

The influence of vegetation and climate on wildfires in  
Jasper, Alberta, over the last ~3,500 years

by

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## **Abstract**

This study employed a multi-proxy approach to gain insights into past fire dynamics within the watershed of Little Trefoil Lake in Jasper, Alberta, Canada. Charcoal analysis and dendrochronology were used to characterize the historical fire regime and place past trends within the context of the present day landscape. A ~3,500-year record of fire events was established by analyzing macroscopic charcoal remains, and pollen analysis was used to determine changes in the dominant vegetation type. Charcoal and pollen analyses indicated that climate has been the strongest control on the fire regime around Little Trefoil Lake over the last ~3,500 years. The contemporary fire record, as reconstructed using tree-ring data, showed that the watershed has experienced a mixed-severity fire regime. Active fire management strategies adapted to this type of fire regime should be pursued to ensure the resilience of the forest as we continue forward in a period of rapid climate change.

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## **Preface**

This integrated article format thesis comprises four chapters, the third of which will be submitted to a peer-reviewed scientific journal. The overall workload for this dissertation took this form: Dr. Michael F.J. Pisaric (MFJP) and Emma L. Davis (ELD) conceived the studies and led the fieldwork; ELD collected the data and conducted the data analyses with oversight from MFJP and suggestions from Dr. Jesse Vermaire (JV); ELD ideated the manuscripts with input and suggestions from MFJP and JV. A version of Chapter 3 will be submitted for publication in the Canadian Journal of Forest Research as: *“Climate, vegetation, and human influences on forest fire activity over the last 3,500 years in Jasper National Park, Alberta.”*

# CHAPTER ONE

## INTRODUCTION

Wildfires are among the most important sources of disturbance in the boreal forest ecosystem. Fire activity is a natural part of ecosystem functioning, and is closely related to various components of vegetation composition, nutrient cycling, and habitat availability (Lotan et al. 1985). Changes in land use resulting from human activities have, and continue to, alter wildfire disturbance regimes to varying degrees. For example, land clearing for human settlement as well as fire suppression and exclusion, which are common derivatives of settlement, have in some areas led to a variety of negative effects on forest health and ecosystem resilience. At the landscape level, these effects are measurable as reductions in biodiversity, landscape homogenization, and a large-scale shift towards late successional tree species (Romme 1982; Rhemtulla et al. 2010). When considering the safety of humans and infrastructure, of additional concern is the accumulation of fuels in unburned areas that increases the likelihood of high severity and potentially devastating fires.

The ability to pursue appropriate ecosystem management is a growing concern for forest managers, landowners, and forestry companies who have come to recognize the need to understand fire, climate, and vegetation processes if environmental integrity is to be maintained in managed and working forests (Flannigan et al. 2009). Without knowledge of past conditions, it is difficult, if not impossible, to establish a frame of reference for the environmental changes that we are witnessing today, and to plan accordingly for the future. It has been suggested that the fire regime of certain regions of

the boreal forest have already been pushed outside of its historical range of variability as a result of forest management (Cyr et al. 2009). Management strategies will continue to be put to the test in the near future as increasingly severe fire seasons are predicted for Canadian forests under future climate change scenarios (Flannigan et al. 2013).

There are several sources of information available that may inform our understanding of past fire events. These sources are primarily found within the geosphere, the biosphere, and the anthroposphere (Conedera et al. 2009), and together they can be used to study the histories of landscapes that are present today. The geosphere includes studies of changes in the geochemistry and the magnetism of sediment deposited stratigraphically through time, both of which have the potential to be affected by erosional processes resulting from fire activity. Studies relating to the biosphere centre on constructing paleoecological records from the biological remains of partially or entirely combusted material (i.e. paleolimnology, dendrochronology, and charcoal analysis). Much information, factual and anecdotal, can be gained from the anthroposphere by examining written documents or other human artefacts that record the occurrence of fire events. In practice, historical fire records are most reliable when these three approaches are taken in tandem. Long-term fire histories, such as the one developed in this thesis, are developed using paleoecological methods that include sedimentary charcoal analysis, pollen analysis, and tree ring data; the importance of applying a long-term perspective when investigating fire histories has been widely noted (Campbell and Flannigan 2000; Brunelle and Whitlock 2003; Cyr et al. 2009; Marlon et al. 2012).

The research presented in this thesis focuses on a paleolimnological analysis of lake sediment cores collected in Jasper, AB (Little Trefoil Lake; 52.89°N, 118.06°W)

(Figure 1; Table 1), and a tree-ring analysis of samples collected within its local to extra-local surroundings. Little Trefoil Lake, a small kettle lake, is located in the Athabasca River Valley of Jasper National Park, situated in the Front and Main ranges of the northern Rocky Mountains. Aboriginal peoples have occupied the area since the retreat of glaciers in the early Holocene (~10,000 yr BP), and European settlement began in the early 1800s as a result of the fur trade, although it was not for another one hundred years, during the construction of the Grand Trunk Pacific Railroad, that the Jasper town site was established (Parks Canada 2013). In Jasper, the first forest warden was appointed in 1909 to address the increasing risk of forest fires resulting from human activity in the area, and an organized effort towards fire suppression began in 1913 (Tande 1979). Presently, some areas of the park are being actively burned in an effort to mimic the effects of naturally occurring wildfires. The information presently used to inform wildfire policy, is, however, based on short to medium term information that may not capture the extent of historical variability in fire activity. Little Trefoil Lake, situated near the present-day location of the Jasper Park Lodge, is suitable for reconstructing paleofire events using charcoal analysis based on its physical characteristics: it is a small, circular lake with no inflowing streams that could distort the fire signal produced by macroscopic charcoal analysis (Whitlock and Larsen 2001). Being situated within a core area of human settlement in the Jasper town site presents an interesting opportunity to compare pre- and post-settlement fire regimes.

The objective of this research is to gain an understanding of how the fire regime of the montane forest ecosystem of Jasper has responded to past changes in climate and vegetation composition by comparing the fire history record to evidence of regional

climate and vegetation changes through time. A chronology of contemporary fire activity will be developed to categorize the current fire regime, and a 3,500-year chronology of fire events will be established for the area surrounding Little Trefoil Lake, using multiple paleoenvironmental proxies, including macroscopic charcoal, tree-ring analysis, and subfossil pollen. A shorter, but detailed, 300-year tree-ring based record of wildfire events already exists in the study area (Tande 1979), however fire suppression activities throughout the last century have made it such that decadal and centennial-scale records likely do not account for the full potential variability of the local fire regime. It has been observed that investigating only the short-term fire regime can lead to erroneous assumptions regarding the role that fire plays on the landscape as well as its controlling factors (Whitlock et al. 2010). Having a detailed and longer-term (covering several millennia) fire history record will help to place current fire activity within the context of past conditions.

This research addresses two main questions: 1) what has been the variation in the frequency of wildfires around Little Trefoil Lake during the past 3,500 years? and, 2) what has been the influence of top-down (climate) and bottom-up (vegetation) controls on these wildfires, particularly during the colder than present Little Ice Age (1500-1850 CE) and the warmer and drier Medieval Climate Anomaly (700-1100 CE)?

This thesis is organized into four chapters as follows: Chapter 1 provides background information and context for the research project. Chapter 2 reviews the pertinent literature related to the research questions that will be investigated in the thesis, and describes the field, laboratory, and analysis methods. Chapter 3 is a presentation of the research findings in the form of a manuscript; and Chapter 4 summarizes the

conclusions and implications of the research and proposes avenues of future research that have developed from the current project.

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1 The boreal forest

It has been suggested that most forests in North America are in some stage of recovery from a fire event (Payette 1992). In boreal ecosystems, wildfire is the dominant disturbance agent and is driven by factors operating across a range of spatial and temporal scales. As we seek to understand the ways in which our future climates are likely to influence fire events, we must also understand the natural range of variability in fire activity that has occurred in the past.

The Canadian boreal forest sweeps across the country, covering 530 million hectares (11% of Canada's landmass), and is present in all provinces except Nova Scotia and Prince Edward Island (Ward and Mawdsley 2000). The physical characteristics of the boreal forest are such that forest fire is ubiquitous across the landscape; from 1990-2000, there were on average 9,500 forest fires a year in Canada, with an annual area burned approaching 3.2 million hectares (Ward and Mawdsley 2000). The dominant conifer trees in the boreal are black spruce (*Picea marianna* (Mill.) B. S. P.); white spruce (*Picea glauca* (Moench) Voss); balsam fir (*Abies balsamea* (L.) Mill.); jack pine (*Pinus banksiana* Lamb.); lodgepole pine (*Pinus contorta* Dougl. ex. Loud.); subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.); and tamarack (*Larix laricina* (Du Roi) K. Koch). The prevailing deciduous trees tend to be pioneer species, colonizing recently disturbed landscapes, and include trembling aspen (*Populus tremuloides*); balsam poplar (*Populus balsamifera* Michx.); and paper birch (*Betula papyrifera* Marsh.) (Bourgeau-Chavez and

Alexander 2000). In the boreal forest the prevalence of fire is a result of a suitable combination of climatic conditions and vegetation composition, as well as adequate sources of ignition (Kasischke 2000). Climate and fire activity, which are closely related, shape the distribution of plant species by controlling the conditions in which the plants need to survive. The distribution of vegetation, in turn, plays an important part in determining the type and amount of biomass accumulation that serves as the fuel for fires. The mosaic of plant species compositions created by fire-climate-vegetation interactions is a result of the effects of the local fire regime.

Fire return intervals vary throughout the boreal forest, but are believed to range from only a handful of years in fire prone locations to over 200 years in others (Arno et al. 2000). Although widely dispersed, fire activity tends to be higher in the western boreal forest of Canada compared to central or eastern Canada, in part due to a generally drier climate that facilitates the ignition and spread of fire (Campbell and Flannigan 2000), but also because the vegetation in the region tends to be more prone to fire events (e.g. flammability of tree species, life history strategies that favor wildfires). The climate of western Canada delivers enough moisture to establish a relatively high level of production, providing ample fuel for forest fires, however periods of extended dry weather during the fire season are common and enable ignition and spread.

It is thought that the majority of fire events take place during a small number of days with extreme fire weather conditions where lightning is the dominant ignition source; a single storm system has the potential to cause several fires as it passes over the landscape (Kasischke 2000). When comparing historic fire records from 1960/70 to those of 1980/90, Kasischke and Turetsky (2006) identified a two-fold increase in the annual

area burned in Canada and a doubling of large fire years (where >1% of the total landmass of an ecozone burned) in the recent period. This trend of increased fire activity was found to be most prevalent in western Canada (Kasischke and Turetsky 2006). That fire events tend to be more frequent in warmer conditions is particularly relevant given the projected increase in mean annual temperatures for northern and high altitude environments (McKenzie et al. 2004).

Given that the controls on the long-term fire regime can operate on multi-decadal to millennial time scales, a method for identifying long-term trends in the fire regime is necessary. Comprehensive historical fire data extends back only as far as the 1970's in North America, when the development of remote sensing techniques facilitated a thorough detection of fires, even in isolated areas (Murphy et al. 2000). Incomplete observational records may, however, be several decades longer in some areas.

Paleoecology, which uses proxy data to reconstruct past environmental conditions, is a useful tool for gaining insight into the range of variability of fire regimes prior to the observational period, over hundreds to several thousands of years, and has successfully been used to reconstruct fire histories (e.g. Long et al. 1998; Walsh et al. 2010; Marlon et al. 2012). The majority of long-term fire histories in North America have been concentrated in central and eastern Canada (Ontario and Quebec) and in parts of the northwestern United States (Campbell and Flannigan 2000). Fewer long-term records exist in western Canada, however efforts are being made to improve the spatial resolution of fire history studies in this region (e.g. Hallett and Hills 2006; Enache and Cumming 2009; Courtney Mustaphi and Pisaric 2013).

## 2.2 Holocene climate change

Changes in climate throughout the Holocene have driven changes in the vegetation composition of Jasper National Park. Deglaciation commenced ~13,000 yrs BP and the Jasper area was ice-free by 10,000 yrs BP (Osborn and Luckman, 1988). Geomorphic activities of subsequent glaciations have shaped many low-lying areas in the region. Three major periods of glacial advance have occurred since the beginning of the Holocene; the Crawfoot advance (4,000 yrs BP); the Tiedemann advance (2,500 – 1,800 yrs BP), and the Cavell advance (900 – 300 yrs BP) (Osborn and Luckman 1988).

Pollen analyzed from a sediment core near Wilcox Pass, AB (core age: 9,600 +/- 350 years), located ~70 km south-east of Jasper near the Columbia Icefield and Sunwapta Pass, indicated that the late Wisconsin vegetation cover was dominated by grasses and tundra-like vegetation assemblages, suggesting cooler than present conditions (Beaudoin and King 1990). The onset of the early Holocene was characterized by a period of milder temperatures, referred to as the Hypsithermal, which enabled the establishment of more complex vegetation assemblages. Isotopic reconstructions of mean annual temperatures suggest that temperatures were between 0.5-1.6°C warmer during the Hypsithermal (8,000 – 5,300 yrs BP) than those of the late 20<sup>th</sup> century (Luckman and Kearney 1986). Luckman and Kearney (1986) identified an advance in tree-line related to this period of warmer temperatures from sediment cores collected from Maligne Lake, AB, during the periods from 8,800 - 7,500 and 7,200 - 5,200 yrs BP. Similarly, Beaudoin and King (1990) noted the initial establishment of arboreal species at Wilcox Pass, which would suggest more favorable growing conditions, around 6,800 yrs BP.

Following the mid-Holocene Hypsithermal, cooler conditions associated with a Neoglacial advance lead to the establishment of modern vegetation assemblages in most of Western Canada around 4,000-3,000 yrs BP (e.g. Beaudoin and King 1990; Hallett and Hills 2006; Courtney Mustaphi and Pisaric 2013). The relatively stable climate of the past 4,000 years is characterized as being cooler than that which occurred previously, with the notable exceptions of the Medieval Climate Anomaly (700-1100 CE; discussed below) and the last 150 years (Luckman and Wilson 2005).

### 2.3 Vegetation characteristics and local geology

Little Trefoil Lake is located in a boreal-montane forest presently dominated by lodgepole pine, white spruce, and Douglas fir (*Pseudotsuga menziesii*). As in all forest systems, the specific fire regime around Little Trefoil Lake plays an important role in determining pathways of succession, species longevity, and species composition, while influencing the distribution and abundance of insects and disease (Lotan et al. 1985).

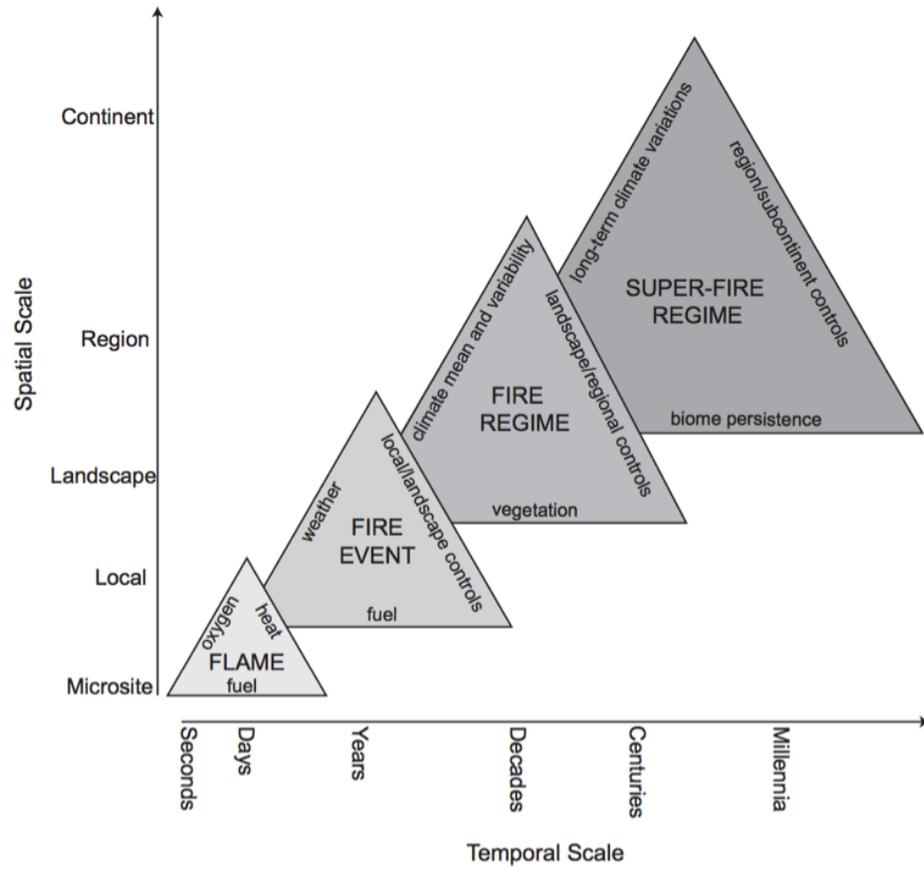
Lodgepole pine, the most abundant species in the Little Trefoil Lake watershed, is well adapted to environments with regular wildfire disturbance, and uniform cohorts of lodgepole pine often become established following a fire due to their ability to rapidly colonize disturbed locations. The thin bark of lodgepole pine makes them susceptible to mortality by fire, but their serotinous cones, which require heat in order to release seeds, makes them able to efficiently repopulate the post-fire landscape (Lotan et al. 1985). Because lodgepole pine is found in a variety of environments, the fire regime in lodgepole pine forests varies between locations. In a previous study, Day (1972) found a fire return interval (FRI, average time between fires) of 67 years in lodgepole pine forests

(Day 1972). Arno (1980) found FRIs ranging between 22-50 years and Romme (1982) concluded there were several centuries between fires in some lodgepole pine forests (Arno 1980; Romme 1982). The variation in the time between fires shows the suitability of lodgepole pine to a variety of fire regimes.

Little Trefoil Lake is situated in the Athabasca River valley, part of a geographically complex region between the Front and Main Ranges of the Canadian Rocky Mountains. The bedrock of the region is predominantly composed of shales, quartzites, and dolomites (Luckman and Osborn 1977). At slope peaks, extending to >3,000 meters in elevation, Precambrian shales and limestones, as well as Cambrian quartzites are common (Luckman and Kearney 1986).

#### 2.4 Various scales of fire controls: Climate, fire, and vegetation relationships

The relationships between fire, vegetation and climate can be represented as a series of fire triangles (Figure 1; Whitlock et al. 2010) that demonstrate how these factors change across temporal and spatial scales. In condensed time-scales of hours to weeks, weather conditions directly influence fuel moisture, the probability of ignition by lightning, and the spread of fire by prevailing winds. Over longer time scales, such as decades and longer, the climatic regime influences vegetation composition and structure making climate, in part through its control on the type and abundance of vegetation, a key driver of fire events. It is these spatial and temporal controls that determine the characteristics of a fire regime.



**Figure 1** The relationship between fire and its main drivers can be viewed as a series of fire triangles that vary across temporal and spatial scales (From: Whitlock et al. 2010). The research presented in this thesis addresses the fire regime and super-fire regime.

Flannigan et al. (2000) describes wildfires as having six main characteristics: fire frequency, size, intensity, seasonality, type, and severity. Fire frequency is regulated by vegetation composition and ignition (Flannigan et al. 2000). Fire size creates patchiness on the landscape, making it more or less difficult for certain species to colonize a recently burned area. The intensity of a fire is closely linked to the amount, arrangement, and connectivity of available fuel, whereas the season in which a fire occurs can influence what vegetation is able to colonize immediately following a fire. Fire type (ground fire versus crown fire) determines the landscape complexity post-fire. Finally, fire severity, most commonly used to categorized fires, impacts the ability of a forest to recover following a fire (Flannigan et al. 2000), and indirectly encompasses the other components of the fire regime (e.g. the combined effects of fire frequency and size and influence the severity of the fire regime).

Historically, a paradigm has existed in which fire regimes were classified into categories of low, moderate, or high severity (Amoroso et al. 2011). More recently, however, it has been realized that in certain locations the landscape may experience both low and high severity fires, resulting in a 'mixed-severity' fire regime. Occurring commonly in areas with a high degree of variability in topography, moisture, and species composition (Schoennagel et al. 2004), regions that experience mixed-severity fires possess conditions amenable for fires of different levels of severity to occur in close proximity at intervals of roughly 30-100 years (Arno et al. 2000). Mid-elevation forests have been noted as being situated in an appropriate location in the altitudinal moisture gradient to be conducive to fires of varying severity (Perry et al. 2011).

Low, moderate, and mixed severity fire regimes result in structurally complex forest stands, meaning they have significant internal heterogeneity, or patchiness, whereas high severity fires lead to stands that are more homogeneous in composition (Amoroso et al. 2011). Mixed-severity fire regimes in particular have been noted for their contribution to beta, or landscape level, biodiversity, as forest stands under these conditions can possess dissimilar and complex stand structures, despite their proximity (Perry et al. 2011). Stand-level heterogeneity is an important feature, as it provides a variety of habitat types for animal populations, and makes the forest more resilient to future disturbances. It has been suggested that between 17-50% of the Rocky Mountain Range experiences a mixed-severity fire regime (Schoennagel et al. 2004), although more research is necessary to characterize location-specific fire regimes. Correctly categorizing the local fire regime is important since landscape management strategies are closely tied to this understanding (Perry et al. 2011).

Forests, no matter the severity of fire regime they experience, are dependent on processes functioning on a variety of spatial and temporal scales that can be characterized as either 'bottom-up' or 'top-down' controls. Bottom-up controls refer to factors that influence the actual potential of a fire to occur (fire events) and tend to vary on fine temporal and spatial scales (Heyerdahl et al. 2001). Abrupt changes in small-scale topographic features, such as slope, aspect, as well as site-level vegetation structure and arrangement are considered bottom-up controls. For example, steep slopes can facilitate the upslope spread of fire, and south or west-facing slopes are generally more susceptible to burning due to the drying-out of fuels caused by a greater exposure to direct sunlight. Vegetation structure and fuel load are also considered bottom-up controls as their

composition can change in relatively short distances and amounts of time (Whitlock et al. 2010). In contrast, top-down fire controls are overriding factors that influence the regional fire regime, producing synchronicity in fire behaviour across space, and vary across larger spatial and longer temporal scales. Regional vegetation and large-scale topographic features (presence of landforms, large fire breaks), in addition to climate, are considered to be top-down controls. Climate is the most significant top-down control of the fire regime through its impact on regional vegetation composition and structure (including fuel arrangement and availability). Further, the regional climate dictates the production and moisture level of fine fuels, two determinants of the likelihood of ignition (Heyerdahl et al. 2001). Investigating historical fire activity at a variety of spatial and temporal scales provides insight into how ecosystems may respond to future changes in top-down and bottom-up controls (Whitlock et al. 2010).

When considering the effects of regional climate on fire regime, large-scale processes should be identified as potential mechanistic controls. Large-scale atmospheric processes, as well as their teleconnections, have been shown to influence the fire activity of western Canada (Schoennagel et al. 2005). El Nino, a component of the El Nino/Southern Oscillation (ENSO), is an interannual phenomenon that is characterized by low atmospheric pressure above the eastern Pacific Ocean, leading to warmer and drier conditions in western North America, especially during winter months (Ropelewski and Halpert 1986). Warm and dry winters would limit ground water recharge by reducing the size of the snowpack and as well as the spring freshet. Its counterpart, La Nina, causes cooler and wetter conditions as the phase reverses. Recent research has shown that in the future, ENSO and its associated weather conditions are likely to move further

eastward due to climate warming (Kug et al. 2010). The oscillation between El Nino and La Nina events has the potential to enhance biomass production in some years (La Nina), and to follow them with warm and dry years that desiccate fuels and increase the likelihood of burning (El Nino).

Operating on longer time scales of 15-25 years, the Pacific Decadal Oscillation (PDO) is also a pattern of climatic variability over the Pacific Ocean (Mantua and Hare 2002). PDO events, considered to be either 'warm' or 'cool', are deviations in sea surface temperatures in the North Pacific Ocean. Warm (positive) PDO events intensify the Aleutian low, which has the effect of deflecting storm tracks towards the northwestern United States rather than their typical paths over western Canada. The results in western Canada are warmer and drier conditions as moisture is directed away from the region (Schoennagel et al. 2005).

That some constructive link exists between the phases of ENSO and the PDO and fire events has also been noted in a number of studies (Schoennagel et al. 2005; Kitzberger et al. 2007; Whitlock et al. 2010). Schoennagel et al. (2005) investigated the relationship between the phases of ENSO and the PDO and fire events in the southern, central, and northern Rocky Mountains of North America. Using tree-ring based fire history reconstructions, their analysis revealed that in Jasper National Park, during the period from 1700-2000, 41% of fires occurred during combined warm phases, which occurred only 30% of the time. The warm phase of ENSO (El Nino) had little relationship to fire events on its own, but the combined effect with the warm phase of the PDO resulted in drier conditions that enabled greater fire activity. Given that the effects of warm PDO and ENSO phases are realized more notably in the winter and early spring,

these findings agree with other climate-fire observations that suggest fire activity increases in response to earlier snowmelt, more moderate springtime temperatures, and an increase in the length of the growing season (Westerling et al. 2006).

In the interior Pacific Northwest, USA, the effect of ENSO on fire events appears to be more significant. Heyerdahl et al. (2002) found that large fires occurred more frequently in the warm and dry El Niño years, but that there was no relationship between the occurrence of small fires and ENSO. They further suggest that the longer-term (decadal) fire regime could be influenced by the PDO, which acts on longer time scales (Heyerdahl et al. 2002). Also in the northwestern United States, Gedalof et al. (2005) found a relationship between the occurrence of blocking events (stationary high-pressure systems) at the 500hPa height field and extreme wildfire years. Blocking events, which can deflect storm tracks and precipitation, cause dry conditions, increasing the likelihood of fire activity (Gedalof et al. 2005).

Although climate and its associated weather conditions are unquestionably important controls on fire activity in Canada, a warm and dry climate is itself not enough to produce fires. An example of this can be seen in desert ecosystems, where temperatures are high and moisture levels are low, but biomass production is insufficient to produce the fuel required for large wildfires (Campbell and Flannigan 2000). Instead, the role of climate is two-fold: it both creates the conditions for the ignition and spread of fire through lightning storms and wind, and also regulates fuel type and composition by facilitating the production of biomass (Campbell and Flannigan 2000). Much effort has gone towards gaining an understanding of the relative importance of climate and

vegetation in controlling fire regimes (e.g. Gavin et al. 2006; Courtney Mustaphi and Pisaric 2013).

When climate is the dominant fire control, fires tend to be synchronous across a region (Kitzberger et al. 2007). Using charcoal analysis and tree-ring evidence collected around two lakes 11 km apart, Gavin et al. (2006) found that the fire intervals differed between their two sites, despite their proximity (Gavin et al. 2006). This suggests that local conditions appeared to be more important than the top-down influence of climate in structuring the fire regimes. Gavin et al. (2006) also demonstrated that locations that presently share similar vegetation composition and structure might have arrived there as a result of different fire histories. In their 2013 study, Courtney Mustaphi and Pisaric found changes in the relative influences of top-down vs. bottom-up controls through time. Their study found that sites with differing slope aspects possessed asynchronous fire histories, suggesting that local factors played an important role in determining fire activity.

In the eastern boreal forest (Québec), Ali et al. (2009) compared historical fire regimes to determine the relative role of local versus regional fire controls (Ali et al. 2009). They found that between 8,000 and 4,000 years BP fire-free intervals and fire events were synchronous between their study sites, while from 4,000 years BP to present two of the sites displayed asynchronous fire histories (Ali et al. 2009). They conclude that in the past, top-down controls, such as climate, were dominant and that in the last 4,000 years site-level factors have had an overriding influence on fire regimes in their study area. In an additional study from the eastern boreal forest, Carcaillet et al. (2001) used tree-ring and sedimentary charcoal records to understand if vegetation or climate was driving fire regimes in a region of the eastern boreal forest (Québec) over the past 7,000

years. Charcoal fire histories and pollen records were developed for three small kettle lakes in both boreal-coniferous and mixed-boreal locations. It was found that despite changes in fire frequency between 7,000-3,000 years BP (longer fire return intervals) and the past 2,000 years (shorter fire intervals) the pollen record remained relatively stable. The absence of change in the relative abundance of highly combustible species in response to the changing fire regime, in addition to an apparent agreement between fire history and climate data, supports the idea that climate has been the main factor controlling the fire regime at their study sites over at least the last 7,000 years (Carcaillet et al. 2001). These studies demonstrate that the relative controls on the fire regime can vary through time and are rarely uniform across different landscapes.

The complex relationships between climate, wildfire, and vegetation outlined above allude to a degree of uncertainty surrounding the mechanisms in which fire mediates the response of vegetation to changes in climate. Whereas increases in fire activity can be justly connected to warm and dry weather, heightened fire activity can also result from a change in vegetation structure or abundance. For example, an increase in conifer species relative to less-combustible deciduous plants can lead to more fire activity (Campbell and Flannigan 2000). Further, vegetation plays a central role in controlling the abundance, distribution, and quality of forest fuels (Higuera et al. 2009). Fire events can also increase habitat availability for plant species colonization, thus leading to a pulse in biomass following a fire, essentially creating more fuel for the next burn.

While the warm and dry conditions resulting from human-induced climate change may increase fire activity (frequency of fires, burn severity), it could also lead to eventual

changes in vegetation structure or abundance that could mediate changes in fire activity. For example, Kelly et al. (2013) suggest that future climate warming may lead to a dominance in deciduous tree species in parts of the boreal forest that could lead to reduced fire frequency and intensity due to the relatively lower flammability of these trees compared to conifers. Terrier et al. (2013) developed a simulation model to infer how fire regimes in the boreal forest could respond to future anthropogenic climate change. The two-scenario model simulated the outcome of warming alone (no adaptive vegetation response) and the outcome if deciduous plants were able to disperse uninhibited. They found that warming temperatures increased the habitat availability for deciduous trees, curbing the predicted increase in fire activity seen in the no-adaptation model (Terrier et al. 2013).

The mediation of climate change by shifts in vegetation community has also been observed in historical records. Higuera et al. (2009), studying boreal forest types in Alaska, found that despite shifts towards cooler and wetter conditions during the mid-late Holocene (8,000-5,000 years BP), subsequent increases in the density of conifer species and the introduction of black spruce (a relatively flammable species due to its low hanging branch morphology) actually increased landscape flammability. This behaviour implies that in areas where fuels are limited, changes in climate that might otherwise reduce fire frequency can illicit a response from vegetation that heightens flammability (Higuera et al. 2009). These somewhat examples highlight the complex ways in which vegetation and climate are interdependent as well as the multitude of pathways these interactions can take.

Because fire disrupts the development of a forest stand more quickly and directly than do changes in climate, an increase in fire prevalence could have the effect of forcing ecosystems to adapt more rapidly to climate change. It has been suggested that long periods of ecosystem stability can conceal changing levels of resilience to disturbances (Johnstone et al. 2010). Johnstone et al. (2010) found that in Yukon, Canada, future canopy cover is based largely on post-fire recruitment of seedlings that occurs in the first decade after a fire. Because recruitment success depends on the ability of available seeds to become established under potentially different conditions than their parent plants, canopy cover in the future could differ from pre-fire composition. In essence, over longer time scales of centuries or more the vegetation response to fire activity has the potential, under suitable conditions, to override the influence of climate itself.

## 2.5 The response of fire and vegetation to past changes in climate

If much can be gained from studying contemporary fire-climate-vegetation relationships, so too can investigating the behaviour of wildfires during past anomalies in climate, enabling researchers to better understand how the current fire regime may respond to future climate change. Using the past as an analogue for the present, the behaviour of fire and vegetation during past periods of warmer and drier conditions, in particular the Medieval Climate Anomaly (MCA; 700-1100 CE), can offer insights into what might be expected as a result of contemporary changes in climate (Hallett and Hills 2006; Kelly et al. 2013). The climates of the MCA can be described as those of a climatic optimum, a period in which relatively warm and dry conditions had landscape effects that included changes in vegetation (Kelly et al. 2013), heightened fire activity

(Marlon et al. 2012), and glacier retreat (Luckman 1986) in the Northern Hemisphere. In their study that used composite pollen records to develop a millennium-scale temperature reconstruction of boreal Canada, Viau and Gajewski (2009) found evidence of summer temperature anomalies of  $\sim + 0.8^{\circ}\text{C}$  at 1000 yrs BP in the region (Table 1). This differs from the interpreted value of Luckman and Wilson (2005) from the same period, presented in Table 1, because they base their anomalous values against different time periods. Both studies, however, point to generally warmer temperatures during the MCA. Although it is challenging to identify the exact timing of the onset of variations in climate, glacier and tree-ring evidence suggests that the MCA occurred between 700-1100 CE in western Canada (Luckman 1986).

A second and more recent climate anomaly, the Little Ice Age (LIA), which is characterized by a cooling climate in the Northern Hemisphere, occurred between 1500-1850 CE (Mann 2002). Mann (2002) has described the global temperature during the LIA to be on average about  $0.6^{\circ}\text{C}$  lower during the 15<sup>th</sup> and 19<sup>th</sup> centuries compared to present, although the timing and degree of temperature decline was regionally variable. In southwestern Alberta, researchers have reconstructed climate variability throughout the late Holocene using proxy data including tree-rings, lichenometry, and radiocarbon dating (Luckman 1986; Luckman et al. 1997; Luckman and Wilson 2005). Luckman (1986) identified LIA glacial advances in the Canadian Rocky Mountains during the 16<sup>th</sup> and 17<sup>th</sup> centuries, with some of the most extensive advances occurring during the mid to late 19<sup>th</sup> century. The positive mass balance associated with glacial advance indicates an onset of colder than present climate conditions during these times (Luckman 1986). An 800-year tree-ring based temperature reconstruction from the Columbia Icefield in

Alberta (Luckman et al. 1997), also showed that the coldest period was the first half of the 19<sup>th</sup> century. Evidence for the occurrence of the MCA was also identified; a 1,000 year-old snag (dead tree) was found 90 km northwest of its present range, suggesting warmer temperatures that enabled tree-line advance (Luckman et al. 1997). Luckman and Wilson (2005) found that during the timing of the LIA, temperatures were an average of 0.78°C cooler in south-western Alberta than during the most recent century (Table 1).

Proxy records developed for Alberta and British Columbia indicate that the MCA was a period of aridity in the region compared to the relatively moisture-abundant LIA (Campbell 1998; Hallett et al. 2003; Edwards et al. 2008). Campbell (1998) analyzed changes in sediment grain-size from a core collected from Pine Lake in southern Alberta as a proxy of moisture availability during the last 4,000 years. Their results highlight a period of decreased moisture that lasted for several centuries centered around 1,000 yrs BP (Campbell 1998). A peak in moisture availability occurred during the LIA (peak inferred moisture at ~500 yrs BP) indicating that conditions were wetter during this time. Hallett et al. (2003), using *Chara* oospores as an indicator of changes in lake level, found similar patterns in lake level change throughout the last 1,000 years. Lake levels at Dog Lake (southeastern British Columbia) were interpreted as being lower during the MCA and higher during the LIA (Hallett et al. 2003). Similar conclusions regarding ‘hydrologic drought’ during the MCA and moisture abundance during the LIA were drawn from reconstructed stream flow records (Edwards et al. 2008) and pollen and macrofossil records (Vance et al. 1992) for the region.

**Table 1** Temperature anomalies during the Medieval Climate Anomaly and Little Ice Age (NB: Viau and Gajewski (2009) data is compared to the reconstructed value from 0 yrs BP; Luckman and Wilson (2005) anomaly values are compared to deviations from 1901-1980 maximum annual temperatures)

<b>Source</b>	<b>Time Period</b>	<b>Observation</b>	<b>Data Type</b>
<b>Viau and Gajewski 2009</b>	1000 yrs BP	Mean July temperature anomaly: ~ +0.8°C	Composite pollen records
-	500-200 yrs BP	Mean July temperature anomaly: ~ 0.0°C	Composite pollen records
<b>Luckman and Wilson 2005</b>	1050-1150 BP	Anomaly of annual maximum temperature: - 0.35°C	Tree-ring data
-	200-500 yrs BP	Anomaly of annual maximum temperature anomaly: - 0.78°C	Tree-ring data

Changes in climate, such as those that occurred during the MCA and LIA discussed above, have been shown to act as controlling mechanisms for fire activity. Proxy-based research has shown that annual area burned is negatively correlated with mean fire-season precipitation, and positively correlated to fire-season temperature (Larsen 1996). Larsen (1997), in Wood Buffalo National Park, found that the time between fires in the contemporary period of their study 1860-1989 was significantly shorter than prior to that date (1750-1859), likely in response to climate warming that followed the Little Ice Age. Fire history studies conducted elsewhere in North America have shown a similar level of sensitivity between climate and the behaviour of wildfires. A fire history record produced for the Kootenay Valley, British Columbia, revealed that a period of low fire activity occurred from 3,500-2,000 years BP, corresponding to glacial advances elsewhere in the Rocky Mountains (Hallett and Hills 2006). The fire return interval then shortened between 2,000-1,200 years ago as fires became more frequent. The subsequent occurrence of the LIA, which brought wetter conditions to the region, resulted in reduced fire activity (Hallett and Hills 2006). The synchronous response of both the fire regime and the pollen record to documented changes in climate indicates that both were controlled by climatic variability. Hallett and Hills (2006) conclude that in the Kootenay Valley, present conditions may be similar to those witnessed ~1,000 years ago during the MCA. Similarly, in interior Alaska, Kelly et al. (2013) found that biomass burning reached a 10,000-year high during the MCA (Kelly et al. 2013).

## 2.6 The influence of humans in controlling fire activity

A review of the factors controlling wildfires would be incomplete without addressing the role that humans have played in altering past fire regimes. As a society, often we seek to suppress fire, as it can potentially pose an immediate threat to life and property (Flannigan et al. 2000). Historically, fire suppression has led to an accumulation of fuels that can result in more frequent and severe forest fires (Gedalof et al. 2005). Apart from suppression activities, humans also influence the fire regime through land-use change. Some of the most significant contributions to land-use change are land clearance for urban development and agriculture (Flannigan et al., 2000). These practices fundamentally alter the fire regime by making the land less prone to fire events.

A recent review of trends in global biomass burning during the Holocene has suggested that across long timescales of centuries or more the role of humans has been outweighed by climatic controls (Marlon et al. 2013). This conclusion is drawn in part because of large-scale synchronous changes in biomass burning witnessed globally (for example, during the period of 3,000 to 2,000 years BP). Although it is difficult to attribute a fire signal to humans or climate directly, it is unlikely that through history humans have contributed to biomass burning with the level of uniformity necessary to produce such a cohesive global signal (Marlon et al. 2013). In more recent history, however, a large-scale decline in biomass burning has occurred in many regions since the late 19<sup>th</sup> century, most likely in response to human activities (Marlon et al. 2008). The relationship between climate, human activity, and fire events is also of interest in the context of increased temperatures as a result of global climate change. Highlighting the variability in the response of wildfires to human activity, Gillett et al. (2004) have

demonstrated that changes in the fire regime have already occurred in response to modern trends in human-induced climate warming. In the past four decades, the area burned by fires in Canada has risen in tandem with an increase in summer temperatures. Flannigan et al. (2013) have suggested that the fire season of high northern latitudes could lengthen anywhere from 3-20 days during the next century. More severe fire seasons are also forecast and would be difficult to control through presently used fire management strategies (Flannigan et al., 2013).

## 2.7 Future fire predictions

There is general agreement that current and future climate change is likely to cause variations in the forest fire regime from what has been seen in the past (Flannigan and Van Wagner 1990; Carcaillet et al. 2001; Gillett et al. 2004). Climate change could increase the regional variability of fire regimes because large-scale processes, such as climate change, are mediated by site-level factors (Ali et al. 2009). Ali et al. (2009) also postulated that large-scale asynchrony in the occurrence of fire events observed during the past 4,000 years is likely to continue under forecasted warming scenarios, indicating a stronger influence of local factors, such as vegetation composition and human activities, than regional climate on the fire regime. While climate will remain a controlling factor of the fire regime, the differential abilities of site-level landscapes to respond to abrupt changes in climate may increase the spatial variability of fire behaviour.

Several studies have proposed that there will be an increase in fire activity during the coming century (e.g. Flannigan and Van Wagner 1990; Gillett et al. 2004). Gillett et al. (2004) have concluded that the total area burned each fire season is determined in part

by fire season temperatures. Because temperatures are anticipated to rise, particularly in northern and high elevation locations, the total area burned in Canada will continue to increase over time unless some other factor mediates fire activity. Flannigan et al. (2000) hypothesized that fire, which reacts much more quickly to changes in climate than vegetation, could play an important role in promoting the adaptive responses of plant communities to climate warming. They suggest that fire can be viewed as a catalyst for vegetation change and may facilitate the adaptation of terrestrial landscapes to climate change (Flannigan et al. 2000). In addition to more severe fire season weather, the area burned in Canada is also predicted to increase by 2100. Flannigan et al. (2005) used the historical relationship between temperature and fuel moisture variables to total area burned in each ecozone of Canada to predict how the area burned could change in the future. Using global circulation model data, they predict a 74-118% increase in total annual area burned (using a 3xCO<sub>2</sub> scenario) by the end of the century (Flannigan et al. 2005). Alternatively, other model (Terrier et al. 2013) and proxy-based (Kelly et al. 2013) studies have indicated the possibility of a shift towards deciduous tree dominance creating a negative feedback in which increased fire activity is mitigated by vegetation change.

Despite the uncertainty surrounding future outcomes, it seems probable that fire frequency and severity are going to increase at least to some degree during the next hundred years, placing additional demands on fire management practices. In an effort to better predict future outcomes, the need for long-term fire history studies has been widely noted (Carcaillet et al. 2001; Brunelle and Whitlock 2003; Ali et al. 2009).

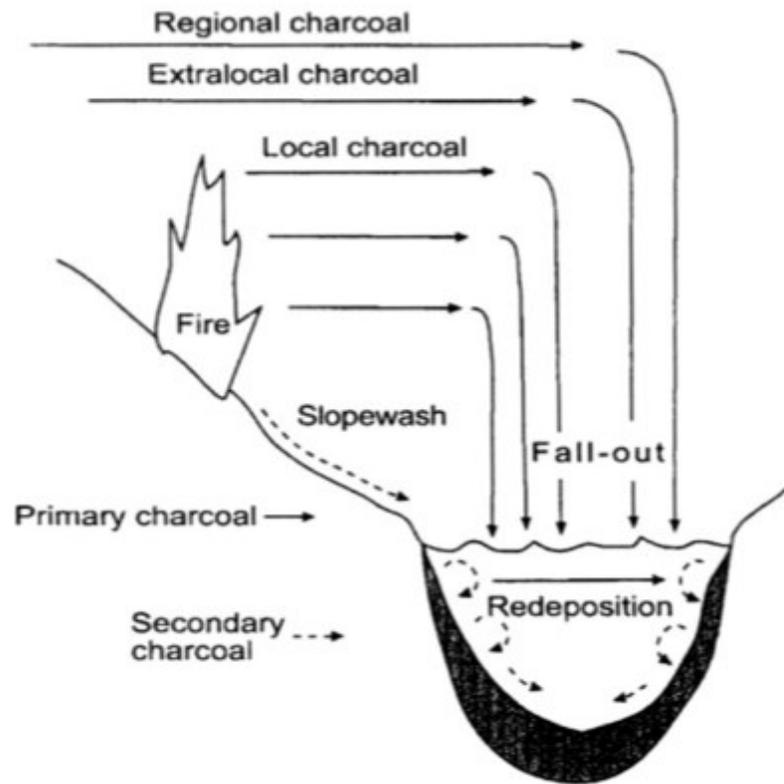
## 2.8 Methodological Approaches

### 2.8.1 Charcoal production, transport, and deposition

The study of lake sediment (paleolimnology) is a useful tool for reconstructing environmental change over long periods of time (seasons to millennia). Macroscopic charcoal (particles  $>150\ \mu\text{m}$ ) analysis is a subdiscipline of paleolimnology and can be used to develop records of fire events through time (Whitlock and Larsen 2001). Charcoal, which is produced during forest fires, results from the incomplete combustion of biomass between  $280\text{-}500^\circ\text{C}$  (Chandler et al. 1983). After becoming airborne, charcoal particles can be deposited on the surface of water bodies and become incorporated into the sediment over time. The result is a stratigraphic record of charcoal influx through time. The type of biomass consumed during a fire is dependent on the ecosystem in which the fire occurs, and consists primarily of accumulated organic matter (particularly leaves, wood, grass, peat).

Charcoal production is mediated by the amount of accumulated fuel in the environment and by the amount consumed during a fire (Clark et al. 1998). It can be introduced into hydrological systems directly after combustion by aerial transportation (primary charcoal), or can derive from secondary sources through surficial run-off and mixing within the lake (secondary charcoal) (Figure 2; Whitlock and Larsen 2001). Both sources of charcoal, primary and secondary, are represented in the sedimentary record, however local fire events are typically identified by the introduction of primary charcoal (Whitlock and Larsen 2001). Through an understanding of taphonomy, or processes influencing a particle from its time of release to time of deposition, a generalized

understanding of the relationships between charcoal production and its depositional location is possible.



**Figure 2** Primary charcoal, the main constituent of sediment-based macroscopic charcoal, is produced during forest fires, carried aloft, and deposited in the lake sediment over time (From: Whitlock and Larsen,

2001)

Strong vortices can form in the atmosphere above a forest fire as a result of intense convective heating during a wildfire (Clark et al. 1999), and act as the transport mechanism for primary charcoal, the main constituent of charcoal records (Pisaric 2002). Once deposited on the terrestrial landscape, secondary charcoal may move through the environment by suspension, saltation, or traction, in relation to the size of the particle (Clark 1988). The smallest charcoal particles are difficult to entrain in the atmosphere, but once they are, they have a tendency to travel the furthest distances (Patterson et al. 1987). There is presently no definitive means of predicting the source area or the distance travelled by charcoal particles found within lake sediment. Further, there exists a range of opinions regarding the extent to which charcoal particles are able to travel once released from a wildfire (Clark 1988; Ohlson and Tryterud 2000; Pisaric 2002; Tinner 2006)

A 1988 study conducted by Clark hypothesised that smaller particles will generally travel greater distances than larger particles (Clark 1988). The models developed suggest that once combusted, small particles remain suspended by convective processes for a relatively longer period of time compared to larger particles that tend to continuously fall-out from the smoke plume. This theory implies that an incidence of large charcoal particles within lake sediment represents a local fire, while small particles in the same sediment represent the regional picture of charcoal transport (which may include local *and* extra-local fires). Clark's (1988) influential model of charcoal transport has formed the basis for charcoal studies throughout the world.

Experimental burns are viewed as convenient for studying charcoal transport because they are predictable in ways that uncontrolled or unintentionally set fires are not. More specifically, they enable the researcher to carefully plan fieldwork and to set up

experiments to test specific theories. Within the last 20 years, several studies have attempted to characterize the aerial transportation of charcoal particles following experimental burns by looking at how far from the burned edge charred material is deposited (e.g. Clark 1988; Ohlson and Tryterud 2000; Lynch et al. 2004). By looking at recently deposited lake sediments, these studies invariably found that the majority of charcoal particles, particularly those large in size, were deposited within the 100-200 metres of the burned edge. Clark et al. (1998) found that 99% of the collected charcoal particles were trapped within 20 m of the burned edge, and that most of the remainder was situated within 60 m. Ohlson and Tryterud (2000) found that most charcoal was deposited within a comparable distance of 100 m from the burned edge, while Lynch et al. (2004) determined that large charcoal particles were most abundant in the traps located within 60 m of a fire's boundary (Lynch et al. 2004). These experimental studies suggest that there is a strong distance-decay relationship between charcoal abundance and the burned edge, with the implications being that for a lake to capture the local fire signal, the fire boundary must be within no more than several hundred meters of the lake itself. These studies do not, however, address what the depositional pattern would be if sediment traps had been placed beyond 60 - 100 m, or how dependent the findings are on the experimental nature of the set fires that by nature tend to be less severe than uncontrolled burns.

More recently, empirical and theoretical studies have shown that charcoal and charred plant remains can travel tens of kilometers before being deposited (e.g. Pisaric 2002; Tinner et al. 2006; Peters and Higuera 2007). Pisaric (2002) collected an inventory of charred plant material transported by convective processes during an intense forest fire

near Bozeman, Montana. Charred plant matter was found up to 20 km from the source area, suggesting that partially combusted material from fires is able to travel much further than previously thought. Similarly, Tinner et al. (2006) identified charred plant matter in litter traps up to five kilometres from a large forest fire in Leuk, Switzerland. In their two-dimensional dispersal model intended to predict charcoal dispersal, Peters and Higuera (2007) found that macroscopic (large) charcoal particles could travel several kilometres prior to deposition. It has been proposed that studies of experimental fires tend to observe patterns of local deposition whereas theoretical and empirical studies tend to support the idea that transport distance is a function of many factors, including the strength of the transport mechanism itself (Tinner et al. 2006). Although uncertainty exists regarding the exact extent to which charcoal particles are able to travel aloft during a forest fire, it is likely that most airborne charcoal is deposited nearest to the burned area, and that a greater amount is deposited in burned than unburned areas (Whitlock and Millspaugh 1996). Peaks in charcoal accumulation in the sediment record, which are interpreted as the occurrence of a fire event, likely represent small, nearby fires, or large fires at varying distances; a complicating factor that means most emphasis should be placed on the timing of the interpreted events rather than the size of the peaks.

### 2.8.2 Lake Site Selection

When seeking a reliable sediment charcoal record it is important that careful consideration be taken regarding the choice of an appropriate site for sediment coring. Depositional patterns within the lake determine the maximum resolution of the data retrieved from the sedimentary record. Sediment deposition within the lake itself is not

necessarily uniform across the lake basin, and so it is therefore important to consider the physical characteristics of the lake (i.e. lake size, basin morphology, presence of littoral vegetation and inflows/outflows), in order to properly address the questions being considered by the research.

The exact relationship between lake size and charcoal accumulation remains unclear, however it is generally accepted that small lakes are preferred for charcoal analysis as they amplify the signal in the sediment record, making ecological changes more discernable in paleolimnological studies (e.g. Cwynar 1978; Whitlock and Millspaugh 1996). A large ratio between the surface area of a lake and its surrounding catchment could have the effect of amplifying the paleoenvironmental signal (Rhodes and Davis 1995). Winkler (1985) used a chemical digestion technique to determine the amount of charcoal found in different sized lakes and concluded that the percent-charcoal in the sediment sample may be inversely dependent on lake size; sediment samples from small lakes were composed of 1-12% charcoal, whereas the sediment collected from large lakes consisted of 1-3% charcoal. Apart from lake size there exist other equally important morphological considerations when choosing a sampling site. There are a variety of mechanisms that impact sediment accumulation within a lake, including bioturbation, water currents, waves, and the shape of the basin (Larsen and MacDonald 1993). The littoral zone of a lake is prone to sediment mixing as material becomes resuspended due to wave action (Hilton 1985; Larsen and MacDonald 1993). Additionally, riparian vegetation at the lake's edge acts as a trap for charcoal particles, either preventing them from reaching the lake's centre or causing a delay in their arrival.

A lake's bathymetry plays a role in determining the pattern of sediment deposition across the lake bottom. Sediment focusing, a term that refers to the redeposition of sediment originating in shallow waters to the deeper areas of a lake, results in differential sediment accumulation over time. Blais and Kalff (1995) discovered that the degree of sediment focusing increased with water depth in all but one of their 12 study lakes in the Eastern Townships and Laurentians of Québec, Canada. Moreover, they found that the steepness of the slope influenced the rate of sediment focusing; steep slopes tended to produce linear rates of sediment focusing. Sediment focusing is highly relevant in interpreting sedimentary charcoal records because if the sediment is redeposited within the lake basin the same processes will transport any charcoal that is also present.

The physical properties of the surrounding catchment may also impact the influx of charcoal, in particular secondary inputs of charcoal into a lake. For example, the steepness of the catchment's slope influences the type of material that is introduced. Hall and Smol (1993) conducted a study on five lakes in southeastern Ontario where they determined that relief plays a role in not only the amount of allochthonous material introduced to a lake, but also the type. Gently sloping watersheds carried relatively more organic matter to the lakes, while steep slopes with faster moving water were able to entrain and introduce heavier mineral matter. Steep slopes are also more prone to erosion and geomorphic processes (Hall and Smol 1993). The extent of erosion in high relief watersheds may be amplified following a fire, and thus peaks in inorganic inputs are often used to support charcoal data indicating the occurrence of a fire. For example, Meyer et al. (2001) found that following forest fires, slopes remained susceptible to

significant erosion during heavy precipitation events for several years following a burn, essentially until root systems were re-established.

Because of the many factors influencing charcoal accumulation within a lake, it is impossible to determine with precision the pattern of accumulation until a sediment core is retrieved. In general, however, small lakes with few inflowing streams, which could introduce secondary charcoal, and intermediate catchment sizes seem to be best suited for fire reconstructions from charcoal. Within the lake itself, targeting the deepest portion is preferred as the higher sedimentation rate may lead to a more defined fire signal. Physical properties external to the lake itself should also be considered. For example, the presence of riparian vegetation and slope gradient should be such that they minimize erosional inputs of charcoal or sediment trapping that could confound the fire signal.

### 2.8.3 Charcoal analysis

Sediment cores are collected in the field and analyzed in laboratory settings. They may either be sectioned into intervals in the field using a vertical extruder (Glew et al. 2001) or may be transported intact. There are a variety of methods that have been used to isolate charcoal particles from other sedimentary material, including pollen slide analysis, thin-sectioning, macroscopic sieving, chemical extraction, and image analysis (Whitlock and Larsen 2001). Each method has its own set of advantages and disadvantages, and centers on the principle that higher occurrences of charcoal (categorized in tallies, total charcoal area, size-classes) represent fire events. Some methods, such as thin-sectioning and image analysis classify charcoal particle size in order to gain insight into the relative distance from source of the fire (i.e. local versus regional fire).

#### 2.8.4 Sample Preparation and Analysis

Pollen slide charcoal has long been used as a proxy to estimate the regional importance of fire at low temporal resolutions (Swain 1973; Cwynar 1978; Faegri and Iversen 1989). Pollen slides are prepared for the purpose of reconstructing historical vegetation assemblages from lake sediments by counting and identifying pollen grains, but the area or amount of microscopic charcoal particles present on the slide can also be quantified and used to approximate the occurrence of fire. Although pollen slide charcoal tallies tend to produce replicable results between sediment cores (Cwynar 1978), they are often prepared at a coarse resolution, meaning that there may be large gaps in the pollen slide charcoal record where fire events may be missed. Further, the preparation method for pollen slides may result in charcoal fragmentation that would impact the size distribution and quantity of charcoal present within a sample (Rhodes 1998).

An alternative method to pollen slide counts is macroscopic sieving, a process in which large charcoal particles are isolated from microscopic charcoal and other sedimentary material by wet sieving. Macroscopic charcoal tends to be more representative of the site-level rather than regional fire regime (Tinner et al. 1998). Tallies and area estimates have become a regular feature in fire reconstructions from lake sediment (e.g. Millspaugh and Whitlock 1995; Whitlock and Millspaugh 1996; Long et al. 1998; Higuera et al. 2009), and their main use is to reconstruct the occurrence of local and extra-local fires on times scales of years to millennia (Whitlock and Larsen 2001). The analysis is relatively quick, easy, and inexpensive, and can be performed on both

varved and non-varved sediments. Macroscopic sieving is well suited for sediments with temporal resolutions of several years per sample.

The procedure of macroscopic sieving begins by sub-sampling sediment cores at continuous intervals. The sample intervals are dependent on desired temporal resolution, which is dictated by the sedimentation rate of the lake. Intervals of 0.5 to 1 cm in thickness are common (e.g. Millspaugh and Whitlock 1995; Long et al. 1998; Hallett et al. 2003; Kelly et al. 2011). It is important that samples be taken contiguously and that the time span of the sampling interval be less than the interval between fires so that fire events are not missed and can be distinguished from one another. From each depth interval, between 1 and 10 cm<sup>3</sup> of sediment is used for macroscopic sieving (e.g. Millspaugh and Whitlock 1995; Clark et al. 1998; Long et al. 1998; Hallett et al. 2003). Carcaillet et al. (2001) found a volume of 1 cm<sup>3</sup> to be the minimum volume necessary for replicable results; using a small sample volume is preferable as using more sediment makes the procedure more time consuming. Once extracted from the sediment core, sub-sampled material is placed in a diluted solution of sodium hexametaphosphate, a deflocculating agent, to facilitate sieving (Bamber 1982). The sediment is wet sieved through a mesh screen to separate macroscopic charcoal from smaller charcoal and mineral particles, and is rinsed into a gridded petri dish for counting.

The definition of macroscopic charcoal is somewhat arbitrary in nature, but over time it has come to mean charcoal particles >125 µm in size. Whitlock and Millspaugh (1996) empirically tested the assumption that differing classes of charcoal particle size produce similar patterns in charcoal accumulation. Their main finding was that the charcoal signal in the three tallied size classes (0.063-125 µm, 125-250 µm, and >250µm)

produced similar patterns of accumulation. The charcoal counts in the smallest size class were an order of magnitude higher than the others and significantly fewer pieces were found in the largest size class. As a result, the mid-range size class has been suggested to be the most practical for macroscopic charcoal analysis as the charcoal particles are not unreasonable in number and are easily identifiable at this size (Millspaugh and Whitlock 1995; Whitlock and Millspaugh 1996). As a result of their work, 125  $\mu\text{m}$  is often used as the lower size limit of macroscopic charcoal.

#### 2.8.5 Charcoal Morphology

Recently, increasing attention has been focused on classifying macroscopic charcoal based on morphology (e.g. Umbanhowar and McGrath 1998; Enache and Cumming 2006, 2007 and 2009; Jensen et al. 2007; Walsh et al. 2010; Courtney Mustaphi 2013). Charcoal morphology classifications may provide a more thorough interpretation of the sediment charcoal record by revealing the type or spatial coverage of organic matter burned (Enache and Cumming 2007; Jensen et al. 2007). Umbanhowar and McGrath (1998) found that experimentally burned grass, leaves, and wood had significantly different length to width ratios, suggesting that the ratio could potentially be used in charcoal analysis as an indicator of vegetation type. More recently, Enache and Cumming (2007, 2009) found that the frequency of certain morphotypes shared a significant relationship with precipitation and the total area burned around the lake, while total charcoal counts were not strongly correlated to these variables. Although all reviewed studies suggest that more research is needed on the topic, analyzing charcoal morphology presents an opportunity to enhance the interpretation of macroscopic

charcoal records since the information gained from analyzing morphotypes is done at the same spatial scales as charcoal accumulation (Jensen et al. 2007). This differs from other paleoindicators, such as sub-fossil pollen grains, which produce a regional rather than local vegetation record.

#### 2.8.6 Analyzing the charcoal record

The sedimentary charcoal record is analyzed using a decompositional approach that separates charcoal accumulation into two components; the slowly changing background charcoal and the more variable peak component (Long et al. 1998). Charcoal accumulation rate (CHAR) is expressed as the number of charcoal particles  $\text{cm}^{-2} \text{ year}^{-1}$ . The background component (bCHAR) represents changing rates of baseline charcoal accumulation over time and is believed to represent extra-local, rather than site-level, fire activity (Marlon et al. 2006). The background charcoal is also thought to be an indicator of the amount of biomass present on the landscape (Whitlock et al. 2003; Carter et al. 2013; Morris et al. 2013). It is thought that closed forests (high biomass abundance) tend to produce a greater amount of background charcoal than open forests or grasslands (lower biomass abundance) (Whitlock et al. 2003), and relative declines in background charcoal have been interpreted as representative of reductions in fuel availability, which is closely related to biomass abundance (Carter et al. 2013). Furthermore, a study by Seppä et al. (2009) identified a linear relationship between pollen grains (specifically, PAR values) preserved in lake sediment and biomass abundance. This relationship adds support to the idea that synchronous changes in both the PAR values of certain species and the background charcoal record would point to biomass abundance as the main

constituent of the bCHAR record. The peak component of the charcoal record represents the portion of charcoal that is introduced to the sediment shortly following a fire event. While the background charcoal component may fluctuate on the scale of decades to centuries, the peak, or fire component, fluctuates over a period of only a few years (Clark and Royall 1996). It is the series of peaks resulting from fire events that constitutes the long-term fire regime.

Several methods have been proposed to separate the background charcoal component from peak values. Clark and Royall (1996) use a Fourier-series filter to identify the background signal, which treats the background variability as a series of sinusoidal peaks and troughs. Peaks are identified by plotting the positive residuals, which indicate the timing of a fire event, of the variation between the filtered background component and the untreated data. A limitation of this approach is that it does not account for long-term variability in the background signal, but rather assumes stationarity.

The background component of charcoal accumulation can also be detected using a locally weighted moving average (Long et al. 1998; Hallett et al. 2003). The moving average is calculated by shifting a 'window' of a certain segment length along the time series and calculating the average of the values within the window at a particular position. This average value is attributed to a point in the chronology, and the moving window progresses to determine the weighted value for each point (Long et al. 1998). The width of the moving window must be carefully considered; if it is too wide, it will not capture actual variations, whereas windows that are too small produce values that are essentially the same as the original measured data. Long et al. (1998) determined the

acceptable width of the moving window through a visual comparison between CHAR data and the background component.

In order to distinguish the peak component from background charcoal accumulation, Long et al. (1998) proposed that a threshold value could be used to identify fire events. The threshold value can be identified by comparing the chronology with calibration data where known fire dates would be matched with the fire record to see what the CHAR values were in years of known fires. Chosen threshold values are typically expressed as a ratio of the background component. For example, a threshold value of 1.0 would suggest that any values greater than the background were peaks.

Using a slightly different approach, Higuera (2009) used a 500-year moving median for their chronologies, and smoothed the resulting data using a 500-year locally weighted regression (Loess). This was done to yield a high signal-to-noise index, which Higuera describes as representing the variance between the fire signal and the variance in peak charcoal in the 500-years surrounding a data point (Higuera 2009). The methods developed by Higuera (2009) have been standardized into a computer program, CHARanalysis, which is freely available via the following website: <http://www.sites.google.com/site/charanalysis>. An advantage to this method is that thresholds separating peak charcoal from the background component can be determined locally rather than remaining constant throughout the time series. Regardless of the specific method used, the decompositional CHAR approach has become the standard in macroscopic charcoal analysis (Long et al. 1998; Hallett et al. 2003; Gavin et al. 2006; Higuera et al. 2009; Higuera et al. 2010; Courtney Mustaphi and Pisaric 2013).

## 2.9 Other proxy data sources used to reconstruct past fire activity

Other forms of proxy data can aid in the interpretation of fire events from the charcoal record. Dendrochronology (tree-ring analysis) is often used to identify years in which fires have occurred by matching growth patterns and fire scars with a local chronology of tree rings of varying widths. This provides an accurate record of fire events at high spatial and temporal resolutions and can be used to help calibrate the sediment charcoal record. Palynology, a study that includes the analysis of pollen spores, provides a record of vegetation changes through time. This is complementary to charcoal analysis because fire and vegetation are closely related and interdependent. Sedimentological data, in particular magnetic susceptibility and loss-on-ignition, allows researchers to gather evidence for fire activity by identifying erosional events that may have accompanied fire activity. The use of these analyses in conjunction with charcoal analysis helps to develop a more complete interpretation of the fire record.

### 2.9.1 Dendrochronology

It has been observed that climate change is altering the relationship between forests and wildfires (Gedalof et al. 2005). Dendrochronology, the study and dating of tree-ring formation, is a method of determining a variety of paleoenvironmental conditions from the annually resolved growth rings produced by trees. The sub-discipline of the science, dendropyrochronology, allows researchers to attribute highly accurate dates to historical fire events based on evidence preserved in dead and living trees in order to better understand stand-forest level fire dynamics (Arno and Sneek 1977;

Kipfmüller and Baker 1998). Dendrochronological fire studies typically present two types of evidence: annually or seasonally dated fire scars, and stand establishment dates of even-aged cohorts.

Fire scars are marks on trees, described as a ‘cat-face’, that record the passing of a non-lethal fire. Their formation occurs when the cambium temperature of a tree is raised to a lethal level by a fire (~60°C) or when the bark, cambium, and xylem of the tree are consumed (Mcbride 1983; Figures 3 and 4).



**Figure 3** Fire scars are evidence of low-severity fires

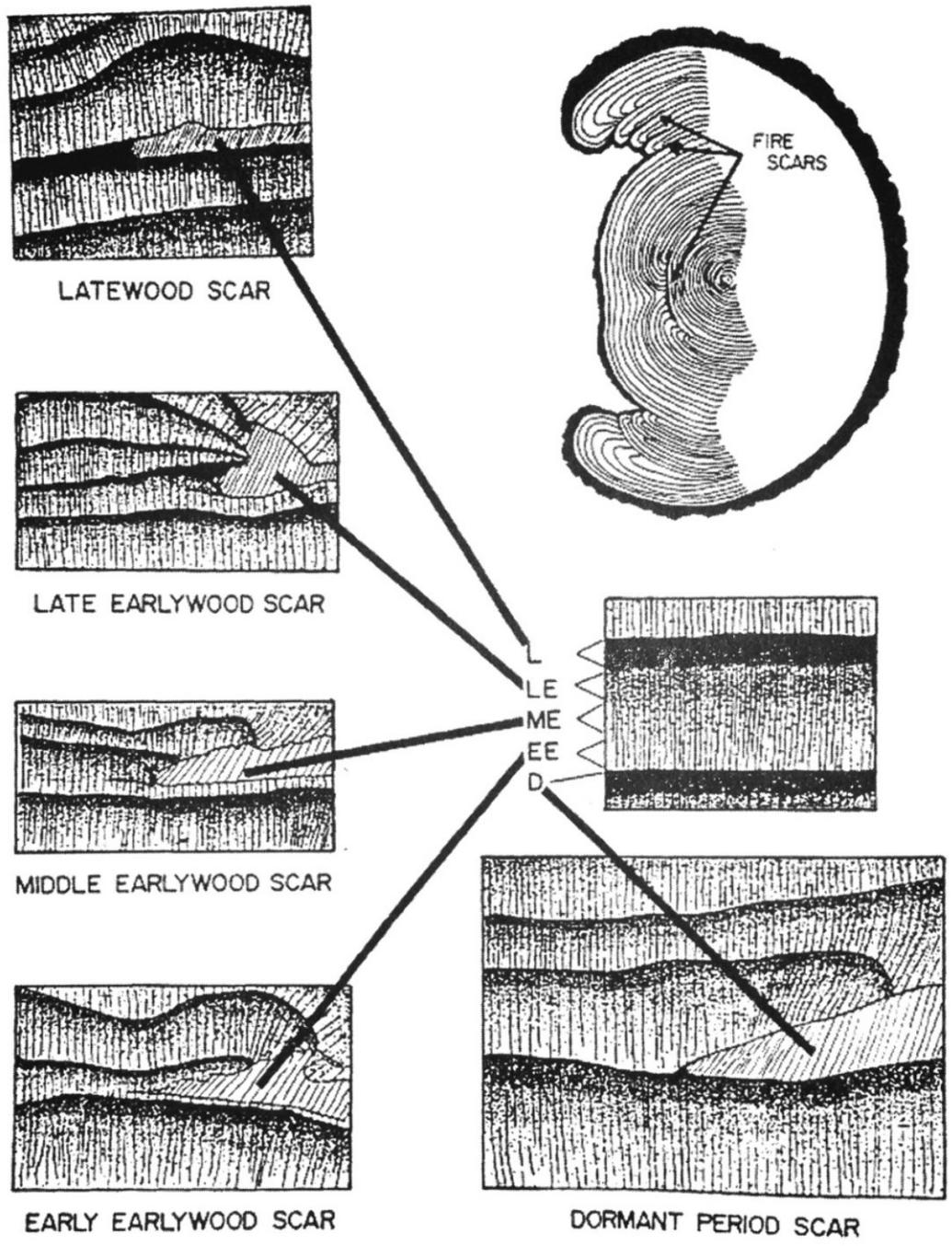


**Figure 4** A cross-section of a fire scar taken from a dead-standing lodgepole pine, Jasper, AB

Fire scars are typically formed on the leeward side of a tree because approaching fires create vortices that lengthen the exposure of the leeward side to the flame. The temperature required to form a scar varies, but can be as low as 60-100°C (Gutsell and Johnson 1996). They are recognizable in the field as barkless plains on the trunk of a tree that are usually triangular in shape (differentiating them from scars resulting from other types of injuries) and become overgrown on each side by new growth. Given enough time, fire scars may heal over entirely and become buried within a tree. Trees of different ages and species are not equally susceptible to the formation of fire scars; young trees often can not sustain the cambium and foliar damage of fire-scar inducing conditions (Gutsell and Johnson 1996). Older trees and those of certain fire-resistant species may have bark thick enough to prevent the rise in cambium temperature needed to form a scar (Mcbride 1983). Scars resulting from fire events are often followed by a period of growth release if the fire results in greater access to resources, or growth suppression if the injury to the tree is severe (Sutherland et al. 1991).

The methods for collecting and analyzing fire scars were originally developed by Arno and Sneek (1977), and many of these methods are now considered standard collection practices. Full cross-sections can be obtained by felling small trees, or from dead woody debris using a chain saw. Partial cross-sections can be collected from living trees by cutting a wedge from the trunk. Cross-sections, whether partial or full, are preferable to increment cores of the fire scar, which have been shown to produce inaccurate fire dates (Mcbride 1983). Once collected, the samples should be dried, sanded, and measured following the standard methods of dendrochronological studies (Stokes and Smiley 1968). Sanding the samples facilitates the identification of annual

ring boundaries, and ring measurements are made using a mounted measuring stage connected to a computer. The year of fire scar formation can then be identified by crossdating the samples (or pattern matching the annual growth pattern) with a tree ring chronology developed from living trees in the area (Fritts 1976). Understanding the timing of cambial growth and recording the position of the fire scar within a tree ring can provide a rough indication of the seasonality of a fire. For example, a scar in the latewood of a tree ring would indicate that a fire occurred late in the growing season (Speer 2010; Figure 5).



**Figure 5** The timing of the formation of fire scars can sometimes be identified down to the season in which they are formed (From: Speer 2010)

In locations experiencing high-severity fires, stand recovery can take the form of even-aged cohorts as the open space created by a fire promotes a pulse of seedling recruitment (Oliver and Larson 1996; Johnstone et al. 2004). This is useful when trying to characterize the local fire regime, as the timing of cohort recruitment can be determined by performing a tree-ring analysis on early seral trees and provides an approximate date of the last stand replacing fire. Heyerdahl et al. (2001) examined the spatial controls of fire regimes using both fire scars and early seral cohort data as evidence for fire events. A challenge of using cohort data is that it can only provide an approximation of the timing of a fire event since tree recruitment is not an instantaneous process and is dependent on many factors (Johnstone et al. 2004). Further, while effort should be taken when sampling to target the base of the tree in order to capture the oldest growth rings, it is difficult when sampling to consistently retrieve the tree's pith and so tree ages often require some level of estimation. Whenever possible, both cohort and fire-scar evidence should be collected in order to ensure a correct classification of the fire regime.

The concurrent use of tree-ring data and macroscopic charcoal analysis can be a complimentary combination for interpreting fire history records. Tree-ring evidence is being increasingly viewed as an important component of fire studies (Millsbaugh and Whitlock 1995; Long et al. 1998; Conedera et al. 2009; Higuera et al. 2010; Whitlock et al. 2010). There are several practical reasons for using tree-ring data as a secondary source of fire history information, not least of which is the fact that dendrochronology has a higher temporal resolution than charcoal analysis. Tree-ring evidence of annually resolved fire dates can be used to calibrate the top sections of the charcoal record by connecting peaks in charcoal with cohort and fire scar evidence. Additionally, comparing

known fires from tree-ring data with interpreted fire events in the charcoal record can provide researchers with confidence that the sediment charcoal record is successfully recording local fire events (Millspaugh and Whitlock 1995). Other studies have used readily available tree-ring records to loosely characterize the fire frequency based on nearby areas with similar physical characteristics (Long et al. 1998). Dendrochronology can also provide an approximate sedimentation rate for the most recently deposited section of the sediment core (Long et al. 1998). Other methods are also used to estimate the sedimentation rate, including  $^{210}\text{Pb}$  and  $^{14}\text{C}$  dating, however the temporal error in these methods is higher than in dendrochronology.

Reconstructing fire events using dendrochronology does, however, have some limitations. Primarily, dendrochronological evidence is limited by its availability (Conedera et al. 2009). Because wood decomposes over time, chronologies are limited in the duration of their temporal coverage; a tree-ring based fire series may be, in its upper limit, 700-1,000 years in length. On the other hand, charcoal analyses may cover many thousands of years. As fires sweep through an area, data can be eliminated completely if trees are unable to withstand burning. This would also indicate that only certain fire ‘types’ are recorded through tree-ring evidence (i.e. low-severity fires affecting a combination of species that are susceptible to fire scars as well as only the most recent of high-severity fires). The abundance of fire history data decreases further back in time due to the death and decomposition of trees from fire and other causes in what is aptly named the erasure effect (Kipfmueller and Baker 1998; Whitlock and Larsen 2001). Logging can also erase fire evidence, however it is sometimes possible to retrieve fire scars from the stumps that remain in situ (Long et al. 1998).

Because the fire evidence is available at different spatial and temporal scales, some disagreement is possible between the fires recorded in the tree-ring record and those expressed as charcoal peaks in lake sediment. Tree-ring evidence can confirm an interpreted event in the charcoal record, but a lack of tree-ring fire evidence does not preclude a charcoal fire event. Although it is important to consider these limitations, the ability of fire scars and tree cores to reconstruct the local fire history at high spatial and temporal resolutions makes dendrochronology an extremely useful accompaniment to charcoal analysis (Whitlock et al. 2010).

### 2.9.2 Pollen Analysis

Pollen analysis has been extensively used to reconstruct the regional vegetation histories of locations around the globe (e.g. Connor et al. 2012; Hallett and Walker 2000) and is considered to be the most important tool for reconstructing past vegetation and environmental conditions (Faegri and Iversen 1989). Sub-fossil pollen is an extremely useful paleoindicator due to its ability to remain preserved in sedimentary beds with minimal degradation for long periods of time, and because the sheer volume of pollen grains released to the environment provide an opportunity for statistical analysis (Faegri and Iversen 1989). It has been estimated that an average hectare of woodland can produce as much as 3,000 litres of pollen per year (Traverse 1988). Pollen analysis relies on the principle that the presence of a plant species in an area can be inferred from the biological remains, in this case sub-fossil pollen grains, that it leaves in the stratigraphic record. Because vegetation type is closely tied to climate, the presence or absence of a vegetation type can be telling about the environmental conditions at a point in time (Traverse 1988).

Many factors, including climate, disturbance, and community-level processes can influence the prevalence of vegetation types in a given area, and a relative abundance or the absence of certain species types can provide evidence in the interpretation of the fire record (MacDonald et al. 1991). For example, studies have demonstrated that changes in the pine to birch ratio may represent shifts in forest development that can be a consequence of fire activity (Swain 1973; Cwynar 1978).

Like macroscopic charcoal, pollen is released into the atmosphere and gradually makes its way into the sediment at the bottom of lakes. Pollen grains, however, are able to travel much greater distances due to their small size (Traverse 1988). The ability of pollen grains to travel large distances makes the source area difficult to quantify and means that the vegetation record is a regional, rather than local, picture of historical changes. Recent advances in simulation modeling have helped to better understand the pollen source area based on landscape characteristics (Davis 2000, Sugita 2007).

Since both macroscopic charcoal particles and pollen grains are transported aerially and depend on undisturbed records of deposition, lakes that are suitable for macroscopic charcoal tallies are also likely to be suitable for pollen analysis. Subsamples can be taken from the same sediment core used for macroscopic charcoal analysis and are chemically treated to remove the non-essential matrix material and to concentrate and facilitate pollen identification. Due to the time intensive nature of pollen processing and analysis, samples are typically analyzed at lower temporal resolution than other proxy records.

Before chemicals are added, pollen samples are often spiked with standardized *Lycopodium clavatum* spores (Stockmarr 1971). Adding the spores provides a point of

reference for determining pollen accumulation rates and comparing these between samples. A recent review of the *Lycopodium* marker-grain method tested if the concentration of the grains was reproducible under different processing treatments while seeking absolute abundance data (Mertens et al. 2012). The findings suggest that certain warming and sieving treatments can reduce the reproducibility of *Lycopodium* counts, but that most other stages of processing had negligible effects. The loss of *Lycopodium* in processing should have a minimal impact for pollen processing, as it is assumed that any loss of pollen grains during processing would impact each species uniformly.

During pollen sample preparation, approximately 1 cm<sup>3</sup> of wet sediment is added to 50 ml centrifuge tubes and the sample is normally spiked with two *Lycopodium* tablets. The wet sediment and *Lycopodium* tablets are then placed in a 10% hydrochloric acid (HCl) solution to remove calcium carbonate from the sediment. Following the HCl digestion, the samples are centrifuged and rinsed with deionized water. Organic matter is removed using a 10% potassium hydroxide (KOH) solution. The sample is heated in a hot water bath for approximately 5-8 minutes to help deflocculate the sample. Following the KOH treatment, the sample is rinsed multiple times with deionized water and centrifuged to remove the remaining KOH. Siliceous material, which includes diatoms, is removed from the sediment by adding a 50% hydrofluoric acid (HF) solution. The sample and HF solution is placed in the hot water bath for 5-8 minutes before centrifuging and decanting the HF into a plastic waste container. Following the HF treatment, the sample is again rinsed with deionized water and centrifuged to remove any remaining HF solution. Following the HF treatment and rinsing, the sample is rinsed with glacial acetic acid (CH<sub>3</sub>COOH) to dehydrate the sample prior to an acetolysis wash to

remove cellulose, including moss, leaves, and rootlets. Acetolysis is highly reactive with water so it is important to thoroughly rinse the sample with glacial acetic acid before proceeding with the acetolysis treatment. Acetolysis is a mixture of nine parts acetic anhydride and one part sulphuric acid ( $H_2SO_4$ ). Following acetolysis and decanting into a glass waste container, the sample is again rinsed with  $CH_3COOH$  to insure the acetolysis mixture is thoroughly removed from the sample. A final rinse with deionized water and tert-Butanol and the sample is transferred to small vials and stored suspended in silicone oil (2000 cs), which is also used to mount the sample. A light microscope can then be used to identify and count the pollen grains at 400x magnification (Faegri and Iversen 1989). Statistical analyses are performed on the pollen accumulation data and, if present, statistically distinct vegetation zones can be identified.

Pollen analysis is not without its unique set of challenges. The preservation of pollen in lake sediments depends on the amount of sporopollenin in the exine, or outer shell, of the pollen grain (Traverse 1988). Species that produce more of this compound, or are high pollen producers in general, tend to be disproportionately represented in the pollen record. Jackson (1990) found that poorly dispersed pollen types found in lake sediment originated from a more local source area than those that were smaller in size and thus more easily dispersed. Further, it is challenging to identify a pollen grain down to the species level; most often pollen grains are identified to the family or genus level because it is difficult to identify morphologies that would distinguish the pollen grains of different species using light microscopy (Traverse 1988).

### 2.9.3 Magnetic Susceptibility

The magnetic susceptibility of lake sediment can be used to infer changes in geomorphic processes in the watershed of a lake, with peaks in magnetic susceptibility typically representing an influx of erosional material into the lake. Like CHAR analysis, magnetic susceptibility can be separated into a fluctuating background component and a series of peaks over time. Thompspon et al. (1975) studied lake sediments from Lough Neagh in Northern Ireland, and found that changing levels of magnetic susceptibility were positively correlated with inputs of inorganic allochthonous material. Erosion can be caused by a variety of factors, including precipitation, earthquakes, deforestation, volcanic eruptions, and fires (Whitlock and Larsen 2001). This suggests that while a peak in magnetic susceptibility may correspond with a fire event (e.g. Millspaugh and Whitlock 1995), there will also be peaks in the magnetic susceptibility record that are unrelated to fire and thus confound the interpretation of the fire history record. This was the case in a study conducted by Long et al. (1998) where little or no correlation between peaks in magnetic susceptibility and charcoal accumulation were identified.

Variations in magnetic susceptibility with depth appear to be reproducible between cores from the same lake, demonstrating that magnetic susceptibility data is an accurate representation of erosional activity from within the watershed and that it can be used to correlate cores (Thompson et al. 1975). Although each peak may not represent a fire event, magnetics can be used to support fire records gathered from other sources such as dendrochronology, macroscopic charcoal, and pollen analysis. It is a relatively quick method of gaining insight into the past geomorphic events that have influenced the

watershed and can help to characterize changes in sedimentation that may affect the charcoal and pollen records (Thompson et al. 1975).

#### 2.9.4 Loss-On-Ignition

Loss-on-ignition is a method of gaining information about the organic and carbonate contents of the sediment. It is often used in conjunction with other paleoenvironmental proxies as a way of characterizing changes in erosion through time (Beer et al. 2007). Changes in sedimentary inputs can result from shoreline and upland erosion (Shuman 2003). For example, peaks in carbonate content could result from secondary inputs of materials due to unstable and easily erodible soil following a wildfire (Whitlock and Larsen 2001), as well as provide evidence of lower lake levels (Shuman 2003).

Standard methods of loss-on-ignition were developed by Dean (1974), and use the principles of percent weight loss to determine relative changes in sediment composition through time (Heiri et al. 2001). At each stage of the process, the sample is heated to a specific temperature to remove a component of the sediment (e.g. 550°C for organic matter; 950°C carbonate content; Dean 1974). The change in weight after heating is accounted for by the component that was burned at each temperature (Heiri et al. 2001). Shuman (2003) investigated the variability in LOI measurements between cores taken from the same small lakes in New England, USA (Shuman 2003). Based on those analyses, Shuman (2003) suggests that changes in organic content greater than 2-5% within a single core are indicative of environmental change.

## CHAPTER THREE

### **Climate, vegetation, and human influences on forest fire activity over the last ~3,500 years in Jasper National Park, Alberta**

#### 3.1 Introduction

Developing long-term, regional fire histories has been widely cited as a research priority for areas where wildfires play an important role in landscape function and where active fire and forest management presently occurs (Brunelle and Whitlock 2003; Schoennagel et al. 2004). In western North America, wildfires play an important role in maintaining the productivity and biodiversity of the forests that cover extensive portions of the land. It has been shown, however, that climate change, land-use change, and decades of fire suppression activities have altered fire regimes (Gedalof et al. 2005; Bowman et al. 2011), in some cases resulting in a homogenization of the landscape and a shift towards late-successional tree species (Rhemtulla et al. 2010). Understanding the relationships between wildfires and their dominant controls, broadly defined as climate, vegetation, and topography, is essential in order to pursue appropriate fire management. Because fire regimes vary regionally (Baisan and Swetnam 1990), in regions where landscape characteristics are highly heterogeneous, such as the Rocky Mountain range, an overarching classification of the fire regime is not sufficient to capture the potentially significant variability found on a local scale (Schoennagel et al. 2004). Because of this, local to regional scale fire histories are important sources of information for contemporary fire management.

Changes in landscape characteristics (i.e. changes in vegetation structure and composition) are ubiquitous across many areas due to the influence of humans and changing environmental conditions. Therefore, using short-term fire histories based on observational records or from remotely sensed data products is often insufficient for management decisions at the current time. Landscape and vegetation characteristics that exist today have arisen as a result of previous disturbances, of which wildfire is significant (Dale et al. 2001; Perry et al. 2011). As a result, in areas where fire is a dominant agent of change, the current forest composition can be viewed as a manifestation of the historical fire regime, and a long-term perspective is needed to fully understand where and if contemporary conditions exist within the range of historical variability.

The fire regime of the Rocky Mountains has historically been characterized as experiencing infrequent, stand-replacing, high-severity fires. More recently, however, it has been demonstrated that some forests in the region are more accurately characterized as possessing a mixed-severity fire regime, where frequent, low-severity (non-lethal) fires overlap spatially with high-severity (lethal) fires (Amoroso et al. 2011; Heyerdahl et al. 2012). It has been estimated that between 17-50% of Rocky Mountain forests experience a mixed-severity fire regime (Schoennagel et al. 2004). The significance of this lies in the complex vegetation structure that results from mixed-severity fires, a source of landscape diversity that is dissimilar from areas that experience low or high-severity fire regimes (Taylor and Skinner 1998). This study, which is situated in Jasper National Park, AB where fire management actively occurs and ecological preservation is a strategic priority, aims to provide a long-term understanding of the relative influences of climate and

vegetation on the historical fire regime. Within Jasper National Park, formal observational fire records extend back to the 1930's, and a ~300 year tree-ring based fire record, developed by Tande (1979), is the main source of historical (1665-1975) fire data for the area. The work presented in this thesis advances the information gained by the work of Tande (1979); whereas the tree-ring data presented by Tande (1979) is geographically extensive but limited in temporal coverage (hundreds of years), our work focuses on a single area within the Jasper town site and extends the fire history records in duration (thousands of years). Furthermore, the tree-ring data presented in this thesis will be statistically verified to ensure the years in which fires occurred are accurately presented, a technique that was not used in earlier tree-ring work. The differentiation between fire-types based on fire-scar and stand establishment data is an additional contribution to the understanding of fire severities in Jasper. The multi-proxy approach used in this study will help to develop a millennial scale fire record that will complement existing datasets and will help to put the current fire regime in a long-term context spanning the past 3,500 years.

To develop a long-term record of fire events, several paleoecological methods are used. Lake sediment collected from Little Trefoil Lake, situated near the Jasper town site, is used as the main source of long-term historical information. Studying sediment from an area impacted by human activities provides an interesting opportunity to compare pre-settlement fire activity to what is occurring today. Macroscopic charcoal analysis, in which the accumulation of charcoal into the stratigraphic sediment record of a lake is used as a proxy of fire events, provides information about the frequency of fires in the area surrounding the lake (Whitlock and Larsen 2001). Pollen analysis from the same

sediment core is then performed to identify changes in vegetation composition through time that may have acted as a bottom-up control on fire activity or may have resulted from changes in the regional climate (Courtney Mustaphi and Pisaric 2013). Furthermore, in order to place the contemporary fire regime in context with what has occurred in the past, a tree-ring record of recent fires is developed using fire evidence preserved in dead and living trees (Higuera et al. 2010). These proxy-based chronologies, in combination with previously documented evidence of fire activity, are then compared to historical changes in regional climate to determine if climate, vegetation, or a combination of both has been the dominant driver of the fire regime around Little Trefoil Lake during the past 3,500 years. Previous studies that have successfully linked fire activity to past changes in climate have suggested that fire activity during historical periods of climatic warming, such as the Medieval Climate Anomaly (700-1100 CE), could be used as an analogue for expected fire behaviour at present (Brunelle et al. 2005; Hallett and Hills 2006). Our aims here are three-fold: 1) to develop a record of fire activity during the late Holocene around Little Trefoil Lake; 2) to identify which controlling factors have most strongly influenced changes in the fire regime through time; and 3) to determine if fire activity in the present is similar to what has occurred during previously warm and dry periods, or if fire suppression and other factors have resulted in unexpected fire behaviour.

### 3.2 Study Site Description

Little Trefoil Lake is among a series of small kettle lakes situated near the Athabasca River (~ 5 m at its nearest point) in Jasper, Alberta (Figures 6 and 7). Little Trefoil Lake has a surface area of 0.63 ha and is approximately 5.2 m deep. The lake has

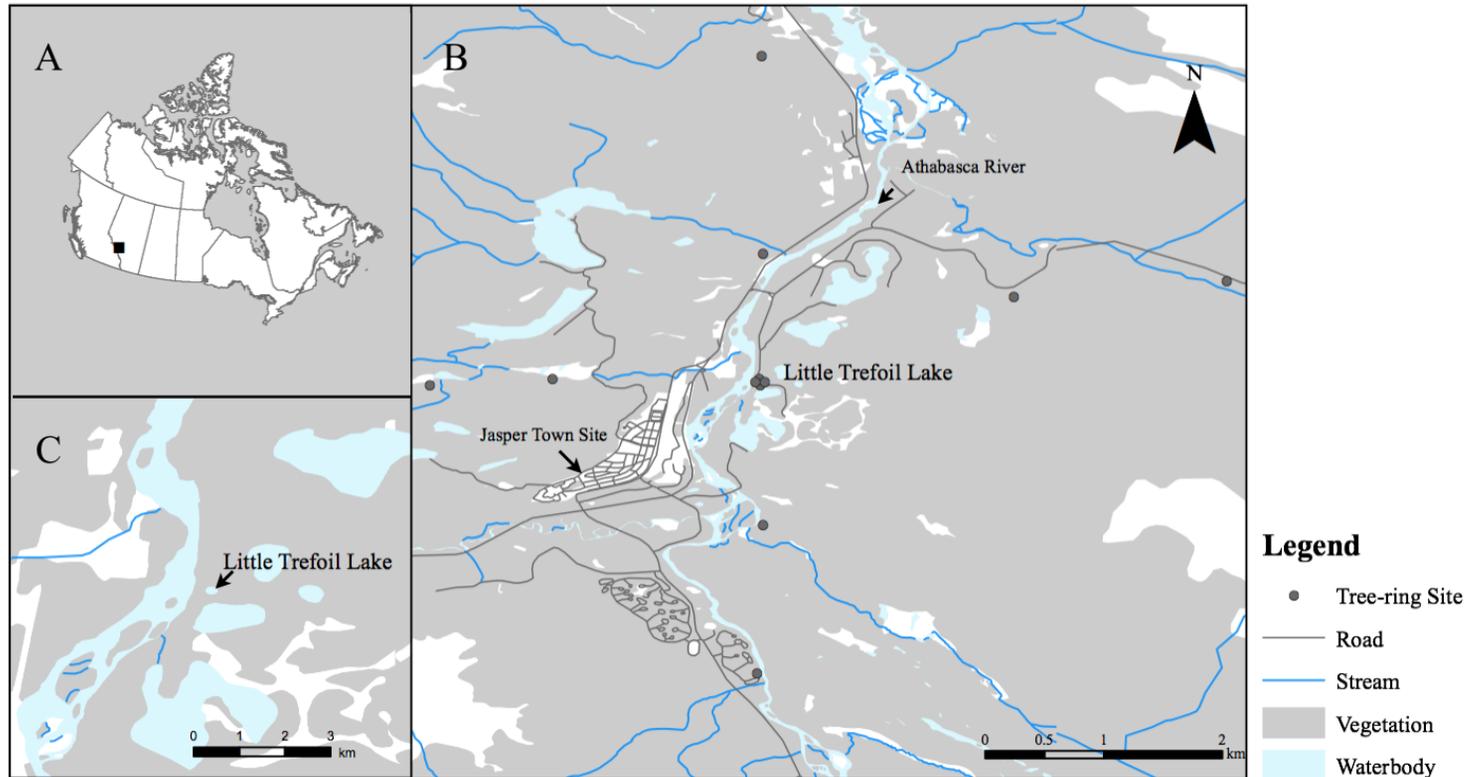
no inflows or outflows (Table 2), and the underlying geology of the area is mainly composed of sandstone, limestone, shale and quartzite (Parks Canada, 2013).

The regional landscape has been strongly influenced through time by glacial processes. Since the start of the Holocene (10,000 yrs BP), three notable periods of glacial advance have occurred; the Crawfoot advance (4,000 yrs BP), the Tiedemann advance (2,500 – 1,800 yrs BP), and the Cavell advance (900 – 300 yrs BP) (Osborn and Luckman 1988). Many of the remaining glaciers in the region are in a period of recession as a result of warmer temperatures during the past century.

Located in the Athabasca river valley of southwestern Alberta, lodgepole pine (*Pinus contorta*) is the dominant canopy species in the area surrounding the lake, although large Douglas fir (*Pseudotsuga menziesii*) and small to medium white spruce (*Picea glauca*) are interspersed throughout with trembling aspen (*Populus tremuloides*) as the dominant deciduous tree. Grasses and small shrubs occupy areas of less dense tree cover.

The continental climate of Jasper, AB has short, warm summers and relatively cold and long winters. The mean monthly temperature is 15°C in July and -10°C in January (climate normal 1980-2010; Environment Canada 2013; Figure 8). Precipitation is highest in the summer (mean = 63 mm), with a mean annual precipitation over 400 mm/year (Environment Canada 2013; Figure 8). Cloud to ground lightning strikes, which are a source of ignitions for wildfires, occur during an average of 14 lightning days per summer, at a density of about 8-32 strikes per 10 km<sup>2</sup> (Kozak 1998). Lower frequency, large-scale atmospheric processes, such as ENSO (El Nino Southern Oscillation) and the

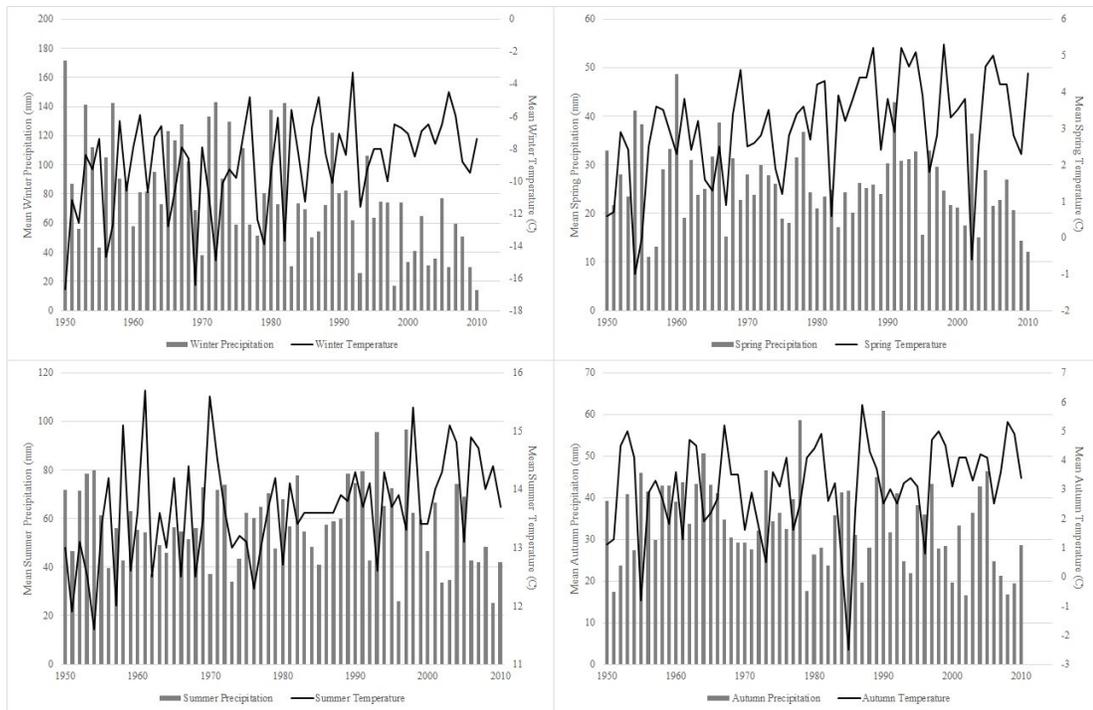
PDO (Pacific Decadal Oscillation), have also been shown to influence fire activity in Jasper National Park (Schoennagel et al. 2005).



**Figure 6** Little Trefoil Lake, located in the town site of Jasper, Alberta (A – Location of Jasper, AB; B – Tree-ring sampling sites in relation to town of Jasper and Little Trefoil Lake; C – Location of Little Trefoil Lake)



**Figure 7** Little Trefoil Lake (area = 0.63 ha), Jasper, AB (Image: Dr. Michael Pisaric)



**Figure 8** Mean seasonal precipitation and temperature values (1950-2010) for Jasper, AB (Environment Canada 2013)

**Table 2** Little Trefoil Lake site characteristics

<b>Location</b>	52.892194 °N, 118.059278 °W
<b>Elevation (MASL)</b>	1026
<b>Lake Depth (m)</b>	5.2
<b>Lake Area (ha)</b>	0.63
<b>Shoreline Characteristics</b>	1-2 meter bank, surrounded by reeds and grasses, no inflows/outflows
<b>Local Vegetation</b>	Lodgepole pine dominated, with white spruce and Douglas fir throughout

### 3.3 Field Methods

A 44 cm gravity core (Glew 2001) and a 5 m overlapping Livingstone core (Wright et al. 1984) were collected from the center of Little Trefoil Lake in the summer of 2007 (core ID: 07 JP 02). The gravity core was sectioned in the field at 0.5 cm intervals, and the long core was sectioned into ~50 cm segments for transportation back to the laboratory and was stored at 4°C until it was subsampled in January 2013. For this study, only the top 3.07 m of sediment was analysed. To complement the sediment charcoal record and to provide annually resolved contemporary fire history data, fire scar and tree-core samples were collected from 12 sites around Little Trefoil Lake during the summer of 2013 (Figure 6). Sampling sites were located approximately 0, 3, and 6 km from Little Trefoil Lake in each of the four cardinal directions. Sites relatively near to the lake were chosen with the aim that the tree-ring data would assist the interpretation of the charcoal data by connecting peaks in charcoal accumulation with annually resolved tree-ring fire evidence.

In areas that experience low frequency and high severity stand-replacing fires, the stand establishment dates were determined by identifying the presence of even-aged canopies (Johnson and Fryer 1989). To verify the presence or absence of even-aged cohorts, 10 canopy and 10 sub-canopy trees (when present) were sampled using Haglof increment borers with an internal diameter of 5.1 mm to determine stand age, following methods adapted from the N-tree design used by Heyerdahl et al. (2006). By sampling subcanopy trees when present, information regarding the stand's growth dynamics and internal heterogeneity could be ascertained. Samples were collected from the tree's base (< 20 cm from the ground) in order to capture the youngest rings produced by the tree.

Tree core samples were stored in clear plastic straws and labeled with an identification code.

Fire scars, which can provide annually resolved dates of non-lethal fire activity, were collected at each site, when present, using chain saws and handsaws. A minimum of five scarred cookies or wedges were collected when present in the vicinity of the cored trees, however any fire instance was recorded and considered as evidence of fire activity. Both living and dead trees were sampled for fire scars, although dead wood and snags were targeted over live trees whenever possible. Downed trees were routinely checked for buried scars. Once collected, all samples were labeled and transported to the Carleton University Paleoecology Laboratory for preparation and tree-ring analysis.

### 3.4 Laboratory Methods

#### *Tree-ring Analysis*

Tree core samples were glued into slotted mounting boards and were air-dried. To prevent warping during drying, the samples were taped or tied to the core mounts. Once dry, the cores were sanded to progressively finer grits (up to 400 grit) using a belt sander to expose a smooth surface containing clear delineations between annual ring boundaries. A similar procedure was followed for fire scar cookies and wedges; the samples were cut to a level surface and then sanded.

The tree-rings of the prepared samples were measured using a stereoscope and a Velmex measuring system (0.001 mm precision), and individual tree-ring measurements were recorded electronically. Once all cores and fire scars from a site were measured, growth chronologies were created using a combination of visual and computer-assisted

crossdating techniques (Stokes and Smiley 1968). The software program COFECHA (Holmes 1983) was used to align tree-ring measurements based on known years of notably large or small ring-width as well as interseries correlation values. In order to achieve an adequate sample depth, trees within the same canopy level were crossdated together regardless of species, however canopy and subcanopy trees were crossdated separately.

For fire scar samples collected from living trees, the year in which the fire occurred was noted. When the year of tree mortality was unknown, which was the case for fire scar samples collected from dead trees, the samples were added to the site chronology by treating them as floating series and identifying their location of highest correlation with the site chronology using COFECHA and visual verification. Using this process, dates could be attributed to the year of fire scar formation in dead as well as living trees. Site level chronologies of tree cores and fire scars were established for 11 of 12 sites.

Because of the interest in identifying even-aged cohorts, the earliest growth year of each tree was recorded when the pith was present. For cores that had missed the tree's pith during coring, but still possessed the arcing pattern of the inner-most rings, the number of missing rings to the tree's centre was estimated using a graphical correction technique (Rozas 2003). Of the 140 collected tree cores, 101 (72%) were age-adjusted. The average adjustment was 7.6 years. Since all cores were collected at < 20 cm from the base of the tree, the tree ages were not corrected for sampling height. The majority of samples were taken from lodgepole pine, which possess high juvenile growth rates (Lotan et al. 1985; Nigh and Love 1999), and so adjustments made for sampling height

would likely fall within the range of error associated with the graphical age corrections. Fire history data from the tree-ring samples were analyzed using the fire analysis programs FHX2 (Grissino-Mayer 2001a) and FHAES.

As in other tree-ring fire studies, we assumed that even-aged cohorts were representative of fire events and not wind-throw or insect disturbance due to the large amount of fire scar evidence in the region (Heyerdahl et al. 2012). Even-aged cohorts were identified as pulses in tree establishment in which at least 60% of canopy trees became established within a common 10 year interval, as it has been suggested that most seedlings in post-fire cohorts become established within the first decade following a fire event (Johnstone et al. 2004). Site-level fire regimes of the tree-ring sites were classified based on the presence, absence, and type of fire evidence. The presence of fire scars ( $\leq 1$  fire date) were used as defining criteria of low-severity fire activity, while even-aged cohorts and an absence of fire scars were definitive of high-severity fires (Heyerdahl et al. 2012; Marcoux et al. 2013). Sites that contained both even-aged canopies and  $\geq 1$  fire date were characterized as mixed-severity. High-severity fire dates based on cohort establishment were attributed 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).

In order to identify if a relationship existed between topographic features and tree-ring inferred fire events, the relationships between slope angles, aspect, the number of fires, and fire severity were explored. A Pearson's correlation was performed on the slope angle in relation to the number of fires and fire severity. Since aspect is measured using a 360° system (meaning that a value of 0° has the same meaning as 360°), each site was attributed a categorical classification based on the dominant cardinal direction it was

facing. Four categories were used (representing North, South, East, and West dominated aspects), and an analysis of variance (ANOVA) was performed to determine if aspect was related to the number of fires or fire severity.

### *Sediment Age Estimates*

The age of the sediment was determined using a combination of radiometric dating methods and calibration between the charcoal and tree-ring records. Sediment from the gravity core was sent to MyCore Scientific Inc. for  $^{210}\text{Pb}$  dating using the constant rate of supply method (Binford 1990). A large charcoal peak recorded in the sediment charcoal analysis that occurs around the time of a large known fire (1889 CE) in Jasper was also used to calibrate the top-most sediment. Evidence of this fire around the study site is found in the tree-ring record described in this study and others (e.g. Tande 1979). From the Livingstone core, five macrofossils collected from various depths were processed for accelerator mass spectrometry radiocarbon dating (Direct AMS, Bothell, WA, USA and Beta Analytic in Miami Florida). Radiocarbon dates were calibrated using CALIB 7.0 software, and were selected using the median probability distribution (Telford et al. 2004). The age depth model was constructed by fitting a cubic smoothing spline, inversely weighted to the two-sigma errors, through the composite of inferred dates.

The top ~3 m of lake sediment was subsampled for macroscopic charcoal analysis at 0.5 cm intervals. The core was also subsampled for loss-on-ignition and magnetic susceptibility at 0.5 cm intervals and pollen analysis at 5-10 cm intervals. One  $\text{cm}^3$  of material was used for each analysis, except for LOI, which used  $0.5 \text{ cm}^3$ . The remaining sediment was stored for future use.

### *Sediment Characteristics*

Loss-on-Ignition (LOI) is a useful method for quantifying changes in lake productivity and as well as sedimentary inputs. LOI was performed at 0.5 cm intervals for the top third of the core, and at 1 cm intervals in subsequent sections. Sediment (0.5 cm<sup>3</sup>) was placed in pre-weighed, dried, and labeled crucibles. The combined mass of the wet sample and the crucible was recorded, and the samples were placed in a 110°C drying oven for 24 hours to dry the sediment. The samples were then reweighed and then heated to 550°C in a muffle furnace for four hours to remove the organic component. The weighing and heating procedure was repeated at a temperature of 950°C for two hours to quantify the carbonate constituent. The percentage of dry sediment lost at each temperature was calculated using established methods (Heiri et al. 2001). The magnetic susceptibility of the samples was also measured as a means of gaining insight into changes in sediment input (Dearing 1983; Courtney Mustaphi and Pisaric 2014). Sediment was brought to room temperature and a Bartington Systems M2SE sensor was used on samples down-core at 0.5 cm intervals. Together, LOI and magnetic susceptibility can be used to identify events of rapid sedimentation that could lead to erroneous sediment age-depths.

### *Macroscopic Charcoal*

The sub-sampled material (1 cm<sup>3</sup>) for macroscopic charcoal analysis was rinsed into a small beaker with a dilute solution of sodium hexametaphosphate to deflocculate the sediment and to remove excess silt and clay particles (Bamber 1982). The samples

were left for a minimum of 24 hours before being sieved through a 150  $\mu\text{m}$  mesh sieve to separate macroscopic charcoal from the smaller, microscopic fractions. The remaining material was then rinsed into a petri dish where macroscopic charcoal was tallied and classified using a morphological key (Courtney Mustaphi 2013) under a Nikon SMZ800 stereoscope. The procedure was repeated for contiguous samples down the length of the sediment core.

The frequency and timing of fire events was identified using the program CharAnalysis (freely available from <http://CharAnalysis.googlepages.com>; Higuera 2009). Charcoal accumulation rates (CHAR; number particles  $\text{cm}^{-2} \text{yr}^{-1}$ ) were estimated by resampling the charcoal tallies at equal intervals to account for changes in sedimentation. The CHAR series was then decomposed into a varying background component (bCHAR) and a peak charcoal (peakCHAR) component (Long et al. 1998). Background charcoal represents varying levels of charcoal influx into the lake, which is related to the amount of biomass in the environment, depositional processes, and extra-local fire activity (Long et al. 1998; Marlon et al. 2006; Carter et al. 2013). Peak charcoal represents the influx of charcoal in relation to fire events that have occurred in the local area surrounding the lake.

To develop a chronology of fire events through time, CHAR values were resampled to account for varying rates of sedimentation and unequal sampling intervals throughout the core (Higuera et al. 2010). Background charcoal was estimated from the CHAR series using a 500-yr lowess smoother robust to outliers (Carter et al. 2013; Courtney Mustaphi and Pisaric 2013; Morris et al. 2013). Fire events were interpreted from the record by identifying peaks in charcoal that were above a locally defined

threshold of charcoal accumulation. A minimum count probability ( $p \leq 0.05$ ) was imposed to ensure that minimum charcoal values in the 75-year window around the charcoal peak had a <5% chance of coming from the same Poisson distribution as the curve created by the peak. The minimum count probability is used to determine the statistical significance of the charcoal peaks (Higuera et al. 2010). The median fire return interval (years fire<sup>-1</sup>) was calculated for each interval as the average years between peaks smoothed over a 1,000-year window. A Welch's two-sample t-test was used to determine if a significant difference existed between FRI values during the MCA and the LIA.

To identify if climate has been a controlling mechanism of fire activity, the length of the charcoal fire chronology was compared to records of past climate change from the region (Cumming et al. 2002; Luckman and Wilson 2005; Hallett and Hills 2006). The influence of vegetation on fire activity was evaluated by comparing the fire history record to changes in vegetation composition determined through the pollen analysis from the sediment core, and by comparing the bCHAR component of the charcoal record to the ratio of closed-open canopy species. It has been suggested that changes in the amount of background charcoal found in lake sediment is related to fuel abundance (available biomass), which is controlled predominantly by climate (Marlon et al. 2006; Seppä et al. 2009; Morris et al. 2013; Courtney Mustaphi and Pisaric 2014). As such, significant changes in mean bCHAR values were identified using a regime shift detection algorithm developed by Rodionov (2005). From this, we can infer the timing of changes in biomass that may have influenced fire activity around Little Trefoil Lake.

### *Pollen Processing*

Pollen processing was performed on 1 cm<sup>3</sup> samples at intervals of 5 cm for the top of the sediment record to 1 m depth and then 10 cm intervals between 1 m and 3.07 m depth. Pollen preparations followed standard techniques described in Faegri and Iversen (1989). The samples were spiked with two *Lycopodium* tablets (batch number 483216) to permit calculations of pollen accumulation rates (Stockmarr 1971). Once fully processed, silicone oil (2000 cs) was added to the remaining residue and smear slides were prepared for each sample. Pollen grains were identified and tallied up to 500 terrestrial pollen grains using a light microscope at 400x magnification. A reference collection of pollen grains at Carleton University and identification manual (Moore and Webb 1978) were used to assist in taxonomic identification

The stratigraphic record of percent pollen by species was analyzed using the program CONISS to identify the presence of statistically significant pollen zones (Grimm 1987). Ratios of pollen accumulation rates (PAR, pollen grains cm<sup>-2</sup> year<sup>-1</sup>) were then used to identify changes in environmental conditions that influenced vegetation composition. Xeric conditions resulting in an increase in open canopy species were inferred from increases in the ratio of *Pseudotsuga* and *Poacea* pollen (open canopy) to *Picea* and *Abies* (wet conditions, closed canopy) (adapted from Hallett and Hills 2006). As in Hallett and Hills (2006), *Pinus* pollen was not included in the ratio analysis because of its large source area and high abundance throughout the record. An exploratory correlation analysis was used to identify relationships between the charcoal record (FRI, CHAR, bCHAR) and the canopy ratio.

### 3.5 Results

#### *Tree-ring Analysis*

The canopy species at the sites surrounding Little Trefoil Lake were found to be a mix of lodgepole pine (seven sites), white spruce (five sites), and Douglas fir (five sites), with white spruce as an occasional subcanopy species (three sites; Table 3). Balsam fir was identified in the subcanopy of one site. The mix of early-seral and late-successional trees within and between sites is characteristic of mixed-severity fire regimes (Arno et al. 2000). Tree-ring chronologies were successfully developed for 11 of 12 sites. Site W1 could not be crossdated due to anomalies in the growth patterns of the trees, probably in relation to the location in which they were growing. The trees at this site were very stunted and growing on a steep and rocky slope.

The average time-span covered by the tree-ring series was 122 years. The interseries correlation values of the crossdated series, which represent the commonality of the growth signal expressed by the trees at a site, ranged between 0.478 and 0.798. Such high interseries correlation values indicate that the growth of the trees is closely linked to a commonly experienced, site-level forcing factor. Mean sensitivity values, a metric that indicates the sensitivity of the trees to environmental conditions, was between 0.211 and 0.416, suggesting an intermediate to high level of environmental sensitivity (Grissino-Mayer 2001b).

**Table 3** Tree-ring site characteristics and chronology results (BF – balsam fir; DF – Douglas fir; LPP – lodgepole pine; WS – white spruce; IC – interseries correlation value; MS – mean sensitivity value; C – canopy; S – subcanopy)

Site	Long. (UTM)	Lat. (UTM)	Elevation (m ASL)	Slope	Aspect	Species	Subcanopy	IC	MS	Chron. Length	# Series
N1	428777	5860846	1044	24.3°	SSE	LPP, DF	No	0.728	0.349	1876-2012	10
N2	428871	5863602	1109	11.2°	NE	DF	No	0.798	0.416	1771-2012	12
N3	428919	5867937	1089	17.7°	NE	DF, LPP	No	0.593	0.274	1913-2012	11
S1	428787	5860713	1043	5°	NNW	WS, LPP	No	0.571	0.227	1916-2012	10
S2	428782	5857638	1059	9.6°	WNW	WS, LPP, DF	Yes	0.696 (C) 0.736 (S)	0.336 (C) 0.289 (S)	1873-2012 (C) 1787-2012 (S)	11 6
S3	428657	5854389	1057	10.5°	E	LPP	No	0.664	0.227	1902-2012	10
E1	428847	5860780	1031	18.1°	SW	WS, DF, LPP	No	0.478	0.241	1896-2012	8
E2	432185	5862607	1128	20.1°	WNW	LPP	No	0.609	0.239	1898-2012	13
E3	435016	5862912	1246	5.8°	WNW	LPP, WS	Yes	0.552 (C) 0.654 (S)	0.217 (C) 0.246 (S)	1901-2012 (C) 1912-2012 (S)	12 10
W1	428726	5860773	1040	6.6°	NNE	WS	No	NA	NA	NA	NA
W2	426035	5860898	1130	51.1°	NNW	WS	Yes	0.550 (C) 0.599 (S)	0.212 (C) 0.275 (S)	1940-2012 (C) 1944-2012 (S)	11 10
W3	424405	5860775	1188	19.8°	NNW	LPP, WS, BF	Yes	0.602 (C) 0.537 (S)	0.211 (C) 0.220 (S)	1896-2012 (C) 1952-2012 (S)	16 10

Fire evidence was found at 8 sites, with fire scar cross-sections collected and crossdated at seven sites (Table 4). Even aged-cohorts were found at four locations (Figure 9). Lodgepole pine was the dominant tree-species of even-age cohorts, all of which became established in the late 19<sup>th</sup> or early 20<sup>th</sup> century.

Based on the site-level fire regime classification, eight sites appeared to be experiencing low-severity fire regimes, three sites mixed-severity, and one site high-severity. The variability expressed among sites suggests that the larger watershed is experiencing a mixed-severity fire regime, with some of the many low-severity fires overlapping spatially with areas that have experienced high-severity fires. Neither slope nor site aspect were correlated to fire severity ( $r = -0.18, p = 0.58$ ;  $F = 0.51, p = 0.49$ ), nor the number of recorded fires ( $r = 0.01, p = 0.97$ ;  $F = 2.15, p = 0.17$ ).

**Table 4** Tree-ring fire evidence by site

Site	Aspect	Slope	Canopy Species	Subcanopy Species	Fire Evidence	Type	Scar Date	Even-aged Cohort	Fire Severity
<b>N1</b>	SSE	24.3°	DF, LP	-	-	-	-	-	Low
<b>N2</b>	NE	11.2°	DF	-	Yes	Scar	1941	-	Low
<b>N3</b>	NE	17.7°	DF, LP	-	Yes	Scar	1953	-	Low
<b>S1</b>	NNW	5.0°	WS, LP	-	-	-	-	-	Low
<b>S2</b>	WNW	9.6°	WS, DF	-	Yes	Scar	1903	-	Low
<b>S3</b>	E	10.5°	LP	-	Yes	Observed	-	Yes (1901)	High
<b>E1</b>	SW	18.1°	WS, DF	-	Yes	Observed	-	-	Low
<b>E2</b>	WNW	21.1°	LP	-	Yes	Scar	1915 1935	Yes (1890)	Mixed
<b>E3</b>	WNW	5.8°	LP, WS	WS	Yes	Scar	1927 1961	Yes (1895)	Mixed
<b>W1</b>	NNE	22.2°	WS	-	-	-	-	-	Low
<b>W2</b>	NNW	51.1°	WS	WS	Yes	Scar	1971	-	Low
<b>W3</b>	NNW	19.8°	LP	WS, BF	Yes	Scar	1915 1925	Yes (1894)	Mixed

**LP**= Lodgepole pine **DF**= Douglas fir **WS**= White spruce **BF**=Balsam fir

Low Severity:            $\leq 1$  Fire scar date           No even-aged canopy  
Mixed Severity:        $\geq 1$  Fire scar date           Even-aged canopy  
High Severity:         0 Fire scar dates               Even-aged canopy

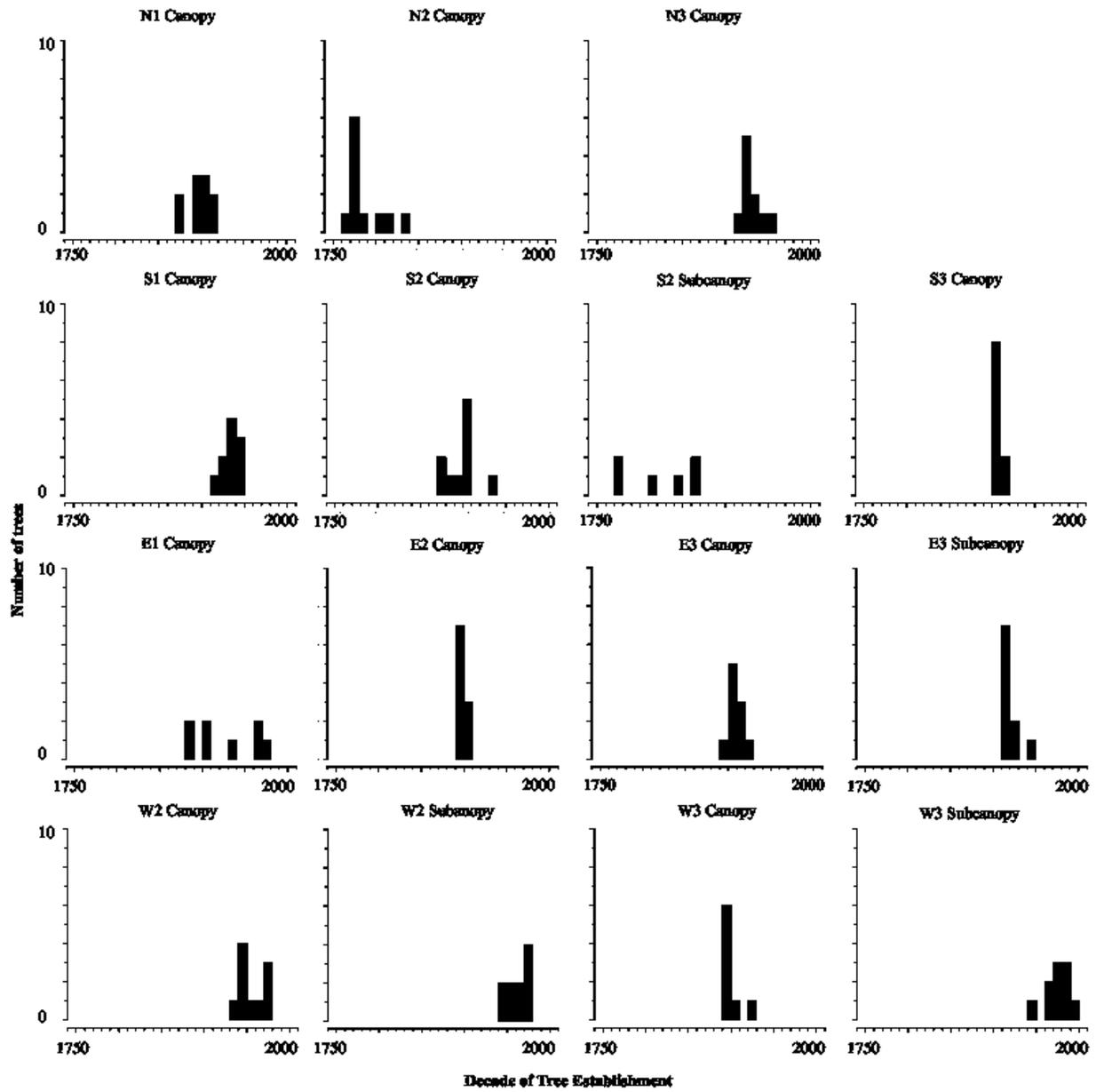


Figure 9 Stand establishment data for 11 crossdated sample sites

### *Chronology and Sedimentology*

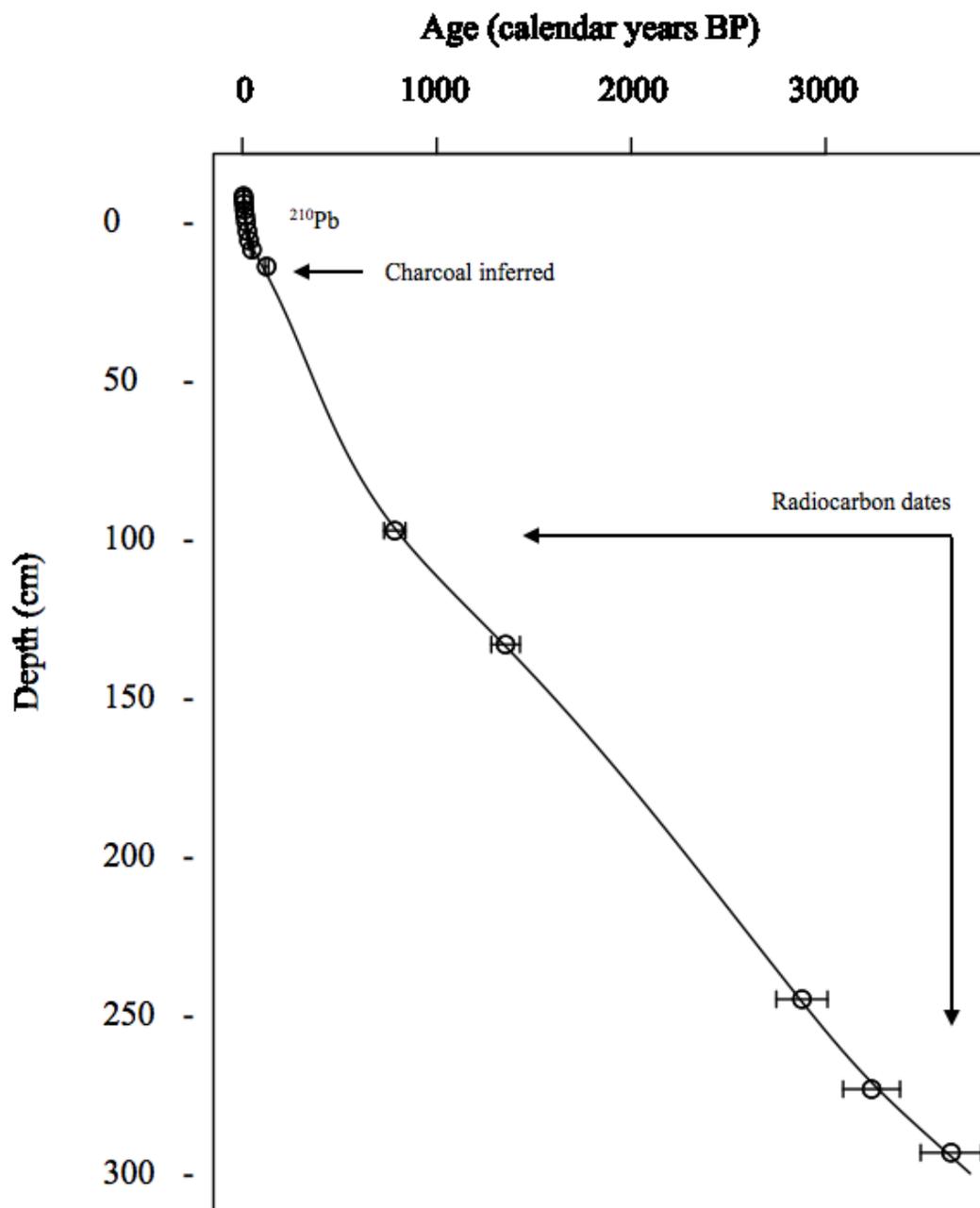
The age-depth model, developed using a composite of nine  $^{210}\text{Pb}$ , one tree-ring/charcoal inferred, and five AMS radiocarbon dates, shows a fairly linear rate of sedimentation throughout the core (Figure 10) with no age reversals. A summary of interpolated dates and their associated errors are presented in Table 5. The average sedimentation rate was 1 mm/year (min: 0.5 mm/year, max: 39 mm/year), with the highest rates of sedimentation found in the less-consolidated sediments of the gravity core.

For most of the duration of the record, the organic content of the sediment varied between 50-75% (Figure 11a), indicating that Little Trefoil Lake is currently, and has been, very productive. There is a conspicuous drop in organic content between 55-66 cm where  $\text{LOI}_{550}$  reaches values as low as 13%.

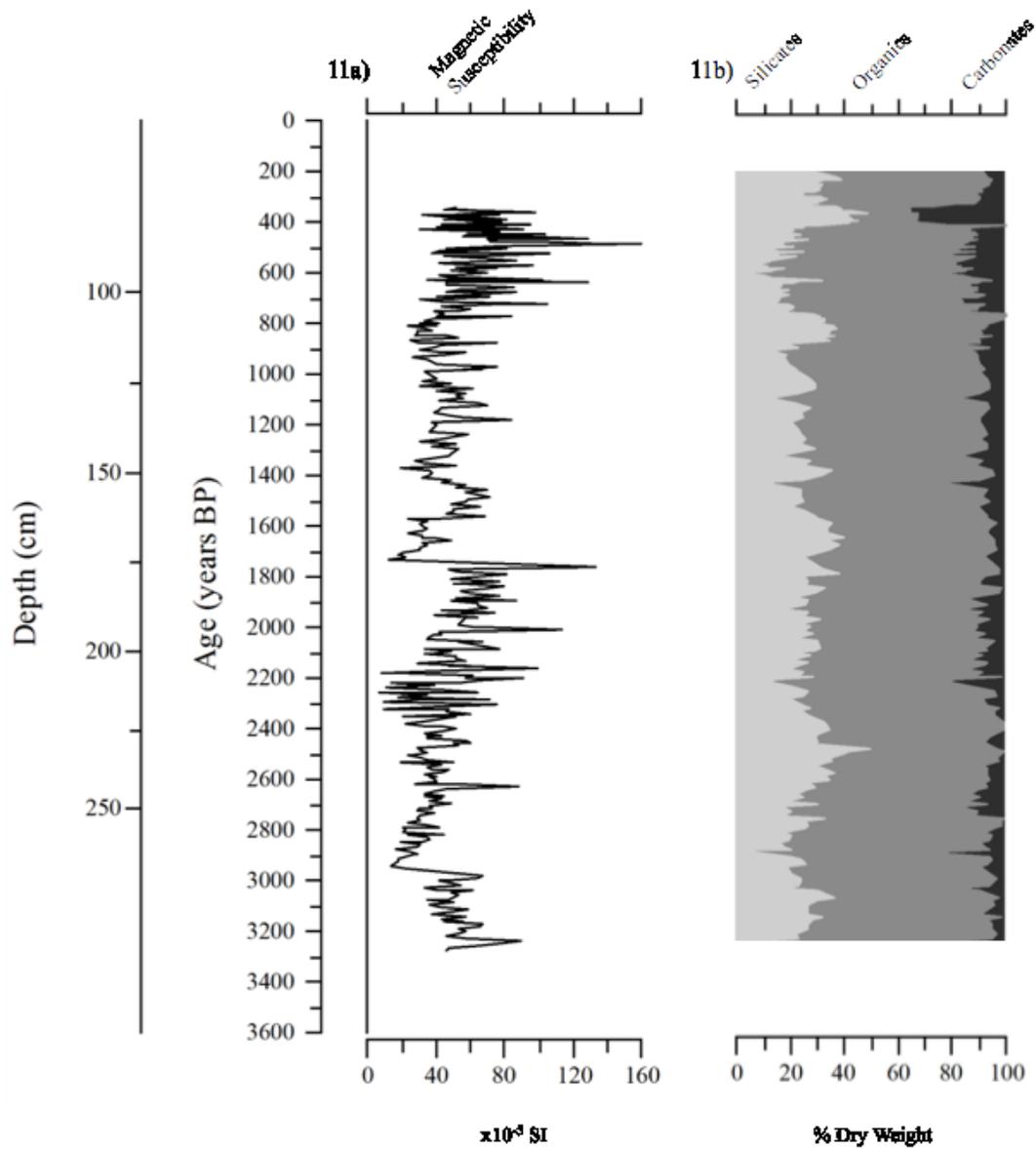
Values of magnetic susceptibility record range from 6.5-160 SI units throughout the core (Figure 11b). An upward trend in the magnetic susceptibility of the sediments is visible from 3000 (minimum: 42 SI units) to 1800 years BP (maximum: 160 SI units), at which point values drop significantly before rising again towards ~500 years BP (maximum: 133 SI units). There does not appear to be a consistent relationship between magnetic susceptibility and loss-on-ignition.

**Table 5** Interpolated sediment depth ages from  $^{210}\text{Pb}$ , charcoal accumulation, and radiocarbon dating

Top Depth (cm)	Bottom Depth (cm)	$^{210}\text{Pb}$ (Bq/g)	$^{13}\text{C}:^{12}\text{C}$ ratio (‰)	Calibrated Age (years before 2014)	Two-sigma Error	Source	Material Type	Dry Weight (g)	Reference
1.0	1.5	0.480	-	6.4	0.00	$^{210}\text{Pb}$	Bulk sediment	0.14	-
2.0	3.0	0.419	-	7	0.00	$^{210}\text{Pb}$	Bulk sediment	0.52	-
3.5	4.0	0.544	-	8.2	0.00	$^{210}\text{Pb}$	Bulk sediment	0.33	-
5.5	6.0	0.701	-	11.1	0.00	$^{210}\text{Pb}$	Bulk sediment	0.37	-
7.5	8.0	0.649	-	15	1.00	$^{210}\text{Pb}$	Bulk sediment	0.51	-
9.5	10.0	0.484	-	19	1.00	$^{210}\text{Pb}$	Bulk sediment	0.51	-
12.5	13.0	0.615	-	26	1.00	$^{210}\text{Pb}$	Bulk sediment	0.54	-
15.5	16.0	0.460	-	35	3.00	$^{210}\text{Pb}$	Bulk sediment	0.60	-
18.5	19.0	0.338	-	50	5.00	$^{210}\text{Pb}$	Bulk sediment	0.59	-
20.0	25.0	0.219	-	125	10.00	Charcoal peak	Macroscopic charcoal	-	Tree-ring inferred fires
110.2	111.7	-	-24.9	784	55.10	Radiocarbon	Conifer stem	0.29	D-AMS 004506
147.4	148.1	-	-26.6	1354	73.69	Radiocarbon	Conifer stem	0.41	D-AMS 004507
263.2	264.7	-	-22.7	2878	131.58	Radiocarbon	Seed capsule/cone	0.41	D-AMS 004508
292.5	293.7	-	-37.9	3236	146.25	Radiocarbon	Stem	1.01	D-AMS 004509
313.2	313.8	-	-25.4	3645	156.62	Radiocarbon	Stem	0.32	D-AMS 004510



**Figure 10** Age-depth model for core 07 JP 02 collected from Little Trefoil Lake. Width of error bars indicate the two-sigma errors



**Figure 11** Magnetic susceptibility (**11a**) and loss-on-ignition data (**11b**) for Little Trefoil Lake. In (b), *organics* represent the percent loss-on-ignition at 500°C and *carbonates* represent the percent loss-on-ignition at 950°C (CO<sub>2</sub> evolved from carbonate material). *Silicates* represent the material remaining after both ashing processes.

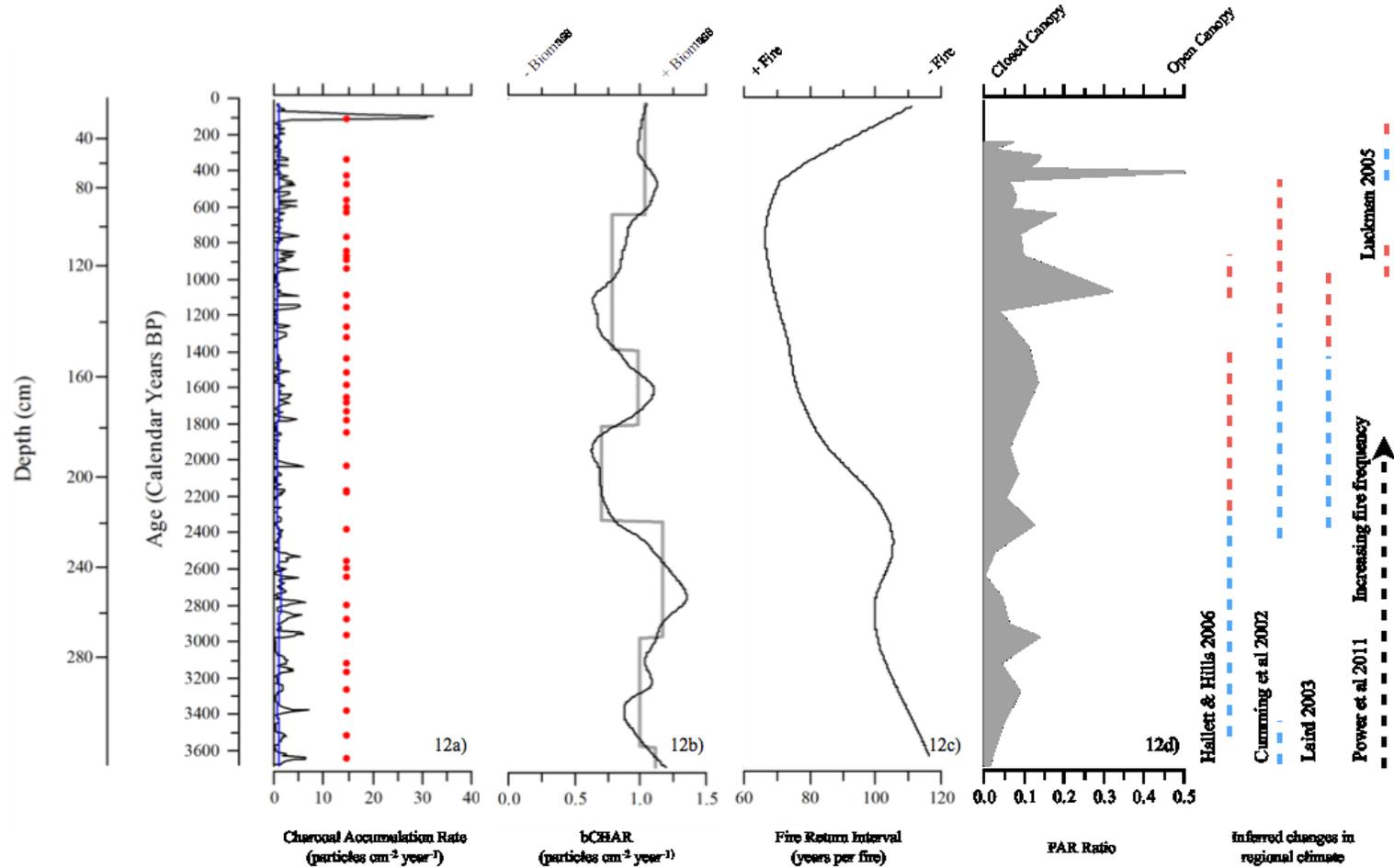
### *Macroscopic Charcoal*

From ~3,700 years BP to present, 40 statistically significant peaks in CHAR (fire events) were identified (Figure 12a). Charcoal accumulation ranged from 0-32 particles  $\text{cm}^{-2} \text{ year}^{-1}$ , with a median value of  $<1 \text{ particle cm}^{-2} \text{ year}^{-1}$ . The largest spike in CHAR, occurred between ~70-110 years BP. Charcoal variability in the record was lowest between 1,200-2,500 years BP, varying between 0-6 particles  $\text{cm}^{-2} \text{ year}^{-1}$  and background charcoal changed only slightly through time. Values of bCHAR fell within a range of  $<1$  to slightly more than 1 particle  $\text{cm}^{-2} \text{ year}^{-1}$ . The regime shift algorithm identified six distinct changes in the mean influx of bCHAR, with an average periodicity of 516 years (Figure 12b)

The fire return interval (FRI; time between fires; Figure 12c) throughout the study period was between 67-122 years and was highest at the beginning and end of the sediment record, corresponding to an inferred shift from a wet/closed canopy at the beginning of the record to a drier/open canopy (Figure 12d), as described below. Moving towards present, the FRI generally declined from ~3,700 to 500 years BP, reaching a minimum FRI of 67 at ~850 years BP, with a short decline in fire activity from ~2,800 to 2,200 years BP. Fire activity inferred from the charcoal record agreed with historical changes in climate inferred from other proxy records in the region (Cumming et al. 2002; Luckman 2005; Hallett and Hills 2006; Power et al 2011). Inferred periods of wetter/cooler conditions at the start of the sediment record agreed well with the relatively low recorded fire activity occurring during the same period, with the relationship reversing as conditions become warmer and drier near the middle of the record, corresponding to a rise in fire frequency. The timing of known climate anomalies, such as

a the Medieval Climate Anomaly (1,300-900 BP; Luckman and Wilson 2005) and the Little Ice Age (500-150 BP; Luckman 2005), appeared to have influenced fire activity; fires are more frequent during the warmer and drier MCA (mean FRI = 70), and less frequent during the LIA (mean FRI = 81). The results of the Welch's t-test indicate the mean FRIs during the MCA and LIA are statistically different from one another ( $t = 8.36$ ,  $p < 0.001$ ).

A large peak in macroscopic charcoal accumulation was apparent at 111 years BP and is representative of a known large fire that occurred in Jasper in 1889 (Tande 1979), and the subsequent period of heightened fire activity indicated by the tree ring records from this study. It appears that several high-severity fires, whose dates are inferred from the stand establishment dates described above, burned within the watershed of Little Trefoil Lake around the turn of the 20<sup>th</sup> century. The fire scar dates of low-severity fires (Table 4) did not correspond with any significant peaks in macroscopic charcoal in the sediment record.



**Figure 12** Stratigraphic diagram of (a) charcoal accumulation ((black line = charcoal accumulation, blue line = background charcoal accumulation, red dots = inferred fire events), (b) inferred biomass (black line = background charcoal accumulation; grey line = regime shift detection), (c) fire return interval, (d) pollen accumulation rate (PAR) ratio, and (e) inferred regional changes in climate and fire activity (blue-dotted= wetter/cooler, red-dashed = drier/warmer)

## *Pollen*

While there were no statistically significant zonations (Figure 13) in the pollen record, some generalizations can be made. *Pinus* pollen remained relatively consistent throughout the record, accounting for 70 to 95 % of the pollen assemblage. *Picea* (2-16 %) and *Betula* (0.5–6%) pollen declined slightly from ~3,200 yrs BP to 1,000 yrs BP, decreasing from 16 % to 4% and 6% to 2% respectively. A relative rise in *Populus*, an open canopy, parkland type species, from 1,400 yrs BP to 200 yrs BP, also occurred, although the percent pollen of this species remained low.

The ratio of the pollen accumulation rates of dry/open canopy pollen to wet/closed canopy pollen (Figure 12d) varied through time (values: 0-0.5), and produced a generally similar pattern of change as the fire return interval. A correlation analysis, however, revealed no significant relationships between the canopy ratio and FRI ( $r = -0.09$ ,  $p = 0.63$ ), CHAR ( $r = -0.17$ ,  $p = 0.37$ ), or bCHAR ( $r = -0.11$ ,  $p = 0.58$ ). Pollen ratio values tend to be lower (more closed canopy vegetation) during periods of low fire activity (i.e. 3,600-1,200 yrs BP). High ratio values, which indicate a prevalence of dry, open canopy species, tended to occur during periods of greater fire activity (i.e. 1,200-300 yrs BP). Based on Figure 12d, it appears that the pollen ratio (vegetation composition) and fire return intervals are expressing a level of synchronicity through time, however the low sampling resolution of the pollen record makes it difficult to compare statistically.

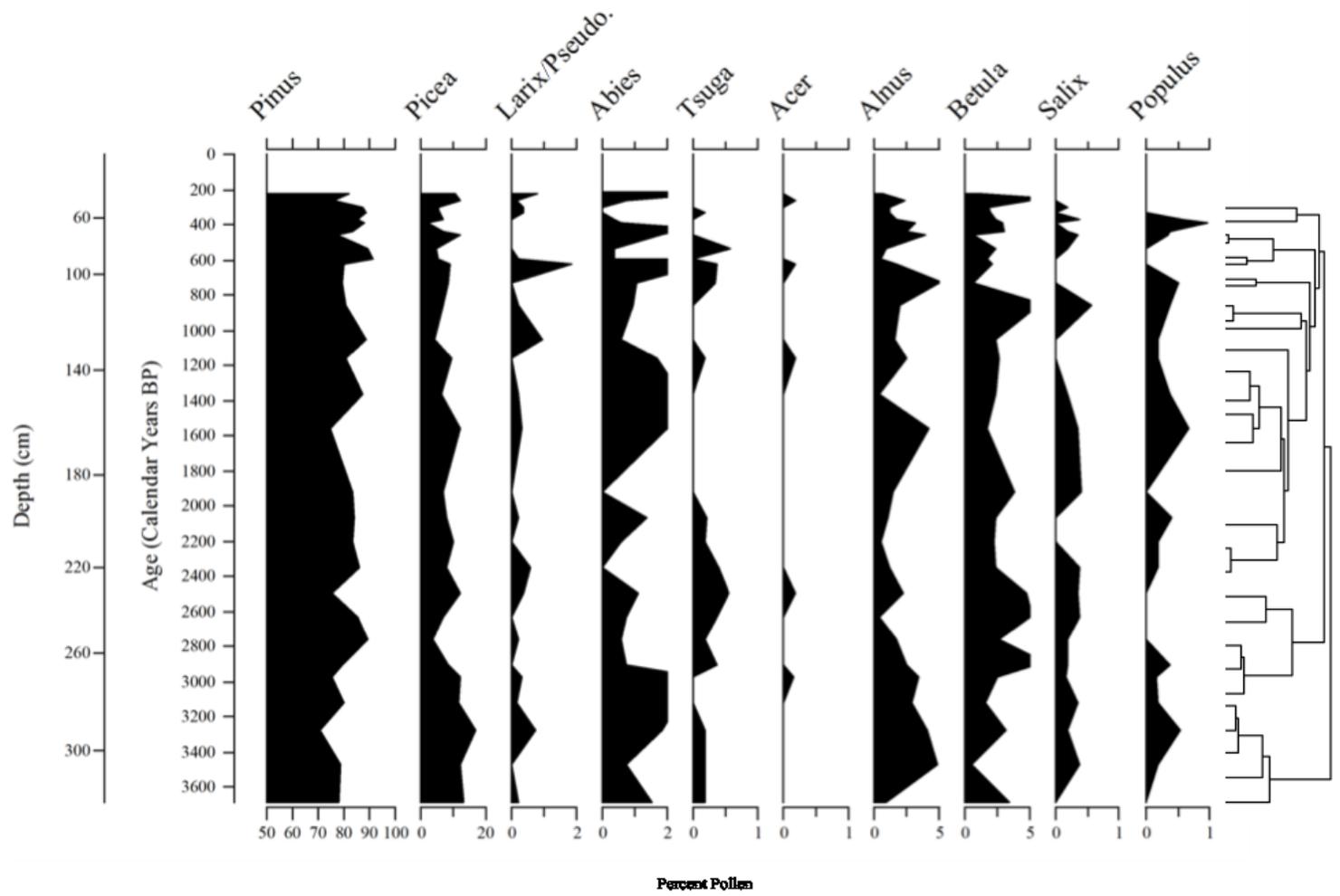


Figure 13 Percent pollen diagram of tree and shrub species >0.5% total pollen

### 3.6 Discussion

Tree-ring and charcoal based records of fire history provide important information about forest ecosystems, but represent fundamentally different aspects of the local to extra-local fire regime. It has been suggested the decompositional approach of charcoal analysis, such as that used in this study, is more suitable for identifying peaks in charcoal that correspond to large wildfires that produce greater amounts of air-borne charcoal (Higuera et al. 2010), a finding that is supported by the tree-ring and sediment records presented here. The lack of agreement between the timing of low-severity fires inferred from the tree-ring record with the charcoal record is not surprising since no even-aged cohorts or crossdated fire scars were found within the sample sites nearest to Little Trefoil Lake (~0 km). In their study linking tree-ring fire evidence to charcoal records Higuera et al. (2010), suggested that charcoal records best capture fire events recorded by tree-rings that occur within 1.2-3 km of the lake. While the high-severity fires beyond this extent (~3-6 km), such as those identified at E2, E3, S3, and W3, may produce strong convective plumes and enough airborne charcoal to create significant peaks in charcoal, low-severity fires at the same distances probably do not. If we assume that fires behave similarly today as they have in the past, it can be concluded that peaks in our sediment charcoal record either represent low-moderate severity fires that have occurred very close (within a few hundred meters) to the lake's edge, or high-severity fires that have occurred at distances of up to 6 km or more. Tree-ring fire evidence was used to establish a temporally and spatially resolved short-term record of low and high severity fires around Little Trefoil Lake.

### *3.6.1 Fire Dynamics*

Wildfires and their effects are heterogeneous across the boreal forest of western North America (Turner et al. 1994; Schoennagel et al. 2004), as well as on small scales of only several kilometers. In the area surrounding Little Trefoil Lake, there is evidence of a mixed-severity fire regime; all three classes of fire severity were identified through our analyses, and several tree-ring sites are characterized by complex stand structures. The non-stationarity of the fire return interval identified in the charcoal record also indicates the presence of mixed-severity fires over longer time scales than what is covered by the tree-ring record. Arno et al. (2000) have suggested that mixed-severity fire regimes possess a fire return interval that varies between a range of 30-100 years in Rocky Mountain forests, while low-severity, non-lethal fires occur much more frequently, and high-severity fires much more rarely. The charcoal record in our study, which records fire events of various severities at variable distances from the lake edge, produced a similar return interval (66-117 years), although it is likely that fires of moderate to high severity were preferentially represented in the charcoal record over low-severity fires due to the disagreement between the contemporary fire record as seen in the tree-ring data and the charcoal record for the 20<sup>th</sup> century.

Mixed-severity fires are typically considered as producing high levels of internal heterogeneity due to the mosaic of overlapping burns of various intensities (Arno et al. 2000; Heyerdahl et al. 2012). This complexity, a feature that makes areas experiencing mixed-severity fires ecologically significant, presents a challenge for those in forest management positions who need to address the variability of the fire regime on both short and long temporal and spatial scales (Lertzman et al. 1998).

### 3.6.2 *Wildfire Controls*

Few patterns emerge when comparing fire activity to topographic and geomorphic indicators. The site-level fire types identified through the tree-ring analysis revealed fires of varying severities within all ranges of slope and aspect. These results indicate that local topographic features are not of greatest importance in controlling the severity of fire activity at our sites. The period of greatest change in sedimentary inputs (decline in organic content, rise in carbonates) revealed in the loss-on-ignition record (55-66 cm) may, however, be related to an increase in fire activity and erosional inputs that occurs only slightly earlier in the record. The relative stability of the LOI record throughout the remainder of the core suggests that factors other than fire activity are generally more important in controlling sediment composition (e.g. flooding event or erosion due to other causes).

Wildfire activity and vegetation change throughout the sediment record agrees well qualitatively with regional climatic activity throughout the late Holocene, suggesting that climate is a significant driver of fire behaviour (as in Hallett and Hills 2006). The beginning of the charcoal record, starting around 3,600 years BP, has the longest fire return intervals on record, indicative of a comparatively low fire frequency. Hallett and Hills (2006), in their study of fire-climate-vegetation dynamics in southeastern British Columbia, found evidence of moist/cool conditions occurring around 4,500-2,400 years BP in the form of less frequent fire events, a shift toward closed canopy species, and higher charophyte-inferred lake levels. Similar to our study, Hallett and Hills (2006) also found that fire activity increased towards present, especially in the period from 2,400-1,200 years BP (lower lake levels, open-canopy species). Cumming et al. (2002) found

evidence for millennial scale shifts in climate from changes in diatom assemblages in Big Lake, Caribou Plateau, British Columbia. In their work, they found evidence of glacial expansion during periods from 3,770-2,300 cal years BP and 1,140-present (Cumming et al. 2002). The cooler conditions necessitated by glacial expansion would most likely cause a suppression in fire activity, the timing of which corresponds well to our charcoal and pollen records; fire events were less frequent at the start and end of the sedimentary record, with a tendency towards more wet/closed canopy species during these periods. Power et al. (2011) found evidence of an increase in fire frequency from 5,000 cal years BP towards present in the northern Rocky Mountains at low elevations (<1,500 masl; an elevation comparable to Little Trefoil Lake) as a result of changes in solar insolation. Their sediment record agreed with other regional records of climate change that indicate drought-like conditions between 1,200-800 cal years BP (Power et al. 2011). Finally, in their review of global biomass burning over the past 10,000 years, Marlon et al. (2013) observed a large-scale pattern of increased fire activity between 3,000 and 2,000 years BP. This regional synchronicity is indicative of a top-down control, such as climate, driving fire activity.

The period of highest fire activity found in the Little Trefoil Lake record corresponds with the timing of the Medieval Climate Anomaly (MCA; 1,300-900 years BP) in the region (Luckman and Wilson 2005). It is likely that warmer and drier conditions led to the most frequent fire activity of the record during and immediately following the MCA. During this period, there is a general increase in the ratio of pollen types indicative of dry/open canopy conditions from pollen types typical of wet/closed conditions. The synchronicity between changes in fire activity, vegetation composition,

and inferred climatic change suggests that fire and vegetation were being controlled by climate, as the two share climate as an over-arching factor. It is likely, though, that fire-vegetation dynamics mediated their respective responses to changes in climate; a shift towards a more open canopy during more frequent fire events could indicate that fire facilitated the establishment of dry-tolerant species.

Following the period of maximum fire activity, around 500 years BP, the FRI began to increase suggesting less frequent fires, likely in response to the onset of Little Ice Age (LIA) conditions. An increase in inferred biomass occurs during the same period. Evidence of glacial activity and tree line advance during this time supports our climate-based interpretations (Figure 12). Luckman and Wilson (2005) found evidence of a warm interval during the 12<sup>th</sup>-14<sup>th</sup> centuries (800-600 years BP) and a period of cold from ~550 to 150 years BP (Luckman and Wilson 2005). Dated glacial moraines in the region indicate that many glaciers reached their maximum extents during the 18<sup>th</sup> and mid to late 19<sup>th</sup> century (Luckman and Kearney 1986). Maximum glacier advances suggest that the onset of cool/moist conditions occurred sometime before these periods due to the time required for glaciers to accumulate the positive mass balance required to reach their maximum extent.

When comparing shifts in the bCHAR record to inferred canopy dominance from the pollen record, an interesting relationship emerges. Background charcoal varies through time with an average periodicity of ~516 years, with periods of higher bCHAR generally corresponding with lower canopy ratio values (closed canopy dominance), and periods of lower bCHAR lining up with periods of inferred open canopy dominance. That changes in the pollen canopy ratio (based on PAR values) and in bCHAR tend to occur at

similar times may indicate that background charcoal is most strongly influenced by biomass availability, which would be higher under closed canopy conditions. It has been demonstrated that modern PAR values occur in relation to biomass abundance (Seppä et al. 2009), and it has been suggested that closed forest with abundant fuels produce greater levels of background charcoal than open forest or grasslands (Whitlock et al. 2003). While the effects of climate appear to be an important factor controlling fire frequency on a long-term scale, vegetation, through oscillations in biomass availability, is also important part of the fire regime. Increases in biomass during the LIA identified in our record may have facilitated the period of heightened tree-ring inferred fire activity in the late 19<sup>th</sup> and early 20<sup>th</sup> centuries identified in this study and others (Tande 1979). Looking at the most recent period of the fire sediment record (past 200 years), it interesting to note that both inferred biomass and the FRI are at a maximum, despite rapidly warming temperatures over this time that would be expected to cause more frequent fires and a decline in biomass abundance.

A possible driving mechanism behind the timing of fire events lies in the large-scale atmospheric circulation patterns that cause deviations in climate over periods of several decades. Studies have suggested that climatic oscillations from warm/dry to cool/wet conditions can result in heightened fire activity as cool periods encourage biomass growth and warm periods help to dry fuel (Westerling et al. 2006). The Pacific Decadal Oscillation (PDO) is a measure of aberrations in mean sea surface temperature and it influences the atmospheric circulation of North America in part by influencing the position of storm tracks and the jet stream. Positive PDO events have been noted as contributing to warmer and drier conditions in northwestern North America due to

atmospheric blocking events that divert the storm track to the south (Schoennagel et al. 2005; Gedalof et al. 2005). Schoennagel et al. (2005) found a positive relationship between fire activity and PDO phase in Jasper National Park with more large fire events occurring during positive PDO phases, when conditions are warmer and drier.

### *3.6.3 Contemporary Fire Activity*

It is noteworthy that the most contemporary portion of the charcoal record shows relatively low fire activity following the large peak of the early 20<sup>th</sup> century. This decline in fire activity is in spite of observations that current temperatures are among the warmest in the past 1,000 years (Luckman and Wilson 2005), a general increase in biomass burning in the boreal forest (Kelly et al. 2013), and predictions of dramatic increases in fire activity over the next century (Flannigan et al. 2013). While still within the range of variability seen in the past (a similar FRI, around 120 years/fire, was found in the earliest part of the record), inferred biomass, the FRI, and the pollen ratio are dissimilar to what occurred during past periods of similarly warm and dry conditions, such as the Medieval Climate Anomaly. For an appropriate explanation it is necessary to look at the influence of humans on the landscape around Little Trefoil Lake. Active fire management in Jasper National Park began in 1913, and although current fire management includes improved strategies such as prescribed burning and fuel management, practices of fire suppression and exclusion are not far in the past. Little Trefoil Lake is within only a few of hundred meters of the Jasper Park Lodge, which was built in 1921, but occupied earlier by settlers in what has been referred to as a “tent city” (Parks Canada 2013). The lodge itself, which burned down in 1951 and rebuilt a year later, would have been from the beginning of the

settlement era, if not before, an area worth protecting from wildfires. A possible result of this would be that during the last century fires have either been suppressed or contained enough to prevent the large convective plume necessary to transport significant amounts of charcoal into the lake.

The decline in contemporary fire activity lends an interesting comparison to fire activity during past warm/dry periods. If we were to use climate, fire activity, and vegetation in the MCA as an analogue for the present (as in Hallett and Hills, 2006; Kelly et al. 2013), we should expect that fire activity in the most contemporary portion of the record would be heightened. This is not the case however, due to several possibilities. Because fire activity is mediated by humans as well as vegetation composition and climate, it is possible that human activity has suppressed fire activity through past forest management activities and land use change. A regionally variable decline in biomass burning during and after the late 19<sup>th</sup> century due to land use conversion and other landscape effects has been observed (Marlon et al. 2008; Marlon et al. 2013). A second possibility for the decline of fire activity around Little Trefoil Lake could be a lagged response in the fire regime to changes in climate. Observed fire activity, which is determined by many factors, does not necessarily respond immediately to environmental changes, and it is also possible that climatic changes have not yet reached the threshold necessary to illicit a change in fire activity. Further studies that combine information from lakes across the region could help to better identify the mechanisms responsible for the present decline in wildfires.

### 3.7 Conclusion

The long-term record of fire events around Little Trefoil Lake shows a close association between climate parameters and charcoal accumulation, indicating that fire activity is largely controlled by changes in climate. Vegetation composition has changed little throughout the sediment record, but the ratio of pollen types representing dry/open canopy species to pollen types representing wet/closed canopy species does appear to respond to inferred changes in climate and supports our interpretation of climate as the main driver of fire activity. The absence of significant charcoal peaks in the sediment record during the last century may indicate that the influence of humans has over-ridden climate controls on fire activity.

The contemporary, tree-ring based fire record shows evidence of a mixed-severity fire regime in the area surrounding Little Trefoil Lake. This type of fire activity, which results in high spatial heterogeneity, is ecologically significant and makes facing the challenges associated with managing forests for this type of fire regime all the more important. A tendency towards landscape homogenization, if not addressed, could reduce forest resilience, making the landscape less adaptable to predicted changes in climate and fire activity over the next century.

## CHAPTER FOUR

### CONCLUSIONS

The focus of this research was to develop a long-term fire history record for the area surrounding Little Trefoil Lake near Jasper, AB, Canada. Two lake sediment cores, a 40 cm gravity core and an overlapping 3 m long Livingstone piston core were collected from the centre of Little Trefoil Lake and were analyzed for evidence of fire activity and changes in vegetation composition through time. A 3,500-year record of wildfires, vegetation, and sedimentary characteristics was established to help determine the controlling factors on fire activity in the watershed surrounding Little Trefoil. Changes in the sediment record were compared to regional climate activity that may have acted as a top-down control on fire activity. By comparing the modern period of the sediment record with what has occurred in the past, it is possible to determine if fire activity, which is presently strongly influenced by human behaviour, is within the range of variability of what has occurred in the past. Fire activity during the past few centuries was characterized by performing a dendrochronological analysis on trees up to 6 km from the edge of the lake. At a total of 12 sites, stand establishment data and fire scar analysis aided the interpretation of the present fire regime of the lake's watershed.

The results of the macroscopic charcoal analysis showed a fairly high variability in the frequency of fire events through time with fire return intervals ranging from 66-117 years. The periods of least fire activity occurred at the beginning and ends of the sediment record, with fires being most frequent around 500 years BP. A comparison between fire activity and the pollen record revealed a coupled response between vegetation canopy type (dry/open vs. wet/closed) and fire events through time, suggesting

that both are being influenced by the same top-down factor. Changes in both records appear to agree well with inferred changes in climate from throughout the region over the past 4,000 years, and support the interpretation that climate is the most important influence on fire activity. During the past two centuries, fire events recorded in the charcoal record are fairly infrequent, despite contemporary changes in climate that have raised temperatures in the region above what has occurred during the past millennia (Luckman and Wilson 2005). A possible explanation for this lies in the influence of human activity on the landscape; the timing of this decline in fire activity corresponds well with the settlement era of the Jasper town site, where Little Trefoil Lake is located (Tande 1979). It is probable that changes in land use, as well as fire suppression activities, have excluded the occurrence of moderate-large severity fires in the Jasper town site that are captured in the charcoal record.

Other variables measured in the sediment record (LOI, magnetics) show little change through time in response to either fire activity or climate, however an exception to this is the variability in the background charcoal component (bCHAR). Background charcoal, which is related to the amount of biomass on the landscape (since relatively more background charcoal is produced when there is more biomass available; Whitlock et al. 2003), appears to oscillate at a fairly regular interval of 516 years. Increases in inferred biomass tend to occur during periods of closed canopy dominance, whereas shifts towards an open canopy cause a reduction in biomass. This close association between biomass and canopy openness suggests that while climate is the dominant factor controlling the characteristics of both fire and vegetation, there still exists an important relationship between the two. In the most contemporary portion of the record, both

biomass and FRI are at a local peak, indicating that the landscape could presently be highly flammable. Land use change caused by human activities is a probable explanation during this period of the record, as land clearing for settlement and active fire suppression tend to reduce biomass burning.

The tree-ring analyses of the 12 sites around Little Trefoil Lake have provided useful information regarding the fire regime of the last few centuries. The combination of low and high-severity fires on the landscape, as inferred from stand establishment and fire scar data, has led to the conclusion that the watershed surrounding Little Trefoil Lake has been experiencing a mixed-severity fire regime over at least the past few hundred years. This type of fire regime, which encompasses fires of varying severities, is a source of landscape level heterogeneity, a contributing factor to forest stand health and resilience. All of the high-severity, stand replacing fires, however, occurred around the turn of the 20<sup>th</sup> century. This, combined with our interpretation of the recent changes in the background charcoal component of the sediment record, would indicate that forests in the watershed are becoming more dense but are not burning as frequently as would be expected given the rapid climate warming of last 100 years. The effect of this could be a greater potential for large, and potentially dangerous fires to occur in the near future. These findings suggest that the forest around Little Trefoil Lake should be actively managed for both low and high severity fires in order to maintain the ecologically significant characteristics of mixed-severity fire regimes.

Several avenues for future research have developed from the findings presented here:

1. It is recommended that additional high-resolution sedimentary charcoal records be developed for the Jasper region. This would provide insight into the synchronicity of fire activity in the area as well as a better understanding about the relative influences of top-down vs. bottom-up controls on fire activity. Since Jasper is located in a topographically complex region, more records would better encompass historical variability that could be related to landscape heterogeneity. An analysis performed on a control lake, located away from the most significant effects of human land use change, would help to better identify if the current suppression in fire activity is a result of human activities.

2. A sedimentary analysis focused on comparing known fire activity to the charcoal record could reveal interesting information about the size/distance relationship between fire events and those recorded in the sediment record. While this study shows that the majority of fires recorded in the sediment record are likely either low-severity fires very close to the lake's edge, or large fires at varying distances, the detailed observational record of wildfires that exists for Jasper presents an opportunity for better understanding what types of fires are being recorded in the charcoal record. This information would be useful for macroscopic charcoal studies elsewhere, and would help to create a more robust record of fire events in Jasper.

3. While the pollen analysis in this study revealed few significant changes throughout the study record, a high-resolution analysis would reveal more information about the relationship between vegetation and fire. Comparing past relationships between pollen (vegetation composition) and charcoal (fire activity) to what is presently occurring

would enhance our understanding of fire-vegetation dynamics. It could also provide insight into the ability of fire to act as a catalyst for changes in vegetation composition.

4. Time-series analysis performed on the sediment charcoal, magnetic susceptibility, and loss-on-ignition records could help to better constrain some of the factors driving fire activity in the Jasper region.

## Bibliography

- Ali, A., C. Carcaillet, and Y. Bergeron. 2009. "Long-Term Fire Frequency Variability in the Eastern Canadian Boreal Forest: The Influences of Climate vs. Local Factors." *Global Change Biology* 15 (5) (May): 1230–1241.
- Amoroso, M. M., L. D. Daniels, M. Bataineh, and D. W. Andison. 2011. "Evidence of Mixed-Severity Fires in the Foothills of the Rocky Mountains of West-Central Alberta, Canada." *Forest Ecology and Management* 262 (12) (December): 2240–2249.
- Arno, S. F. 1980. "Forest Fire History in the Northern Rockies." *Journal of Forestry* 78 (8): 460–465.
- Arno, S. F., D. J. Parsons, and R. E. Keane. 2000. "Mixed-Severity Fire Regimes in the Northern Rocky Mountains : Consequences of Fire Exclusion and Options for the Future." *USDA Forest Service Proceedings* 5 (15): 225–232.
- Arno, S. F., and K. M. Sneck. 1977. "A Method for Determining Fire History in Coniferous Forests of the Mountain West - Technical Report INT-42."
- Baisan, C. H., and T. W. Swetnam. 1990. "Fire History on a Desert Mountain Range: Rincon Mountain Wilderness, Arizona, U.S.A." *Canadian Journal of Forest Research* 20: 1559–1569.
- Bamber, R. N. 1982. "Sodium Hexametaphosphate as an Aid in Benthic Sample Sorting." *Marine Environmental Research* 7: 251–255.
- Beer, R., O. Heiri, and W. Tinner. 2007. "Vegetation History, Fire History and Lake Development Recorded for 6300 Years by Pollen, Charcoal, Loss on Ignition and Chironomids at a Small Lake in Southern Kyrgyzstan (Alay Range, Central Asia)." *The Holocene* 17 (7) (November 1): 977–985.
- Beaudoin, A. B., and R. H. King. 1990. "Late Quaternary vegetation history of Wilcox Pass, Jasper National Park, Alberta." *Palaeogeography, Palaeoclimatology, Palaeoecology* 80: 129-144
- Binford, M. W. 1990. "Calculation and Undertainty Analysis of 210Pb Dates for PIRLA Project Lake Sediment Cores." *Journal of Paleolimnology* 3: 253–267.
- Blais, J. M., and J. Kalff. 1995. "The Influence of Lake Morphometry on Sediment Focusing." *Limnology and Oceanography* 40 (3): 582–588.
- Bourgeau-Chavez, L., and M. Alexander. 2000. "Distribution of Forest Ecosystems and the Role of Fire in the North American Boreal Region." In *Fire, Climate Change,*

- and Carbon Cycling in the Boreal Forest*, edited by Eric S. Kasischke and Brian J. Stocks, 111–131. New York: Springer-Verlag.
- