meidinger and Pojar 1991).

2.2 Historical fire perimeters

We used the British Columbia Wildfire Service (BCWS) Historical Fire Perimeters GIS database (BC Wildfire Service 2021a), which documents fire events since 1919 (in the East Kootenays) and is updated annually. Fire events are 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., sketch map, buffered point, GPS digitization) used to spatially represent the event (BC Wildfire Service 2021a). Pre-2000 fire event features were obtained from the Pacific Forestry Centre (Victoria, BC) through the BC Natural Disturbance Database project (2006), which digitized and georeferenced historical hardcopy maps. Post-2000 features were collected using GPS, satellite, drone, and low altitude fixed wing aircraft observations and obtained from the BC Wildfire Service (BCWS) and Forest Analysis and Inventory Branch (BC Wildfire Service 2021a).

We supplemented the BCWS Historical Fire Perimeters dataset with 9 other wildfire events contributed by Parks Canada within the borders of Kootenay National Park from the Canadian National Fire Database (CNFDB, Canadian Forest Service 2020). We excluded fires <20-ha in size from our analysis because historical fires <20-ha were not digitized by Taylor *et al.* (2006). Given our aim of investigating broad patterns in shifting fire regimes over a regional spatial scale (2.8 million ha), we consider 20-ha to be a sufficient recording threshold. We evaluated fires caused by lightning (n=416) or human (n=504) ignitions. We included fire event polygons intersecting or wholly included in the East Kootenays to ensure inclusion of all events influencing the region.

2.3 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). Breakpoint analyses were conducted in R (version 4.0.5) statistical software (R Core Team 2021) using the *strucchange* package (Zeileis *et al.* 2002). Breakpoints are statistically derived abrupt variations in time series data which may represent important phased transitions in the value of an attribute (Aminikhanghahi and Cook 2017). We used ordinary least squares (OLS) regression-based CUSUM tests and the Bayesian information criterion (BIC) to determine the most parsimonious breakpoint number, and built segmented regression models following methods of Zeileis et al. (2003, 2005). We selected this particular procedure after assessing multiple modelling constructs to optimize trade-offs between statistical power and type I error probability while maintaining low temporal autocorrelation (Militino *et al.* 2020).

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.

2.4 Comparisons to historical fire frequency

To quantify departures from historical fire frequency, we calculated time since fire for the flammable landscape (excluding areas of rock, water, and ice or permanent snowpack) and the number of fire events (burns and reburns) across the landscape. Using the georeferenced historical fire perimeters dataset, we used a geographical information system (GIS) (ESRI Inc. 2020) to derive a 30-m raster layer containing the year of the most recent fire event and calculated time since fire (from 1919 to 2019) for each pixel of all overlapping and non-overlapping fire events within the East Kootenay region. We selected the flammable landscape using the BCWS Fire Fuel Types dataset (BC Wildfire Service 2020), 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.

2020), which can identify the number of fire events in each pixel. We calculated the area and proportion of the landscape occupied for each decade (time since fire) and number of burns (reburns) using the *landscapemetrics* package in R (Hesselbarth *et al.* 2019). Finally, we calculated the fire return interval (FRI; the average number of years between the occurrence of fire, Coogan *et al.* 2021) on the flammable landscape for the phases identified through breakpoint analysis.

3. Results

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

3.1 Fire regime phase transitions

We detected significant changes in 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, Fig. 3, Table 2). 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 2). 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 1).

Annual number of fires was initially high and decreased from 1919 to 1940 at a rate of about 1 fire per year (Fig. 2, Table 2). Between 1940 and 2019, the number of fires was low, and the rate of change decreased significantly to 0.01 fires per year ($p = 6.76\times10^{-4}$). Phase transitions in number of fires were detected in 1940 for lightning-caused fires and 1936 for human-caused fires (Table 2, Fig. 2). The number of human-caused fires declined from 1919 to 1936, 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) (Fig. 1, Table 1). Lightning-caused fires increased to >50-percent relative abundance in the 1930s, 1950s, and 2000s, and up to 80-percent in the 2010s (Fig. 1, Table 1).

Area burned was initially low and increased between 1919 and 1936 at a rate of 3,320 ha · yr^{-1} (Fig. 2, Table 2). Area burned subsequently decreased and remained low from 1936 to 2004, 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, and 1934 for human-caused fires (Fig. 2, Table 2). Area burned by lightning ignitions increased from 1919 to 1936, then decreased in 1936 and plateaued until 2004 ($p = 1.94\times10^{-4}$). 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 area occurring in the 2000s (93-percent) and 2010s (96.8-percent, Fig. 1, Table 1).

