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Determinants of fire activity during the last 3500 yr at a wildland–urban interface, Alberta, Canada

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ABSTRACT

Long-term records of wildfires and their controlling factors are important sources of information for informing land management practices. Here, dendrochronology and lake sediment analyses are used to develop a 3500-yr fire and vegetation history for a montane forest in Jasper National Park, Alberta, Canada. The tree-ring record (AD 1771–2012) indicates that this region historically experienced a mixed-severity fire regime, and that effective fire suppression excluded widespread fire events from the study area during the 20th century. A sediment core collected from Little Trefoil Lake, located near the Jasper townsite, is analyzed for subfossil pollen and macroscopic charcoal (>150 μm). When comparing the tree-ring record to the 3500-yr record of sediment-derived fire events, only high-severity fires are represented in the charcoal record. Comparisons between the charcoal record and historical climate and pollen data indicate that climate and vegetation composition have been important controls on the fire regime for most of the last 3500 yr. Although fire frequency is presently within the historical range of variability, the fire return interval of the last 150 yr is longer than expected given modern climate and vegetation conditions, indicating that humans have become the main control on fire activity around Little Trefoil Lake.

Introduction

Of the many natural disturbances that affect the forest systems of western North America, including insect outbreaks, fungal diseases, wind-throw, and avalanches, wildfire is particularly important at the landscape-scale because of its role in maintaining landscape complexity and diverse habitat for wildlife (Arno et al., 2000). Over the past century, the cumulative effects of climate change and policies of fire suppression have altered fire regimes and forest stand structures in many areas of western Canada and the United States (Day, 1972; Rhemtulla et al., 2002; Gedalof et al., 2005; Bowman et al., 2011; Pellatt and Gedalof, 2014). In Jasper National Park, located in west-central Alberta, Canada, decades of fire suppression in the coniferous montane forests, including restrictions imposed on the use of fire as a land management tool by First Nations peoples and Métis homesteaders, have contributed to landscape homogenization (Chavardès and Daniels, 2016), changes in forest age-structures (Rhemtulla et al., 2002) and in the seasonality of fires (Dinh, 2014). Increasing forest fuel loads, which result from the absence of regular burning events, increase landscape flammability and triggers a greater potential for large and hazardous fires to occur. In much of western Canada, the risks posed by wildfires are expected to be amplified in the future by more frequent extreme fire weather events that are expected as a result of climate change (Wang et al., 2015).

Progress in fire management strategies in Jasper National Park and other protected areas in Canada is on-going (Theberge et al., 2015); however information regarding the long-term variability

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in fire activity and its causes is limited. Active management strategies to counter the effects of fire suppression, which can include controlling fuel loads, maintaining fire breaks, and prescribed burning, involve making value-based decisions using the best available information. Although short-term fire histories based solely on observational records or from remotely sensed data are available for many parts of Canada (Canadian Forest Service, 2016), they provide a narrow representation of the temporal variability in fire events. Additionally, where suppression activities pre-date detailed observational records it is difficult to separate the effects of fire suppression from interacting natural processes because changes manifest over the course of several decades (Keane et al., 2002). Using a paleoecological approach to develop fire, climate, and vegetation histories we can address these limitations by providing a long-term (100s–1000s of years) context for understanding present-day ecosystems (Froyd and Willis, 2008; Keane et al., 2009; Pellatt and Gedalof, 2014). Long-term records can reveal important interactions between the controls on fire activity before the onset of modern fire suppression (Conedera et al., 2009), and provide empirical data to constrain computer modeling (Brücher et al., 2014; Marlon et al., 2015).

Proxy data from dendrochronology, sedimentary charcoal analysis, and pollen analysis are commonly used to gain insights into historical fire regimes, vegetation composition, and climate variability (e.g., Long et al., 1998; Whitlock et al., 2004; Higuera et al., 2010b; Heyerdahl et al., 2012; Courtney Mustaphi and Pisaric, 2013). Tree-ring analysis provides information about the timing of low-severity and stand-replacing fires when evidence of these events is preserved in the tree-ring record as fire scars and even-aged cohorts (e.g., Amoroso et al., 2011; Heyerdahl et al., 2012). A growing body of research has provided evidence that many forests in interior British Columbia and southwest Alberta experience mixed-severity fire regimes (Arno, 1980; Amoroso et al., 2011; Heyerdahl et al., 2012; Marcoux et al., 2015; Chavardès and Daniels, 2016), where frequent, low-severity (non-lethal to mature trees) fires overlap spatially or temporally with infrequent, high-severity fires (high degree of mortality). Accurately categorizing mixed-severity fire regimes requires tree-ring sampling methods that can identify the presence of both low- and high-severity fires (Heyerdahl et al., 2012; Marcoux et al., 2013) and is important for the development of fire and vegetation management plans because different fire-severity regimes require unique fire management strategies.

Tree-ring fire histories have high temporal and spatial resolution, but are typically limited to a few centuries in duration as subsequent fires remove evidence from the landscape over time (Kipfmueller and Baker, 1998; Whitlock and Larsen, 2001). Records of past fire preserved in undisturbed sediment deposited on lake bottoms can extend the length of fire histories by many thousands of years, albeit with a lower temporal and spatial resolution. Millennial-scale changes in fire frequency derived from sediment-based macroscopic charcoal analysis can be compared with proxy records of climate and long-term vegetation change to infer important ecological interactions (Conedera et al., 2009). Combining tree-ring fire histories with macroscopic charcoal analysis can also help to calibrate the sediment record and provides a more complete picture of the local fire regime (Whitlock et al., 2004; Higuera et al., 2010b; Brossier et al., 2014; McLauchlan et al., 2014).

Understanding the dominant controls on fire activity is a necessary step in developing land and fire management strategies in areas impacted by fire suppression to maintain biodiversity and increase ecological resilience. In protected areas in Canada, managers are tasked with balancing the safety of humans and the protection of infrastructure with the ecological integrity afforded by maintaining natural ecosystem processes such as wildfire (Theberge et al., 2015; Wright, 2015). This challenge is perhaps most difficult in wildland–urban interfaces of protected areas where the risks of increased fire severity could pose the greatest threat to public and private property and human wellbeing. In an effort to generate information about the historical fire regime that is pertinent to existing management objectives, the goals of this study are to identify the influences of climate, vegetation, and human activities on the fire regime near the town of Jasper, and to determine if contemporary fire activity at the wildland–urban interface is within the historical range of natural variability of the last 3500 yr. This period serves as a baseline of natural historical range of variability in fire disturbance (Morgan et al., 1994) because vegetation composition and solar insolation have remained largely unchanged in the region since ca. 4000 cal yr BP (Vance et al., 1983; MacDonald, 1989). A number of complementary paleoecological studies have taken place in Jasper National Park (Tande, 1979; Kearney and Luckman, 1987; Beaudoin and King, 1990; Dinh, 2014; Chavardès and Daniels, 2016); however, this is the first to combine information about fire frequencies derived from tree rings with a well-resolved record of fire activity and vegetation change from lake sediments. The results will provide much needed data on ecologically important fire frequencies, the long-term controls on wildfires, and information about the historical range of variability in fire activity.

Study area

Jasper National Park is located in the Cordillera Ecozone of west-central Alberta; a region that has been heavily influenced by glacial processes during the late-Pleistocene. Thus, the area is typified by surficial deposits mainly composed of glaciofluvial deposits and tills that include clasts of sandstone, limestone, slate and quartzite (Stringer and La Roi, 1970). The vegetation of the study area is characterized by montane forest species interspersed with deciduous trees and grasslands. Lodgepole pine (*Pinus contorta* var. *latifolia*) is the dominant canopy species in the study area, with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), white spruce (*Picea glauca* (Moench.) Voss) and black spruce (*P. mariana* (Mill.) BSP.) occurring throughout the region (Nadeau and Corns, 2002). The predominant deciduous tree, trembling aspen (*Populus tremuloides* Michx.), can be found growing at open or recently disturbed locations, and grasses and shrubs occupy areas of less dense tree cover.

At present, Jasper has a continental climate with short, warm summers (mean July temperature = 15°C, 1977–2007; Vincent et al., 2012) and relatively cold and long winters (mean January temperature of −10°C, 1977–2007). Precipitation is greatest in the summer (June–August mean precipitation of 180 mm, 1977–2007) and mean annual precipitation is 433 mm/yr. Recent climate change has most substantially impacted winter temperatures and precipitation. Winter temperatures have increased and precipitation decreased steadily throughout the past 60 yr (Vincent et al., 2012). Summer temperatures show a more modest increase while precipitation has remained relatively stable. Wildfires in the region that occur during the summer fire season are strongly influenced by the occurrence of multi-day high pressure conditions (Johnson and Larsen, 1991). At longer timescales, multi-annual patterns of fire activity are moderated by synoptic processes (El Niño Southern Oscillation, the Pacific Decadal Oscillation, and their teleconnections) which generally lead to warm temperatures and reduced fuel moisture (Schoennagel et al., 2005). Jasper has been described as being situated within a lightning-fire shadow (Rhemtulla, 1999) where relatively few ignitions result in fire spread (Wierzchowski et al., 2002). Cloud-to-ground lightning strikes occur in Jasper during an average of 14 lightning days per summer at a density of 8–32 strikes per 10 km^2 (Kozak, 1998).

Jasper has a unique land use history, having been occupied by First Nations peoples, Métis, immigrant settlers, and now managed as a townsite within a National Park. First Nations peoples and Métis homesteaders historically used fire as a tool to facilitate travel, to dry firewood, and for land clearing prior to their displacement from the park in 1907 (MacLaren, 2007). Non-aboriginal settlers tended to perceive fire differently, primarily viewing it as a threat to safety and resources. A series of severe fire seasons motivated the development of fire suppression policies in Canada in the early 1900s (Flannigan et al., 2009) and active fire suppression began in Jasper in 1913. Since the late 1990s, efforts to adopt sustainable forest management practices in Jasper National Park have included prescribed burning and fuel management (MacLaren, 2007).

The fire and vegetation history presented here is derived from lake sediments retrieved from Little Trefoil Lake (unofficial name; 52°53.53′N, 118°3.56′W, 1026 m asl), a small kettle lake adjacent to the Athabasca River, and tree-ring data collected from the surrounding region (Figs. 1 and 2). Little Trefoil Lake has a surface area of 0.4 ha and has a maximum depth of approximately 5.2 m with no surficial inflows or outflows. It is located approximately 750 m from the Jasper Park Lodge, which was destroyed in 1952 by a human-caused building fire and was later rebuilt (MacLaren, 2007).

The record we present can be placed in a longer-term, regional Holocene vegetation and climate record that has been developed using a variety of paleoecological methods. The early Holocene (10,000–7000 cal yr BP) was characterized by warm, dry conditions, as evidenced by elevated treelines and the presence of vegetation typically found in xeric environments (Luckman, 1986; MacDonald, 1989; Beaudoin and King, 1990; Beierle et al., 2003; Hallett and Hills, 2006). The mid-Holocene (7000–4000 cal yr BP) saw an onset of mesothermic conditions (Luckman and Kearney, 1986; Luckman et al., 1993; Hallett and Hills, 2006); Luckman and Kearney (1986) estimate that temperatures in south-central Alberta were an average of 1.2–1.6°C warmer during this period than during the late 20th century. Modern climatic conditions, which are relatively cool and wet compared to earlier in the Holocene, arose during a transitional period around 4500–3500 cal yr BP (Hallett and Hills, 2006). The onset of neoglacial conditions beginning around 3500 cal yr BP introduced a relatively stable climate characterized by periodic glacial advances and by cool and wet conditions relative to earlier in the Holocene (MacDonald, 1989; Luckman et al., 1993; Smith et al., 1995; Luckman, 2000; Beierle et al., 2003). Glacial advances, inferred from the dates associated with glacial moraines and in-situ deadwood, include the Peyto advance at ca. 3500–2500 cal yr BP (Luckman et al., 1993), and the more recent Little Ice Age (700–100 cal yr BP; Luckman et al., 1993; Smith et al., 1995; Luckman, 2000).

Field methods

The fire and vegetation history in this study was developed using dendrochronology and the analyses of macroscopic charcoal and subfossil pollen from lake sediment. A tree-ring record of recent fires was developed to characterize the contemporary fire-severity regime and to calibrate the sediment record. Tree-core and fire scar samples were collected from 12 sites located at approximately 0, 3, and 6 km from the edge of Little Trefoil (Fig. 1). Sites near the lake were chosen with the aim that the tree-ring data would assist the interpretation of the charcoal record by associating peaks in charcoal accumulation with annually resolved tree-ring fire evidence.

Tree-core samples were used to identify even-aged cohorts that are indicators of high-severity fire events (Johnson and Fryer, 1989). At each of 12 sites, 10 canopy and 10 sub-canopy trees (when present) were sampled using Haglöf increment borers with an internal diameter of 5.1 mm to determine stand age using an N-tree design (adapted from Heyerdahl et al., 2006). Samples were collected from the tree base (<20 cm from the ground) in order to capture its true age (Arno and Sneck, 1977). Fire scars, which provide annually resolved dates of non-lethal fire activity, were collected using chainsaws and/or handsaws. A minimum of five

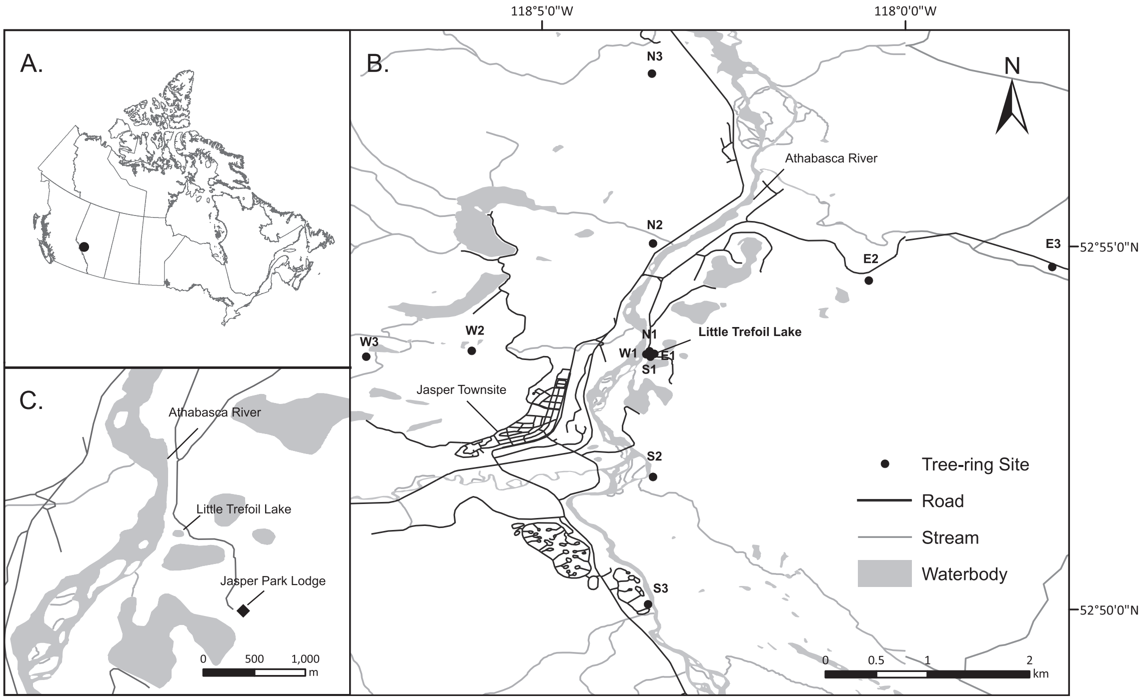

Figure 1. Maps of study location; a) Jasper National Park located in west-central Alberta, Canada; b) the position of Little Trefoil Lake and tree-ring sites near the Athabasca River and Jasper townsite; c) detailed inset of features around Little Trefoil Lake.

Figure 2. Site photos of Little Trefoil Lake and features from the surrounding forests; a) Little Trefoil Lake, situated in the Athabasca River valley; b) a fire-scarred lodgepole pine tree; c) the dense forest stand and abundant biomass of tree-ring site W2 (photos: E. Davis and M. Pisaric).

scarred cookies or wedges were collected from dead and living trees when present in the vicinity of the cored trees. Downed trees within the site area were sampled for buried fire scars.

During the winter of 2007, a Livingstone piston corer (Wright et al., 1984) was used to collect 5 m of sediment from the center of Little Trefoil Lake (Glew et al., 2001). A Kajak-Brinkman gravity corer with a plastic tube attached (internal diameter: 6.5 cm) was subsequently used during the summer of 2007 to collect a 44 cm long sediment core that overlapped with the Livingstone core and preserved the sediment–water interface (Glew et al., 2001). The Livingstone core was sectioned into 50-cm segments for transportation and subsampled in the laboratory at 0.5-cm intervals, and the gravity core was sectioned in the field at 0.5-cm intervals. This study presents an analysis of the top 3 m of the composite sediment record, representing approximately 3500 yr of deposition.

Laboratory methods

Tree-ring analysis

Tree-core and fire scar samples were prepared and analyzed using standard dendrochronological methods (Stokes and Smiley, 1968) and were crossdated using a combination of visual and computer-assisted techniques (COFECHA; Stokes and Smiley, 1968; Holmes, 1983). For samples with missing piths, the number of missing rings were estimated using a graphical correction technique (Rozas, 2003). Tree ages were not corrected for sampling height because all cores were collected <20 cm from the ground.

Even-aged cohorts representing high-severity fires were defined as pulses in tree establishment in which at least 60% of canopy trees became established within a common 10-yr interval. It has been found that the majority of post-fire regeneration of lodgepole pine, the species most likely to form even-aged cohorts in this forest system, occurs within the first decade following a fire event (Johnstone et al., 2004). High-severity fire dates were assigned a calendar date of the year prior to the pith date of the oldest tree at the site (Amoroso et al., 2011; Marcoux et al., 2013). The dates of low-severity fires were inferred by noting the year of scar formation from crossdated fire scarred samples. All fire scar and cohort establishment dates are presented in years AD.

Site-level fire severity regimes were determined based on the presence, absence, and type of fire evidence. The presence of fire scars ($\leq$1 fire date) was used as defining criteria of low-severity fire activity, whereas even-aged cohorts and an absence of fire scars were definitive of high-severity regimes (Heyerdahl et al., 2012; Marcoux et al., 2013). Sites that contained both even-aged canopies and multiple fire scar dates were characterized as mixed-severity. The landscape-scale fire regime was determined based on the dominant site-level fire regimes.

Sediment age-depth model and sedimentary analysis

The chronology for Little Trefoil Lake was developed using ^{210}Pb and ^{14}C dating techniques. ^{210}Pb dates for the upper 43 cm of the core were determined from 15 samples using alpha spectroscopy at MyCore Scientific Inc. in Deep River, Ontario. Samples were analyzed every 0.5 cm in the top 6 cm, 1.5 cm between 6 and 10 cm, 2.5 cm between 10 and 20 cm, and 3–4.5 cm below 20 cm (Table 2). Five terrestrial macrofossils (seeds and wood) were dated using accelerator mass spectrometry (AMS) at Direct AMS in Bothell, Washington. Terrestrial sources of organic material were used for ^{14}C dating to avoid problems of old carbon contamination that can occur when aquatic plants incorporate ^{14}C depleted dissolved inorganic carbon from lake water that has come in contact with old carbon sources such as underlying carbonate rocks or glacial till (MacDonald et al., 1991). The radiocarbon dates contain no age reversals or other anomalies (Table 2). The chronology for Little Trefoil Lake was developed by Gall (2016) using the ^{210}Pb and ^{14}C dates in Bacon, an age-modeling software package (Blaauw and Christen, 2011), within the R statistical program (R Core Team, 2015). Sediment ages were calibrated in Bacon using the IntCal13 calibration curve (Reimer et al., 2013) and are presented in calibrated years BP (AD 1950 = year 0).

Pollen analysis

Pollen processing was performed on 1 cm^3 samples at intervals of 5 cm from the top of the Livingstone sediment core to 1 m depth and then at 10 cm intervals between 1 and 3 m depth. Pollen preparations followed standard digestion techniques described by

Table 1
Summary of species composition and fire history information of the 12 tree-ring sites. The multiple site-level fire regimes identified indicate that the broader area has experienced a mixed-severity regime for at least the past few centuries.

Site	Canopy species	Subcanopy species	Series length	Scar date	Even-aged cohort	Severity class
N1	DF (9) LP (1)	–	1872–2012	–	–	Low
N2	DF (10)	–	1771–2012	1941	–	Low
N3	LP (7) DF (3)	–	1911–2012	1953	–	Low
S1	WS (9) LP (1)	–	1911–2012	–	–	Low
S2	WS (9) DF (1)	–	1776–2012	1903	–	Low
S3	LP (10)	–	1902–2012	–	1901	High
E1	WS (8) DF (2)	–	1889–2012	–	–	Low
E2	LP (10)	–	1896–2012	1915 1935	1895	Mixed
E3	LP (9) WS (1)	WS (10)	1896–2012 (C) 1912–2012 (S)	1927 1961	1895	Mixed
W1	WS (10)	–	NA	–	–	Low
W2	WS (10)	–	1934–2012	1971	–	Low
W3	LP (10)	WS (7) BF (3)	1895–2012 (C) 1952–2012 (S)	1915 1925	1894	Mixed

LP = Lodgepole pine **DF** = Douglas-fir **WS**= White spruce **BF**=Balsam fir.
Low Severity: <1 Fire scar date + No even-aged canopy.
Mixed Severity: >1 Fire scar date + Even-aged canopy.
High Severity: 0 Fire scar dates + Even-aged canopy.

Table 2
Summary of ^{210}Pb and ^{14}C dates from sediment and macrofossil samples, respectively, for Little Trefoil Lake. Radiocarbon dates are presented in uncalibrated years before 1950. Dates were calibrated in Bacon (Blaauw and Christen, 2011) using the IntCal13 Calibration curve (Reimer et al., 2013).

Material	Depth (cm)	210Pb (Bq/g)	210Pb age (AD)	1 σ error (yr)
Sediment	0–1.0	0.480	2007, 5 mos.	0
Sediment	1.0–1.5	0.480	2007, 3 mos.	0
Sediment	2.0–3.0	0.419	2006, 10 mos.	0
Sediment	3.5–4.0	0.544	2005, 5 mos.	0
Sediment	5.5–6.0	0.701	2002, 10 mos.	0
Sediment	7.5–8.0	0.649	1999	1
Sediment	9.5–10.0	0.484	1995	1
Sediment	12.5–13.0	0.615	1988	1
Sediment	15.5–16.0	0.460	1978	3
Sediment	18.5–19.0	0.338	1964	5
Sediment	21.5–22.0	0.219	1948	10
Sediment	25.0–25.5	0.130	1929	24
Sediment	30.0–30.5	0.077	1888	70
Sediment	35.0–35.5	0.047	Background	Background
Sediment	40.0–40.5	0.046	Background	Background
Sediment	43.0–43.5	0.020	Background	Background

Material	Depth (cm)	Lab no.	Δ 13C (per mil)	Uncalibrated radiocarbon age (BP)	1 σ error (yr)
Conifer stem	99.8–100.3	D-AMS 004506	−24.9	810	31
Conifer stem	134.8–135.5	D-AMS 004507	−26.6	1360	35
Seed capsule	252.4–253.0	D-AMS 004508	−22.7	2718	29
Woody stem	281.7–282.9	D-AMS 004509	−37.9	2991	28
Woody stem	302.5–303.1	D-AMS 004510	−25.4	3341	32

Faegri and Iversen (1989). Two *Lycopodium* tablets (batch LY483216; X = 18,583 grains per tablet) were added to each sample to permit calculations of pollen accumulation rates (Stockmarr, 1971). Pollen grains were identified from prepared slides and tallied up to a minimum of 500 terrestrial pollen grains using a light microscope at 400× magnification. A reference collection of pollen grains and identification manual (Moore and Webb, 1978) were used to assist in taxonomic identification.

The stratigraphic record of percent pollen by taxa was analyzed using a broken stick model in the statistical package ‘rioja’ (Juggins, 2015) in R (R Core Team, 2015) to identify significant pollen zones. A normalized ratio of *Picea:Pinus* pollen influx was developed to identify changes in the relative abundance of these dominant conifers (Pellatt et al., 2000; Higuera et al., 2014). A high abundance of spruce relative to pine can be used as an indicator of increased forest density and fuel availability. Following a fire event, spruce colonization occurs gradually over many years (Day, 1972; Johnstone et al., 2004), whereas lodgepole pine tends to establish rapidly and thins out naturally after several decades (Johnson and Fryer, 1989). Landscape flammability increases as fuels accumulate during the transition to *Picea* dominance, effectively increasing the likelihood of a fire event.

Interpretation of the pollen record can be assisted by modern surveys of vegetation found growing in the area (e.g., Stevenson et al., 1976; Nadeau and Corns, 2002). Lodgepole pine, white spruce, and Douglas-fir grow abundantly in the study area and are therefore assumed to be the main constituents of *Pinus*, *Picea*, and *Pseudotsuga/Larix* pollen spectra, respectively. *Betula* pollen could represent the tree species *Betula papyrifera* Marsh., *Betula occidentalis* Hook., and/or non-arboreal *Betula* sp. shrubs, all of which grow in the Athabasca River valley. No arboreal birch species were found at our study area, and we therefore believe that pollen grains of *Betula* in the sediment record likely represent the shrub species. *Alnus* and *Populus* pollen likely derives from green alder (*Alnus crispa* (Ait.) Pursh.) and trembling aspen that grow at forest edges and recently disturbed areas.

Macroscopic charcoal analysis

The subsampled material (1 cm^3 taken at 0.5 cm contiguous intervals) for macroscopic charcoal analysis was rinsed into a small beaker with a dilute solution of sodium hexametaphosphate to deflocculate the sediment (Bamber, 1982). The samples were left for 24 h before being rinsed through a 150-μm mesh sieve to separate macroscopic charcoal representing local fire events from finer materials (Whitlock and Larsen, 2001). The remaining material was then rinsed into a Petri dish where charcoal particles were tallied under a stereomicroscope (6–40× magnification). The procedure was repeated for contiguous samples to a depth of 3 m.

The timing and frequency of fire events was determined using the program CharAnalysis (Higuera, 2009; available from http://CharAnalysis.googlepages.com). Charcoal accumulation rates (CHAR; number of particles/cm^{2}yr) were estimated by resampling the charcoal concentrations at equal intervals (median sample resolution; 7 yr) to account for changes in sedimentation and unequal sampling intervals. The CHAR series was then decomposed into background (bCHAR) and peak charcoal (peakCHAR) components (Long et al., 1998). Background charcoal represents varying levels of charcoal influx into the lake that are related to regional biomass burning (Marlon et al., 2006; Seppä et al., 2009; Carter et al., 2013; Morris et al., 2013) and is mainly controlled by changes in temperature over long time scales (Daniau et al., 2012).

bCHAR was estimated from the CHAR series using a LOWESS smoother robust to outliers with a 500-yr window. Fire events were identified in the record as peaks in charcoal above a locally defined threshold of charcoal accumulation. peakCHAR represents the influx of charcoal from fire events in the local area surrounding the lake (Peters and Higuera, 2007). A minimum count probability ($p \leq 0.05$) was imposed to determine the statistical significance of interpreted fire events by ensuring that minimum charcoal values in the 75-yr window around the charcoal peak had a <5% chance of coming from the same Poisson distribution as the curve created by the peak (Higuera et al., 2010a). The median fire return interval (mFRI; yr/fire) was calculated for each interval as the number of identified fire events within a 500-yr window and smoothed with a tricube weight (Gavin et al., 2006; Higuera, 2009). The window widths for detecting bCHAR and peakCHAR were chosen to ensure a high signal-to-noise ratio throughout the length of the record (SNI > 3; Kelly et al., 2011).

Evaluating fire-climate-vegetation interactions

The charcoal fire history was compared to records of climate change from the region and to the pollen record derived from the sediment core to identify interactions between climate, vegetation, and fire activity. Based on previous research in this region, six climatic zones were determined for the Holocene. Climate zone 1, from 3500 to 2500 cal yr BP, was characterized as cool and wet based on evidence of high lake levels (Hallett and Hills, 2006) and the Peyto glacial advance (Luckman et al., 1993). Between 2500 and 1200 cal yr BP (climate zone 2), warm and dry conditions persisted as inferred from low lake levels and increased fire frequency (Hallett and Hills, 2006). Prior to the Medieval Climate Anomaly (MCA), a short wet and cool period occurred between 1200 and 1000 cal yr BP (climate zone 3) evidenced by increases in lake depth (Laird et al., 2003) and regional glacial advances (Gavin et al., 2003; Hallett and Hills, 2006). The onset of the MCA between 1000 and 700 cal yr BP (climate zone 4) was characterized by warm and dry conditions inferred from tree-ring reconstructions of summer temperatures (Luckman and Wilson, 2005), low lake levels (Hallett et al., 2003; Laird et al., 2003; Hallett and Hills, 2006) and high fire frequency (Hallett et al., 2003). Following the end of the MCA and after 700 cal yr BP, the onset of the Little Ice Age (LIA; climate zone 5) ushered in cool conditions with variable moisture, which is shown by glacial fluctuations and tree-ring reconstructions of temperature and precipitation (Luckman, 2000; Watson and Luckman, 2001; Luckman and Wilson, 2005). The LIA persisted until ~100 cal yr BP (climate zone 6) when summer temperatures became warmer than at any time in the past 800 yr (Luckman and Wilson, 2005).

Results

Tree-ring analysis

The canopy species of the tree-ring sites were a mix of lodgepole pine, white spruce, and Douglas-fir, with white spruce and balsam fir as occasional subcanopy species (Table 1). Douglas-fir and lodgepole pine were found in open, dry areas, whereas white spruce was characteristic of closed canopy, wet sites. Crossdated tree-ring chronologies were successfully developed for 11 of 12 sites (Pearson correlation values: 0.48–0.80, $p < 0.01$); site W1 could not be crossdated due to anomalies in the growth patterns of the trees that may be attributed to the rocky substrate on which the trees were growing. Of the 140 tree cores collected, 101 (72%) were age-adjusted for missing piths (average adjustment = 7.6 yr). The average time-span covered by the series was 122 yr (full record: AD 1771–2012; Table 1).

Fire evidence (even-aged cohort and/or presence of fire scars) was identified at nine of the 12 tree-ring sites, with even-age cohorts at four and fire scars at seven of the nine burned locations (Table 1; Fig. 3). Lodgepole pine was the dominant canopy species of even-age cohorts, all of which established in the late 19th or early 20th century. All low-severity fire events (n = 10) occurred prior to the mid-1970s. Using the site-level fire regime classification, eight sites were classified as low-severity, three as mixed-severity, and one as a high-severity fire regime. The multiple site-level fire severities indicate that the landscape experiences a mixed-severity fire regime.

Age-depth model

The ^{210}Pb activity profile from Little Trefoil Lake approximates an exponential decline with increasing depth (Fig. 4a, Table 2; Binford, 1990). Unsupported ^{210}Pb declines to a depth of ~35 cm, after which only supported ^{210}Pb remains. Based on the ^{210}Pb dating, the top 30 cm of the sediment core represents the past ~120 yr of sediment deposition (Fig. 4b).

Five radiocarbon dates on terrestrial plant material were also used to determine the age profile for Little Trefoil Lake (Table 2). Combined, the radiocarbon and ^{210}Pb dates approximate a linear age-depth profile for Little Trefoil Lake (Fig. 4c).

Vegetation composition

Pollen assemblages were fairly stable over the last 3500 yr (Fig. 5) and no statistically significant zones were identified. *Pinus* pollen dominated the record, accounting for 70–95% of the pollen assemblage, indicating that the area has probably remained a lodgepole pine-dominant forest for the duration of the late Holocene. *Picea* (2–16%) and *Abies* (0–4%) were a minor component of the surrounding forest, and *Alnus* (0.4–5%) and *Betula* (0.5–6%) were the most abundant shrub species. Although their contribution to the pollen record was relatively constant, *Abies*, *Alnus*, and *Betula* all showed a peak and decline in abundance early in the pollen record (*Abies and Alnus*: 3400–2500 cal yr BP; *Betula*: 3400–2000 cal yr BP) and are generally more abundant during climate zone 5 (700–100 cal yr BP). The *Picea:Pinus* ratio (Fig. 6d), which represents relative changes in forest density and fuel availability, showed a general decline in ratio values towards present (see trendline, Fig. 6d). On shorter time-scales, the *Picea:Pinus* ratio is variable with notable peaks at ca. 3200, 2400, 1500, 450, and 150 cal yr BP. The lowest ratio values occurred around 2700, 1000, 350 cal yr BP.

Macroscopic charcoal

From 3500 cal yr BP to present, 45 statistically significant charcoal peaks were identified in the sediment record from Little Trefoil Lake (Fig. 6a). The signal-to-noise index (SNI) was >3 throughout the record (range = 4.33–21.19, mean = 6.36) indicating that the charcoal record from Little Trefoil Lake was suitable for peak detection (Kelly et al., 2011). Charcoal accumulation ranged from 0 to 29 particles/cm^2 yr, with a median value of 0.91 particles/cm^2 yr. Periods of high charcoal accumulation (Fig. 6a) occurred between 3100–2300 and 1100–400 cal yr BP, and the largest peak in CHAR occurred between 58 and −5 cal yr BP. The two most recent charcoal peaks corresponded well with the dates of large fires in Jasper inferred from tree-rings (Tande, 1979). Tree-ring dated fires occurred in AD 1847 and 1889, while peaks in macroscopic charcoal from Little Trefoil Lake occurred in AD 1811 and 1902 (Fig. 6a).

Background charcoal (bCHAR) varied throughout the record between 0.64 and 1.39 particles/cm^2 yr. The long-term variability in bCHAR indicates cyclical fluctuations in regional biomass. The

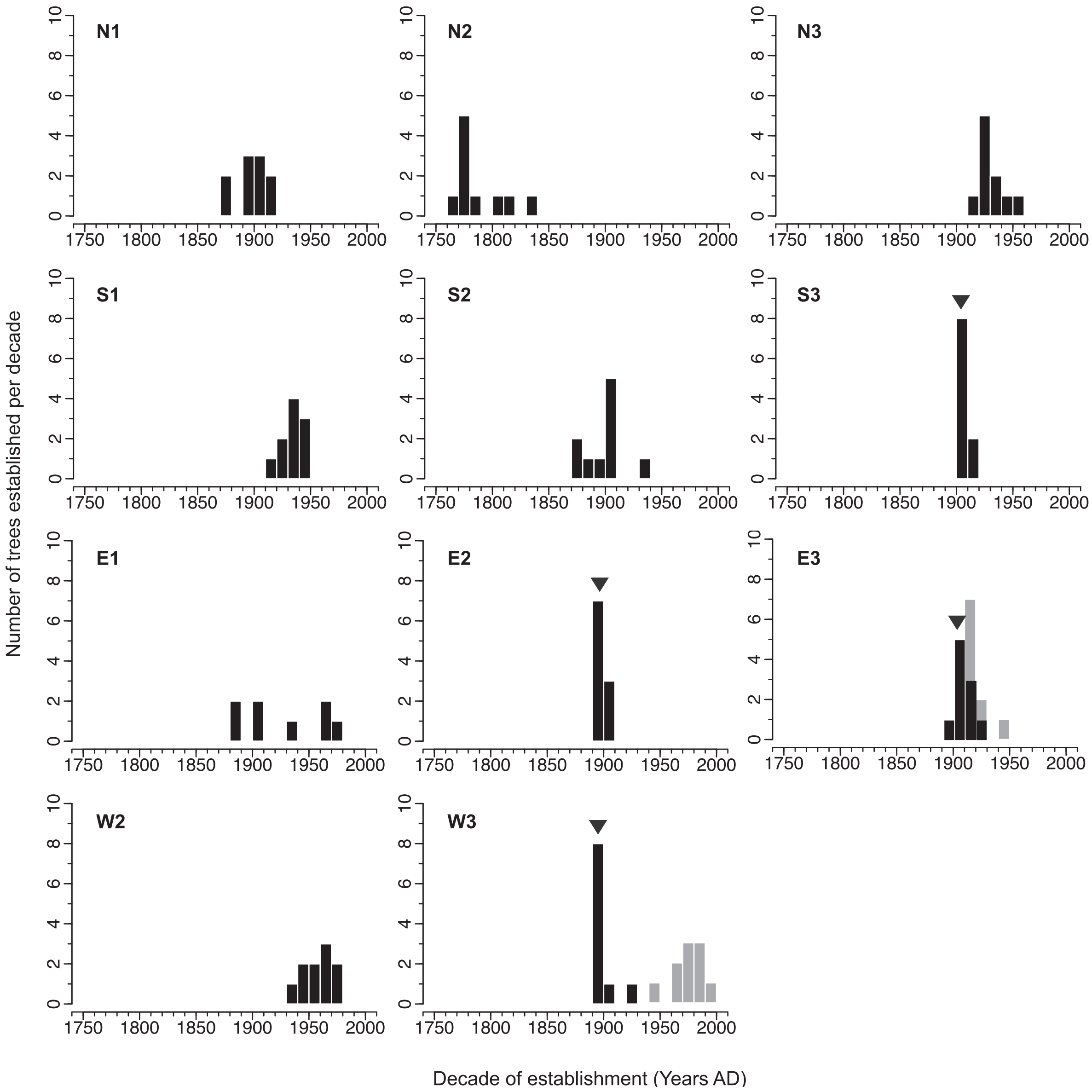

Figure 3. Bar plots of cohort establishment data from the 11 crossdated tree-ring sites. Black bars represent canopy establishment, grey bars indicate sub-canopy establishment, and inverted triangles indicate the decade of establishment of an even-aged cohort. Establishment data from site W1 is not included because samples collected from the site could not be crossdated.

range of fire return intervals (mFRI; smoothed median years between fires; Fig. 6c) was between 50 and 115 yr/fire and was highest at the beginning and end of the sediment record, indicating less frequent fire events. The mFRI generally declined from 3500 to 600 cal yr BP, reaching an absolute minimum mFRI of 50 yr/fire from 640 to 520 cal yr BP. In addition to a gradual decline in mFRI over time (indicating more frequent fire events), the distribution of smoothed fire return intervals exhibits an oscillating pattern of burn frequencies about 700 yr in length, except the most recent which is approximately 1200 yr.

Discussion

The contemporary fire-severity regime

The combined presence of even-aged cohorts and fire scars at our tree-ring sites indicates that the contemporary fire regime of the area surrounding Little Trefoil Lake is best categorized as one of mixed-severity. Similar evidence of mixed-severity fire regimes has been identified in the dry forests of interior British Columbia (Heyerdahl et al., 2012; Marcoux et al., 2013), the foothills of the Rocky Mountains (Amoroso et al., 2011) and elsewhere in Jasper National Park (Chavardès and Daniels, 2016). Although pre-dating the usage of the ‘mixed-severity’ classification, Tande (1979) found fine-scale variability in forest structure and fire distribution in a detailed tree-ring fire history of Jasper (including the Jasper townsite area), further supporting a mixed-severity classification in our study area. A notable feature of our tree-ring fire history record is the absence of high severity fires and general decline in low-severity fires throughout the past century.

The paucity of recent fire events raises the question of whether the fire-severity regime will persist as mixed-severity in the future. Significant declines in fire frequency and an absence of fire events, especially for the period after 1950, have been documented in this

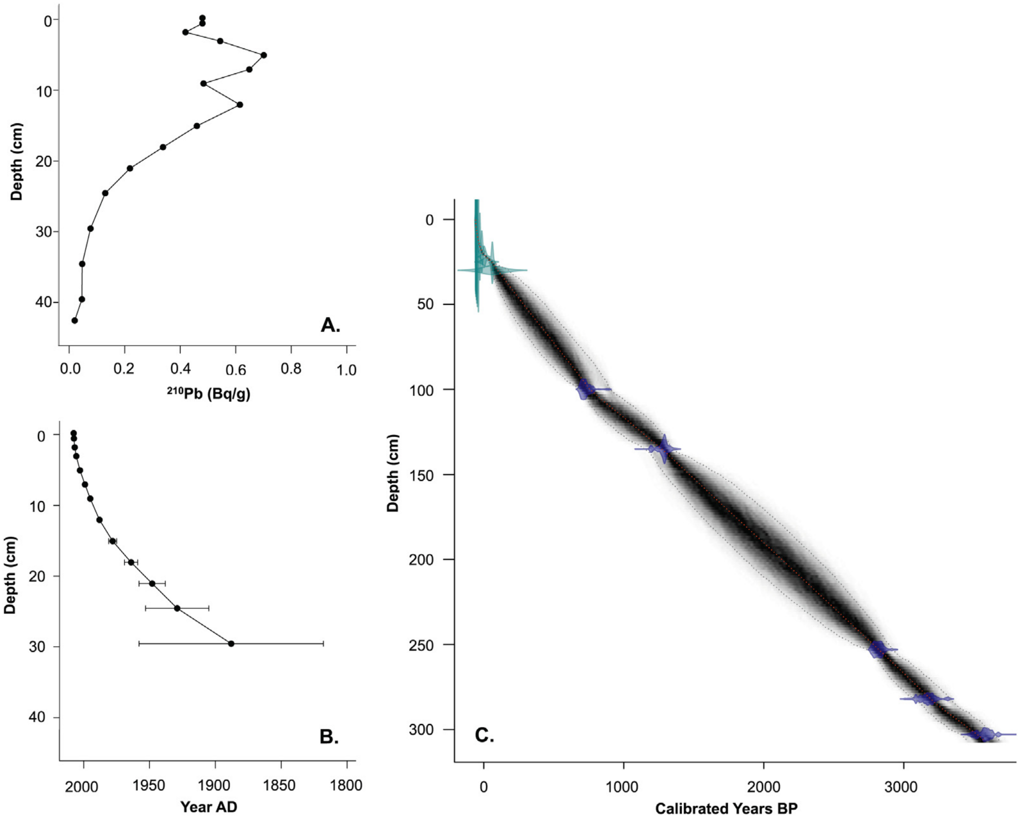

Figure 4. Age-depth models of the gravity core and composite record of sediment collected from Little Trefoil Lake; a) variations in ^{210}Pb activity (Bq/g dry wt.) with depth; b) ages of samples used for ^{210}Pb dating with error bars indicating ±1 standard deviation; c) age versus depth relationship for the composite sediment record from Little Trefoil Lake developed using Bacon (Blaauw and Christen, 2011; Juggins, 2015). The green and blue areas indicate calibrated distributions of the ^{210}Pb and calibrated ^{14}C dates respectively (IntCal13 calibration curve; Reimer et al., 2013), and the outer dashed grey lines indicate the 95% confidence envelope.

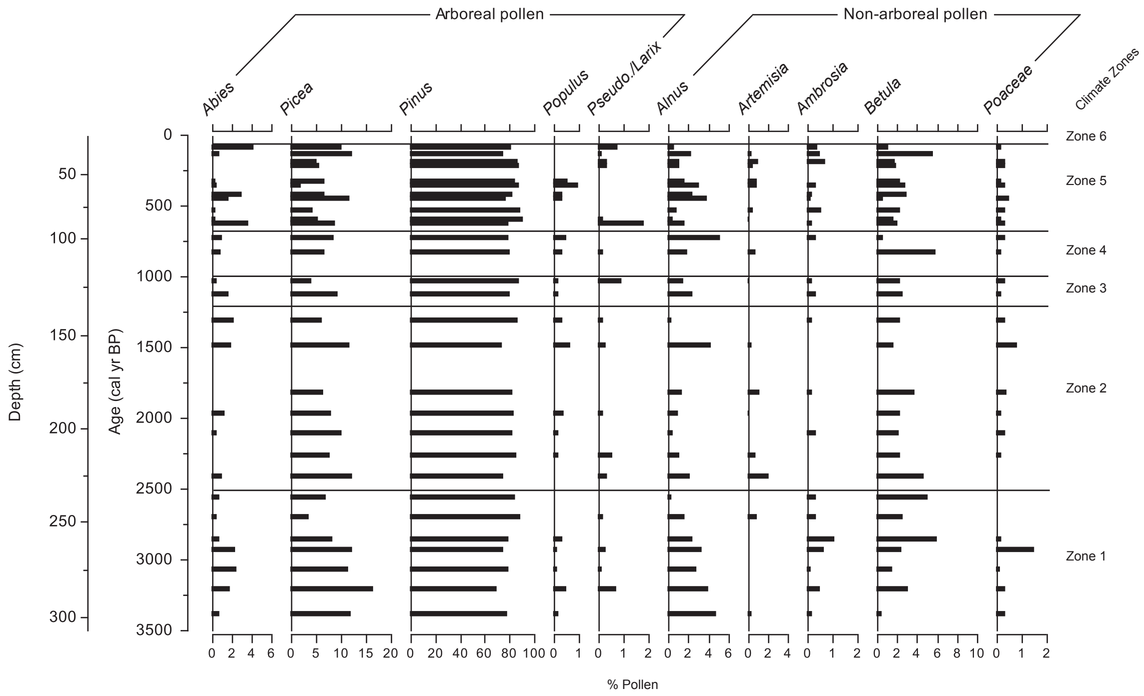

Figure 5. Percent pollen diagram of arboreal and non-arboreal species reaching >0.5% abundance. Stratigraphic delineations represent six inferred climate zones. No significant pollen zonations were identified.

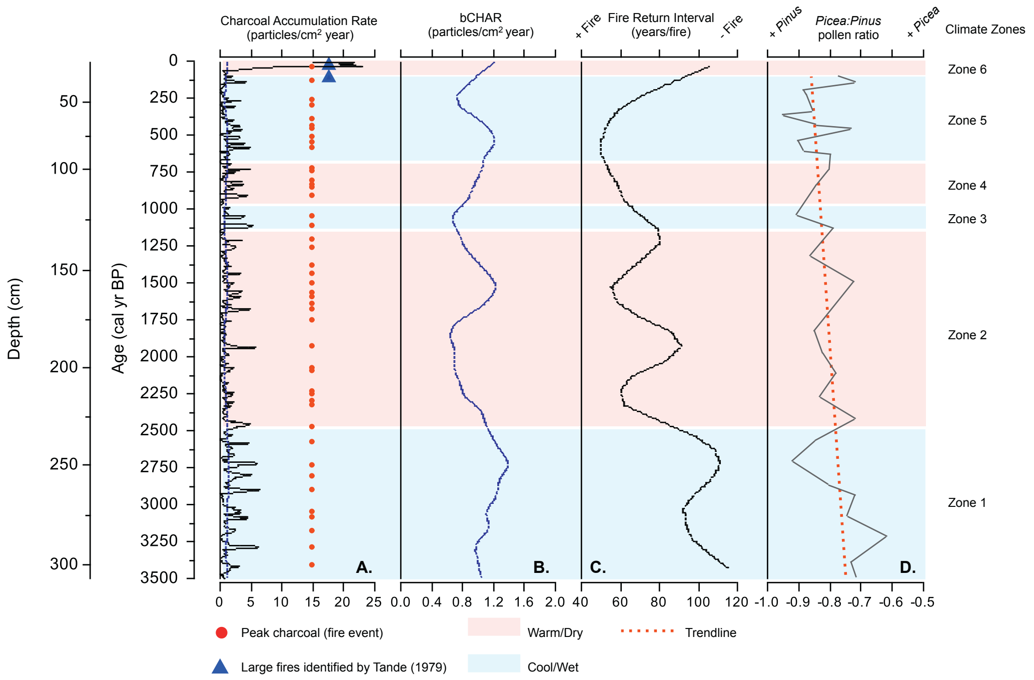

Figure 6. Summary diagram of the fire history record derived from macroscopic charcoal (6a-c) and the *Picea:Pinus* ratio (6d).

study and others from the region (Tande, 1979; Dinh, 2014; Chavardès and Daniels, 2016) and could indicate an on-going shift in the fire-severity regime. Similar to the results of our study, Dinh (2014) noted a decline in the prevalence of large fires as well as surface fires following the onset of the fire suppression era in Jasper. Rhemtulla et al. (2002) have suggested that the exclusion of low-to moderate-severity fires in Jasper, which are more effectively suppressed than high-severity fires, has contributed to forest homogenization and the loss of grasslands in Jasper's montane zone. The accumulation of forest fuels in the absence of fire, especially when combined with warming temperatures and declining moisture availability, increases both landscape flammability and the likelihood of high-severity fires that are more difficult to control (Keane et al., 2002). Increases in the future size and severity of wildfires would have significant implications for vegetation composition, the type and quality of habitat available to animal species, and for human safety (Arno et al., 2000). Widespread, high-severity fires create landscapes that are homogeneous (e.g., large vegetation patch sizes) compared to those created by mixed-severity fires (e.g., variable vegetation patch sizes). As a result, mixed-severity fire regimes tend to generate landscapes with complex patterns of vegetation and coarse woody debris that provides a diverse habitat for wildlife (Agee, 2005).

Combining tree-ring and charcoal fire histories

This study combined tree-ring data with macroscopic charcoal analysis to extend the fire history to 3500 cal yr BP. Tree-ring and charcoal records represent fundamentally different aspects of the local to extra-local fire regime (Whitlock et al., 2004) and combining them revealed a more complete picture of fire activity in the study area. For example, whereas the charcoal fire history record provided long-term information about trends in fire activity, our tree-ring fire history identified several low-severity fires around Little Trefoil Lake (Table 1) that were not recorded in the sediment record. Both the tree-ring and charcoal records indicate a decline in contemporary fire activity, and combined provide insights into the range of fire variability throughout the late Holocene and detailed information about the recent fire history of the study area.

The absence of charcoal peaks during most of the 20th century, despite evidence of low-severity fires in the form of fire scars, could be explained by several possibilities. First, it is possible that the low-severity fires were not intense or close enough to the lake for significant charcoal accumulation to occur. Intense fire events can carry macroscopic charcoal particles several kilometers (Pisaric, 2002; Tinner et al., 2006), however, deposition from low severity fires tends to only occur proximal to the fire (Clark, 1988; Peters and Higuera, 2007). Peaks in macroscopic charcoal are thus typically described as representing small fires that occurred close to a lake or large fires that occurred at variable distances (Whitlock and Larsen, 2001). The low-severity fires that occurred in the 20th century and the human-caused Jasper Park Lodge fire in 1952 were at distances ≥0.5 km from the lake edge and outside of the lake's catchment (4 ha), which is likely beyond the range of macroscopic charcoal deposition. Second, it is conceivable that the large charcoal influx from 58 to −5 cal yr BP (AD 1892–1955) obscured subsequent charcoal peaks due to its magnitude and duration. We used a locally-defined threshold for charcoal peak identification (Higuera et al., 2010a); however, even with this precaution it is possible that small increases in charcoal from low-severity fires could not surpass the threshold influenced by such a large peak. With a median sampling resolution of 7 yr, any charcoal influx from low-severity fires in the early-mid 20th century would be registered within a small number of samples from the large charcoal peak. Finally, it is also possible that the large charcoal peak represents more than one fire event of either high- or low-severity. We are not able to rule out this possibility, however based on modern fire return intervals for Jasper (mean FRI = 15.6 yrs, Dinh, 2014; fire intervals = 11–165 yrs, Chavardès and Daniels, 2016) we expect that our sampling resolution was adequate to detect most individual fires.

Unlike low-severity fires, the two cohort establishment dates are shared with the most recent charcoal peak in the sediment record. This correspondence and the range of fire return intervals in the sediment record leads us to believe that high-severity fire events may be preferentially represented in the charcoal record. The cohort establishment dates from our study correspond well with a large peak in CHAR (described above) beginning at 58 cal yr BP (AD 1892). This peak was probably caused by a series of severe fire seasons in the late 19th century that began with a large fire in AD 1889 (Tande, 1979) during a period of below average precipitation (Watson and Luckman, 2001). An earlier peak in CHAR also aligns with a widespread fire event in the area that occurred in AD 1847 (Tande, 1979). Additionally, the range of mFRI values from the sediment record are more similar to those of large, high-severity fires in Jasper than of small surface fires (Tande, 1979; Dinh, 2014). Interpreting the meaning of inferred fire events is a challenge common to all charcoal fire history studies (Whitlock and Larsen, 2001) that may only be addressed with further advances in analytical techniques.

Fire-climate-vegetation interactions

Presently, large fires in Jasper National Park tend to occur during warm and dry periods that are driven by synoptic processes (Schoennagel et al., 2005). In our sediment record, fires were most frequent during climate zones 2 and 4, both of which are characterized by warm and dry conditions in the region (Hallett et al., 2003; Laird et al., 2003; Hallett and Hills, 2006). Increases in fire activity during these two time periods have also been identified in nearby southeastern British Columbia (Hallett et al., 2003; Hallett and Hills, 2006). Fires tended to be less frequent during the cool and wet zones 1 and 3, possibly due to the inability of fuels to dry adequately. Reduced fire frequencies during climate zones 1 (3500–2400 cal yr BP) and 3 (1200–1000 cal yr BP) have been described in sedimentary charcoal studies from British Columbia (Gavin et al., 2003; Hallett and Hills, 2006; Courtney Mustaphi and Pisaric, 2014) and in the larger Rocky Mountain region (Power et al., 2011). Fires occurred frequently at the beginning of the Little Ice Age (climate zone 5) and became less frequent towards the most recent end of zone 5 during a period of increased precipitation and decreased summer temperatures (Luckman, 2000). It is possible that suitable climate conditions for wildfires existed during some intervals of this overall cool and wet period and/or that human-caused ignitions contributed to more frequent fire events. Fire frequency during the most recent climate zone 6 was found to be low despite the warming trend that has prevailed throughout it (Vincent et al., 2012). As with the scarcity of fire found in the tree-ring record and in agreement with previous studies conducted in Jasper (Tande, 1979; Dinh, 2014; Chavardès and Daniels, 2016), the low fire activity in zone 6 is a likely artefact of fire exclusion that prevailed throughout the last century.

The record of vegetation composition from Little Trefoil Lake compares well with pollen records from elsewhere in western North America (Vance et al., 1983; Luckman and Kearney, 1986; Beaudoin and King, 1990; Pellatt et al., 2000; Pisaric et al., 2003; Hallett and Hills, 2006; Carter et al., 2013; Courtney Mustaphi et al., 2015) that similarly show only modest variations in forest vegetation composition over the past 3500 yr. The relative pollen contributions of the individual conifers (percent pollen; *Pinus, Picea,* and *Abies*) is of similar magnitude to other study areas within Jasper National Park (Luckman and Kearney, 1986; Beaudoin and King, 1990) and in nearby south-eastern British Columbia (Hallett and Hills, 2006).

The variability in the contributions of *Abies* and *Alnus* pollen (Fig. 5) to the sediment record could be indicative of a response to changing moisture conditions between climate zones. *Abies* and *Alnus* grow well in cool and moist environments (Franklin, 1974; Harrington et al., 2008), and appear in greatest abundance during zones 1 and 5 when these conditions prevailed. *Betula* pollen is also slightly more abundant in zones 1 and 5, a possible reflection of the shrub species' adaptation to cool and wet conditions. Although vegetation composition is relatively stable throughout, comparisons between the charcoal record and the pollen ratio (Fig. 6) did reveal some notable interactions between fire and vegetation. Relationships between forest composition (*Picea:Pinus* ratio), regional biomass burning (bCHAR), and local fire activity (mFRI) are apparent throughout most of the sediment record. Local peaks in the *Picea:Pinus* ratio tended to correspond with periods of greater fire frequency until ~700 cal yr BP. This could indicate that an increased abundance of *Picea* in the forests surrounding Little Trefoil Lake, an indicator of forest density and fuel accumulation, is necessary for frequent large fire events to occur.

Just as fuel availability influences the frequency of fire events, the frequency of fire events also plays an important role in determining population dynamics in pine–spruce forests (Johnson and Fryer, 1989). Over the longer time-span covered by the full sediment record, the relationship between the *Picea:Pinus* ratio and the fire return interval reverses, suggesting that as fires become more common towards present, *Pinus* became more dominant on the landscape (see trend line in Fig. 6d). Lodgepole pine is better adapted to fire than white spruce (Nadeau and Corns, 2002) and could therefore have a competitive advantage during the long-term increase in fire frequency over the past 3500 yr.

The role of humans in controlling the fire regime

Humans have occupied the Rocky Mountain region of western North America for thousands of years. Oral histories, written accounts by early European settlers, and evidence preserved in proxy records indicate that First Nations peoples frequently used fire as a management tool (MacLaren, 2007). Opinions on the contribution of human-caused ignitions in fire histories vary (see Baker, 2002 for discussion); however it is clear that their impact would be greatest in the most heavily frequented areas, such as important travel corridors and montane valleys. The Athabasca River valley has historically been an important area of trade and settlement, and fires have been set intentionally there for at least the past few centuries (MacLaren, 2007; Dinh, 2014).

Although it is difficult to determine the cause of fire events identified in proxy-based fire history records, changes in the interactions between the components of environmental history records can help to surmise the possible impacts of humans. The lack of coherence between the *Picea:Pinus* ratio and fire frequency in the sediment record after 700 cal yr BP leads us to infer a possible change in human activities around Little Trefoil Lake at this time. In areas where lightning ignitions are rare, such as in the 'lightning shadow' of the eastern Rocky Mountains (Rhemtulla, 1999), human-caused fires have the greatest impact on fire-vegetation interactions by increasing ignition sources. Throughout most of the sediment record, the *Picea:Pinus* ratio appears linked to the frequency of fire events, with shorter fire return intervals associated greater proportions of *Picea*; however the relationship breaks down after 700 cal yr BP. It is possible that the reduced abundance of *Picea* after this time could be due to the cool conditions of the Little Ice Age; large-scale mortality events during the Little Ice Age have been documented at treeline locations in Jasper National Park (Luckman and Kavanagh, 1998). No similar trend arose in our record during earlier cold periods (e.g, climate zones 1 and 3), however, and tree mortality in the montane zone would have been less likely than it would be in the alpine zone. An alternative explanation is that the decrease in *Picea* after 700 cal yr BP is a reflection of reduced biomass related to land clearing for human settlement and the intentional use of fire.

Throughout the past century, the relationship between humans and fire has undergone significant change. Rather than being used as a tool, fire became viewed by the public primarily as a threat to human safety and resources early in the 20th century. The important role of wildfire in maintaining ecological processes was not fully recognized, and a policy of fire suppression was adopted in Jasper in 1913 (MacLaren, 2007). The sediment and tree-ring fire history records demonstrate that changes in the fire regime due to human activity have been underway for at least the last 150 yr. The low charcoal accumulation and absence of even-aged cohorts representing high-severity fires throughout most of the 20th century suggests that the landscape around Little Trefoil Lake could be experiencing a shift away from a mixed-severity fire regime. The effects of fire suppression are currently being felt throughout the Rocky Mountain region and pose a significant challenge for land managers and planners responsible for implementing forest and fire management plans (Keane et al., 2002). In protected areas, such as Jasper National Park, this challenge is made even more difficult as a result of the dual mandate required of those working there. Maintaining ecological integrity is a foremost aim of federally protected areas in Canada (Parks Canada Agency, 2014), and the active reintroduction of fires to maintain ecological processes and ensure ecosystem health is an essential component of addressing this aim (Theberge et al., 2015). At the same time, in areas with high tourism activity and infrastructure, the prospect of wildfires could equally be viewed as a threat to safety and property.

Our charcoal record reveals that the current fire return interval is within the historical range of variability of the past 3500 yr, but that it is most similar to the earliest period of the record when the climate was cool and wet. Based on the anticipated effects of warming temperatures and the changes in fire-vegetation interactions described here, it is clear that continued efforts to reintroduce fire to the landscape are necessary. In the absence of wildfires under continued warming, there is a greater risk of large and severe fires occurring. Primed by decades of fuel accumulation, intense fires would have negative effects for humans (e.g., threats to public safety, lost revenue from tourism) as well as having significant ecological implications (e.g., changes in fire regime, forest species composition, and habitat availability for wildlife). Careful planning of prescribed burns and fuel management are needed to lessen the risk of fire regimes moving outside the natural range of variability which could lead to significant changes in the vegetation composition and ecological processes that are characteristic to the area (Adams, 2013; Stephens et al., 2013).

Conclusions

Over the last 3500 yr the montane forests of Jasper National Park have experienced regular disturbance by mixed-severity wildfires. Our results show that the frequency of these wildfires is driven by climate and vegetation composition, with more fires occurring during warmer and drier periods with high biomass availability. During the past century, active fire suppression has led to an artificially long fire return interval causing the fire regime to become disconnected from the climate and vegetation conditions of the study area. As a result, a shift to a higher-severity regime in the future may be expected under prolonged warm and dry conditions. This is an important consideration for developing land and fire management strategies, especially at the wildland–urban interface of the Jasper townsite where the risks posed by wildfire to the safety of humans and infrastructure are likely greatest. Continuing action to reintroduce fire to the landscape will be critical for maintaining the mixed-severity fire regime that is characteristic to the region as well as for reducing the risk to safety imposed by high-severity fire events.

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