Mean fire size was initially low and increased from 1919 to 1936 at a rate of 105 ha · yr^{-1} (Fig. 2, Table 2). Mean fire size subsequently decreased and remained low from 1936 to 2003, increasing at a rate of 0.64 ha · yr^{-1} ($p = 4.81\times10^{-3}$). 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 (Table 2, Fig. 2). Mean lightning fire size increased significantly from 1919 to 1936, decreased in 1936, and plateaued until 2004 ($p = 1.01 \times 10^{-2}$), after which time it increased until 2019 (Fig. 2, Table 2).

3.2 Time since fire and reburning frequency reveal a major fire deficit

The majority 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 1940, 38.1-percent of the flammable landscape burned (55 year FRI, Fig. 3). From 1940 to 2003, 8.5-percent of the flammable landscape burned (740 year FRI, Fig. 3). Finally, from 2003 to 2019, 7.9-percent of the flammable landscape burned (203 year FRI, 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 1940, 6.7-percent last burned between 1940 and 2000, and 6.9-percent last burned between 2003 and 2019 (Fig. 4). Most pixels only burned once over the past century (84.9-percent, 833,975 ha). Of the landscape that burned, 15.1-percent experienced reburns (multiple 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).

4. Discussion

We widely recognize that wildfire activity has been increasing in Canada and western North America since the 1980s (Kasischke and Turetsky 2006; Morgan *et al.* 2008; 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 analyze multiple fire regime attributes using an additional 60 years of data (1919–2019) in a regional context (2.8 million ha), to find a recent (2003) fire regime shift in the East Kootenays driven by lightning ignitions. In addition to a recent increase in wildfire activity, we identify and describe three distinct phases of fire activity since 1919. Finally, we connect 20th century fire records to dendrochronological reconstructions, concluding that the majority of the landscape is in a fire deficit and is significantly departed from pre-colonial fire frequency.

Between 1919 and 1940 the fire regime was active with large fires contributing the substantial burned area; however it was altered by centuries of colonization and land-use. Wildfire activity decreased significantly and was low after 1940 until 2003, coinciding with active fire suppression and a period of relatively cool and moist climate (Appendix A). A legacy of fire suppression combined with accelerating climatic changes fueled a significant shift in fire activity after 2003, marked by increased burned area and average 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 fire activity we noted in the 1940s was correlated with a decrease in both human and lightning ignitions; however, the recent increase since 2003 in burned area and mean fire size was driven primarily by lightning ignitions.

4.1 Modern fire regimes are departed from historical fire frequency

When compared to pre-colonial (1600–1850) fire regimes, contemporary fire regimes reveal a significant fire deficit. Supported by Indigenous burning, open forest canopy conditions, and limited woody surface fuels, frequent surface fire events historically occurred at 7 to 15 year intervals in dry valley bottom and lower montane settings (Greene 2021), and moderately frequent low and moderate severity fire events occurred at 7 to 56 year intervals in mid-montane and lower subalpine forests (Da Silva 2009; Marcoux *et al.* 2013, 2015). However, only 39.9-percent of this landscape burned in the past century, 26.2-percent of which last burned between 1919 and 1940. Of the patches that burned, only 15.1-percent of that area experienced multiple fire events (Fig. 4). Using these conservative estimates of historical fire frequency, forests in the East Kootenays would have likely burned at least twice in the past century. Instead, we find that at least 89% of the flammable landscape has not experienced a fire event in at least 60 years (Fig. 4) and is missing between 1 and 14 fires, depending on the forest type. Based on these findings, we suggest that the majority of the landscape is departed from its pre-colonial fire frequency. Dry, low elevation forests in the southern RMT are most departed due both to the historical frequency of low-severity surface fire (Greene 2021) and the extremely effective exclusion of fire over the past century, creating a large fire deficit (Fig. 3, Fig. 4). This level of departure presents a fundamental challenge for modern wildfire management.

4.2 20th century fire-regime transitions

4.2.1 An active but altered fire regime: 1919–1940. In the early 20th century, fires were frequent and large with 38.1-percent of the flammable landscape experiencing a fire event (55 year FRI, Fig. 3). Of the 10 fire events in the record (all >20,000-ha) in size, 9 occurred between 1919 and 1940. Although fires were abundant during the droughts of the 1920s and 1930s (Appendix A), they were markedly different from historical fire regimes (Hessburg *et al.* 2019;

Greene 2021), having already been altered by a century of colonial land-use. Widespread 19th-century land clearing for homesteads and agricultural use by settlers, often using fire, (Fulton 1910; Whitford and Craig 1918; Dombeck *et al.* 2004) had produced grasslands and meadows, which served as conveyor belts for spreading the early 20th century fires (Hessburg et al. 2019). In the 1920s and 30s, residual slash from early logging combined with persistent drought produced large and uncontrollable wildfires (Dombeck et al. 2004), while an era of natural resource extraction began to permanently alter forests and fuels (Drushka 1998; Daniels *et al.* 2011).

Human ignitions coupled with lightning from late-summer thunderstorms (Agee 1993; Wierzchowski *et al.* 2002) drove high levels of fire activity. However, the source of human ignitions shifted from pre-colonial low-severity Indigenous ecocultural burning to intentional and unintentional ignitions of varying severity set by Euro-Canadian colonists. Unintentional human ignitions in the early 20th-century 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 and those associated with resource extraction (hillslope burning to expose mineral veins, loggers using machinery and locomotives) were also common during this period, contributing to the large fires of the era (Parminter 1981; Drushka 1998).

4.2.2 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 1). From 1940 to 2003, only 8.5-percent of the flammable landscape burned, with a 740 year FRI revealing a severe fire deficit (Fig. 3). A disruption in fire frequency is also observed in fire history and cohort analyses after 1940, which is attributed to variations in climate, elimination of Indigenous burning, and fire exclusion by various means (Da Silva 2009; Marcoux et al. 2015; Chavardès and Daniels 2016; Greene 2021). Mild climate in the mid-20th-century (Appendix A) supported a growing fire suppression program (Morgan *et al.* 2008; Meyn *et al.* 2013). 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, an aerial attack fleet) (Dombeck *et al.* 2004; Copes-Gerbitz *et al.* submitted). The cool and wet conditions of the 1940s and 1950s (Appendix A) provided time for newly augmented fire suppression systems and technology to develop (Morgan *et al.* 2008), as suppression personnel and equipment became widely integrated.

As the climate began to shift to warmer conditions in the 1970s and 1980s (Appendix A) 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 multiple fire events escaping suppression became relatively rare (*e.g.,* 1985) (Aikenhead 1985) and occurred under extreme fire weather conditions, hinting at the fragility of a wildfire management system.

While burning was excluded from fire-adapted forests for over a century, land-use practices became increasingly industrialized. Forests were harvested for large, old, early-seral trees and restocked as high density monocultures of preferred species at large spatial scales (McWilliams and McWilliams 2009) resulting in increased fuel connectivity and lost heterogeneity (Chavardès and Daniels 2016; Hessburg *et al.* 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, sparse woodlands, and forests filled in with fire-intolerant species and fuel ladders. These transitions created hazardous conditions that were conducive to high-severity crown fire-driven events (Stockdale *et al.* 2019; Hessburg *et al.* 2019; Greene 2021; Hagmann *et al.* 2021).

4.2.3 The modern era of wildfire: 2003–present. At the turn of the 21st-century, an exceptional fire season threatened WUI communities, warning that complete control may be a concept of the past. The "2003 FireStorm" (Filmon 2004) was an especially damaging fire season, marking a tipping point in BC. For the first time, provincial fire suppression resources were unable to meet demands, as large fire events displaying unprecedented fire behavior threatened communities and resulted in over 45,000 evacuations (BC Wildfire Service 2021b). We identified a phase transition in fire activity in 2003, after which burned area and mean fire size increased significantly (Fig. 2). Confidence intervals (CIs) around the location of this breakpoint are large at the lower end of the estimate (Table 2), but the upper end of the CI at 2005 for burned area and fire size suggest that this was an important shift in fire regime attributes. Although 2003 was widely regarded as a harbinger of the dangers to come, record-breaking 2017 (Abbott and Chapman 2018), 2018, and 2021 fire seasons confirm that extreme fire years are becoming increasingly frequent.

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 1). The fire return interval decreased to 203 years but remains departed from historical fire frequency (Fig. 3). These levels of fire activity are lower than those of the early 20th-century, and under low to moderate fire weather conditions (the most numerous days), wildfire suppression remains highly effective (BC Wildfire Service 2021c). Increasingly, when fires escape suppression, they exhibit dangerous fire behavior because they occur under the most extreme fire weather conditions that are driven by climate change (Higuera & Abatzoglou, 2021; Kirchmeier-Young et al., 2019; Parks & Abatzoglou, 2020; Wang et al., 2015).

Meanwhile, the continued growth of the wildland-urban interface (WUI) further increased the potential for human ignitions in hazardous fuels (Balch *et al.* 2017), and the likelihood that fires would be suppressed to protect values at risk (Camp 2016; Parisien 2016; Johnston and Flannigan 2018). Patterns of aggressive and effective fire suppression are most apparent in the southern RMT of the East Kootenays (Fig. 3), where population density is highest and ignitions are quickly and effectively suppressed. The combination of climate change, fuel accumulation, WUI exposure, and a century of colonial land-uses created a volatile environment, producing high severity fires which now threaten communities and other ecological and social values.

4.3 Increasing importance of lightning ignitions

Lightning has historically been a major driver of fire activity in the East Kootenays. In southeastern British Columbia, 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 importance of lightning ignitions is also increasing. Lightning ignitions drove the 2003 shift in wildfire activity (Fig. 2, Table 2) 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 1). Increases in lightning-caused fires in western Canada were also found by Hanes et al. (2019) and Coogan et al. (2020). Using a similar dataset over a longer time period, this finding may be the result of increasing report efficiency, as lightning detection systems have been improved over time. However, recent research suggests that climate change is increasing the frequency of lightning discharges and lightning-caused fires in the Pacific

Northwest as well (Romps *et al.* 2014; Veraverbeke *et al.* 2017). Nonetheless, human factors related to management and suppression likely contribute to patterns in lightning ignitions and escaped wildfires.

The success of public messaging initiatives (i.e., radio advertisements, highway signs, and more recently social media) 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 in remote locations where suppression is 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 are threatening human communities and WUI in the front country (Podur and Wotton 2010).

4.4 Fire perimeters illustrate where fire suppression failed

The wildfire perimeters dataset, while representing the longest spatially explicit provincial record of wildfire in Canada, is neither exhaustive nor without error. Not all fires have been mapped (Taylor *et al.* 2006) and the accuracy of fire perimeters likely varies due to differing mapping techniques (Skakun *et al.* 2021). For example, historical fire perimeters frequently overestimate burned area by not excluding unburned areas within fire perimeters and unburnable areas (e.g., water, rock, bare ground) (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.

Our analysis focused on evaluating trends at a regional scale. We intentionally excluded fire events <20-ha in size owing to these detection concerns. 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) and they are influential to blocking and shaping fire flow on the landscape. Additional fire regime attributes (*e.g.,* seasonality, duration, fire severity) are also vital to quantifying the extent to which fire regimes have shifted (Hanes *et al.* 2019; Parks and Abatzoglou 2020; Hagmann *et al.* 2021; Coogan *et al.* 2021); however, many of these attributes are not available for landscapes prior to 1980.

Most importantly, observations of fire events during an era of intensive land-use and management show us where fire suppression was unsuccessful at meeting its intended goals. In British Columbia, 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 associated with extremely effective fire suppression. Our findings begin to quantify the extent to which the East Kootenay fire regime has been disrupted. Additional research is needed to identify where surface and canopy fuels have most accumulated, how future fire will behave in response to these accumulated fuels, and where fuel treatments, prescribed fire, and other restorative or adaptive treatments are most appropriate.

5. Synopsis

Contemporary fire regimes in the East Kootenays are significantly departed from historical fire regimes, transitioning through three phases into the present. Fire was active from 1919 to 1940, with frequent and 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 wet climate. After 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, the majority of the flammable landscape (89-percent) is in a fire deficit. The policies that drove transitions in fire regimes reflect the perspectives and values of the period—a phenomenon that remains true today. 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.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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Figures

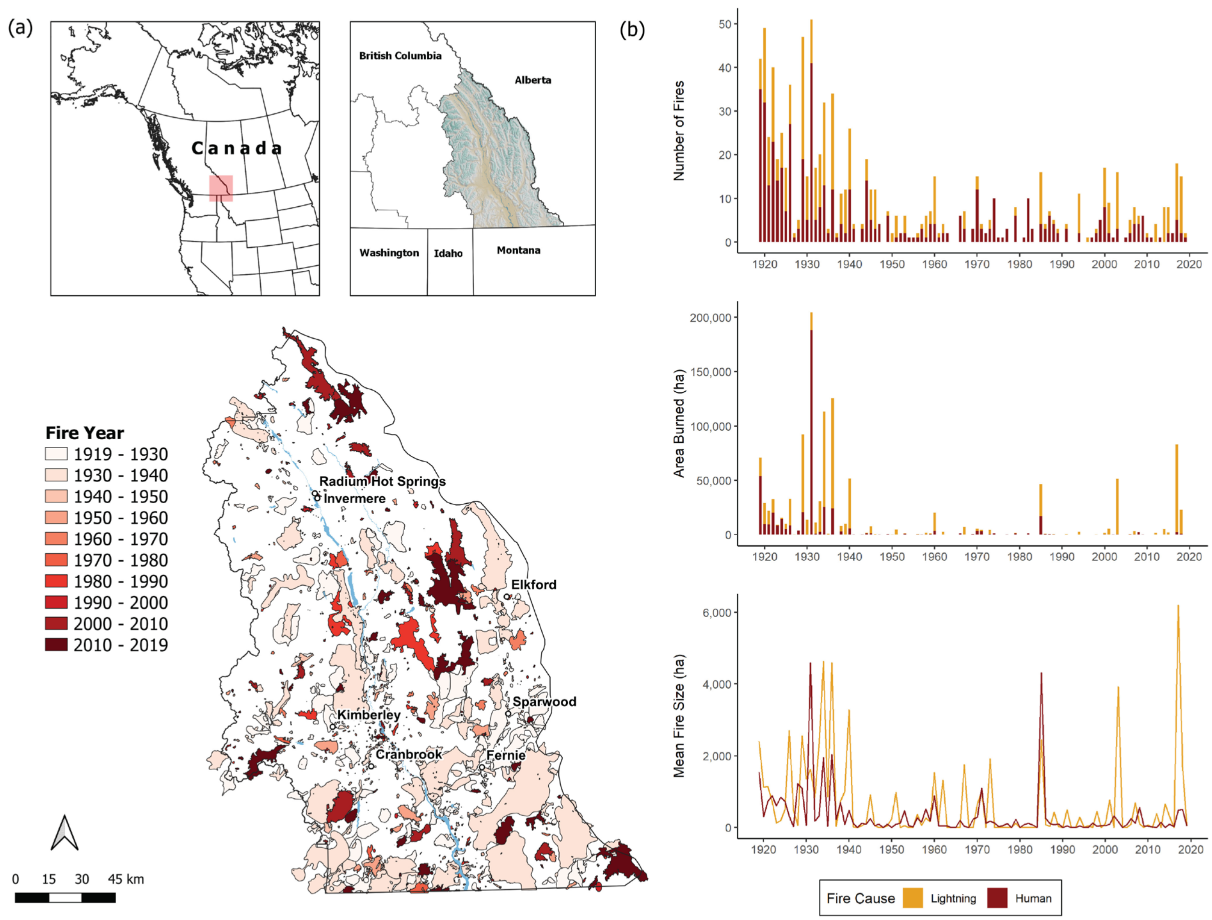

Figure 1. (a) Historical fire perimeters in the East Kootenays, British Columbia, Canada from 1919–2019. (b) Annual number of fires, area burned (ha), and mean fire size (ha) by fire cause (lighting and human) derived from historical fire perimeter records in the East Kootenays, British Columbia, Canada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

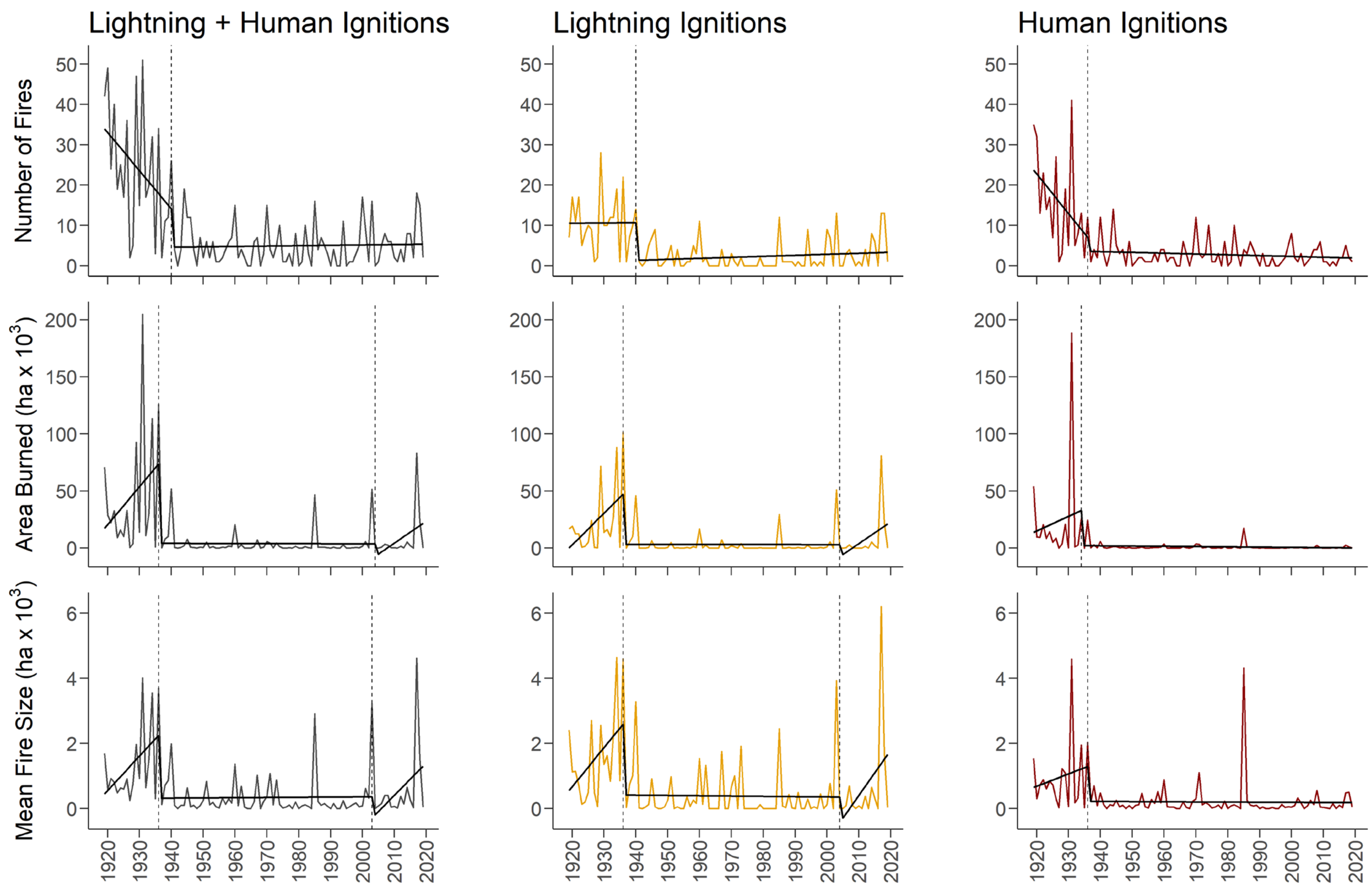

Figure 2. Breakpoints (dashed lines) and model predictions (black lines) for annual number of fires, area burned (ha), and mean fire size (ha) by fire cause in the East Kootenays, British Columbia, Canada from 1919–2019 (see Table 2).

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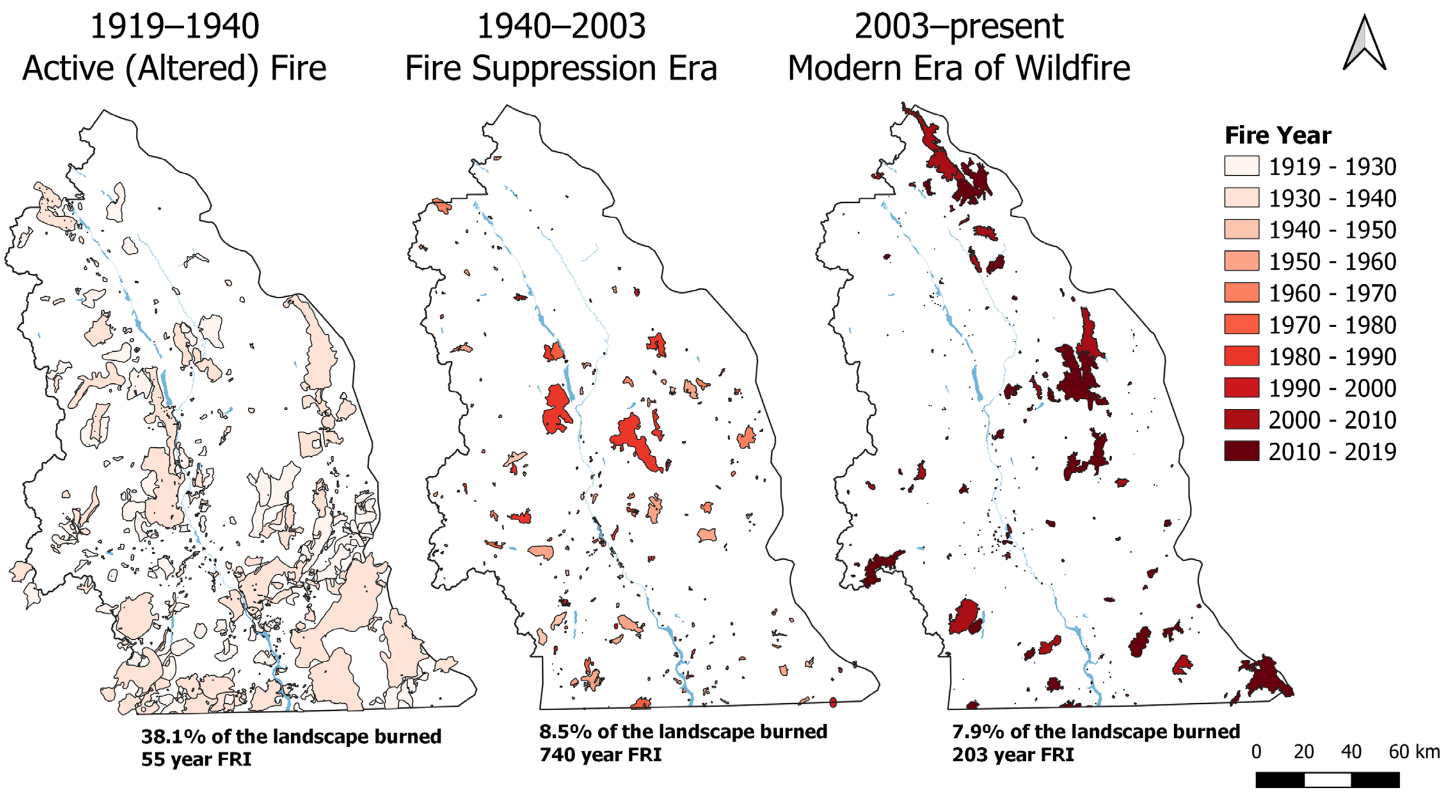

756

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

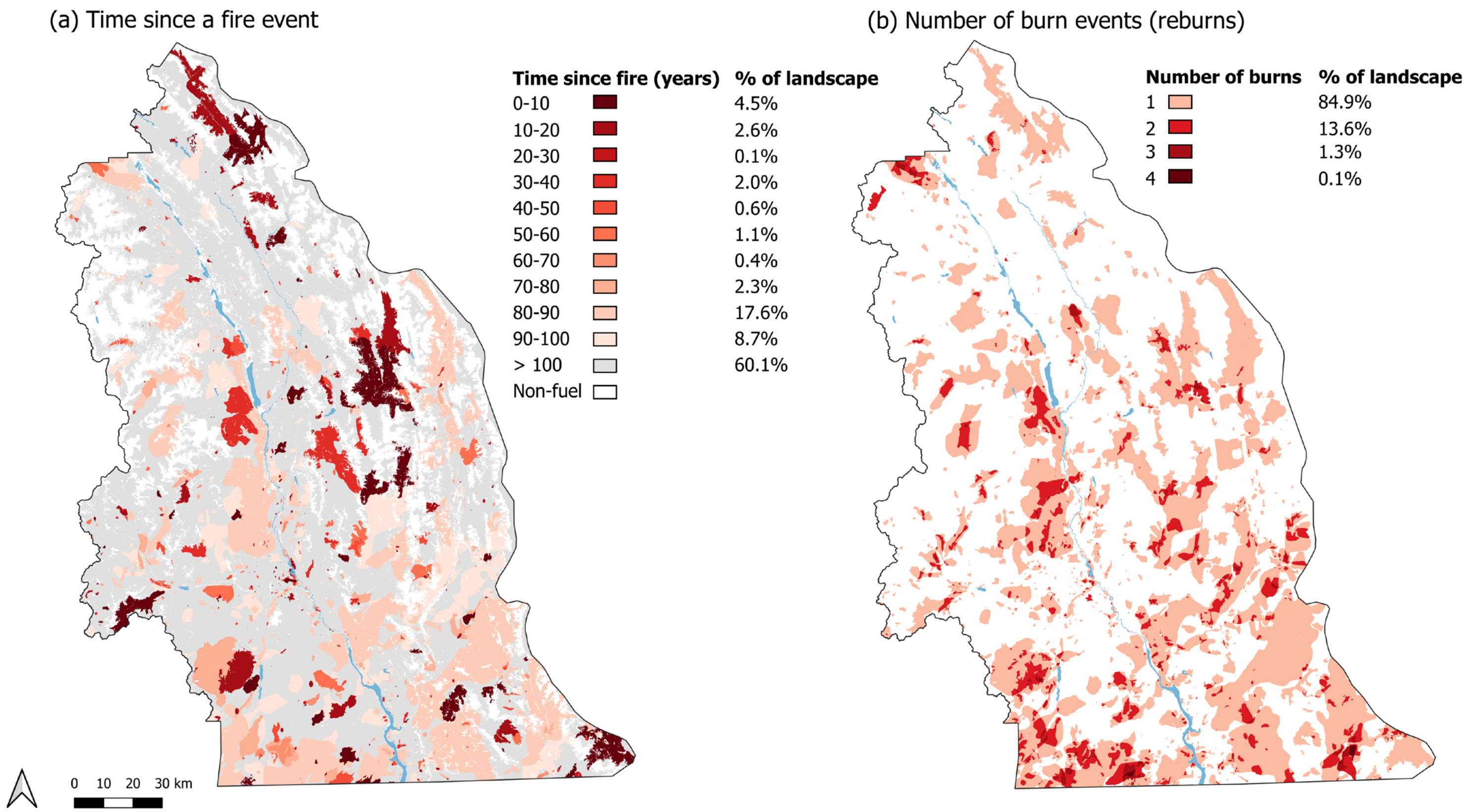

Figure 4. (a) Time since a fire event (years) and (b) number of burn events (reburns) derived from historical fire perimeter records in the East Kootenays, British Columbia, Canada from 1919–2019. 89% of the flammable landscape has not experienced a fire event in at least 60 years, exceeding historical fire frequency and revealing a fire deficit.

Tables

Table 1. Number of fires, area burned, and mean fire size (1919–2019) summarized by decade and fire cause (see Figure 1).

Decade	Number of fires			Area burned (ha)			Mean fire size (ha)		
	L + H[1]	L	H	L + H	L	H	L + H	L	H
1920s	**306**	115 (38%)	191	**319,225**	164,813 (52%)	154,412	**875**	1,095	754
1930s	**197**	104 (53%)	93	**518,346**	273,165 (53%)	245,181	**1,636**	1,802	1,019
1940s	**88**	38 (41%)	50	**63,653**	53,568 (84%)	10,085	**317**	643	163
1950s	**37**	21 (63%)	16	**11,182**	7,848 (76%)	3,335	**240**	306	210
1960s	**39**	18 (46%)	21	**32,398**	26,620 (82%)	5,778	**363**	1,185	214
1970s	**49**	8 (15%)	41	**17,741**	7,066 (36%)	10,675	**295**	926	249
1980s	**49**	16 (27%)	33	**50,614**	29,913 (59%)	20,701	**373**	603	643
1990s	**25**	12 (43%)	13	**4,289**	3,609 (83%)	680	**81**	321	60
2000s	**69**	38 (57%)	31	**65,665**	60,670 (93%)	4,994	**534**	948	189
2010s	**61**	46 (80%)	15	**115,344**	111,404 (97%)	3,940	**774**	1,337	171

[1] L + H: lightning and human caused ignitions; L = lightning only; H = human only.

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

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

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

Metric	Fire cause	Time period (estimate)	95% CI (lower)	95% CI (upper)	Slope	Intercept	p-value
Number of fires	Lightning + Human	1919–1940	1939	1946	-9.44×10^{-1}	1.85×10^{3}	[A]
		1940–2019			9.49×10^{-3}	-1.38×10^{1}	**6.76×10^{-4}**
	Lightning	1919–1940	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	1919–1936	1935	1945	-9.81×10^{1}	1.91×10^{3}	[A]
		1936–2019			-2.01×10^{-2}	4.26×10^{1}	**1.10×10^{-4}**
Area burned (ha)	Lightning + Human	1919–1936	1935	1952	3.32×10^{3}	-6.34×10^{6}	[A]
		1936–2004	1956	2005	-6.19	1.60×10^{4}	**4.68×10^{-3}**
		2004–2019			1.92×10^{3}	-3.86×10^{6}	4.60×10^{-1}
	Lightning	1919–1936	1935	1950	2.77×10^{3}	-5.31×10^{6}	[A]
		1936–2004	1959	2005	-2.27	7.42×10^{3}	**1.94×10^{-4}**
		2004–2019			1.91×10^{3}	-3.84×10^{6}	4.65×10^{-1}
	Human	1919–1934	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	1919–1936	1935	1945	1.05×10^{2}	-2.02×10^{5}	[A]
		1936–2003	1953	2004	6.37×10^{-1}	-9.16×10^{2}	**4.81×10^{-3}**
		2003–2019			9.97×10^{1}	-1.99×10^{5}	9.17×10^{-1}
	Lightning	1919–1936	1935	1946	1.20×10^{2}	-2.29×10^{5}	[A]
		1936–2004	1954	2005	-8.81×10^{-1}	2.12×10^{3}	**1.01×10^{-2}**
		2004–2019			1.40×10^{2}	-2.80×10^{5}	7.92×10^{-1}
	Human	1919–1936	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}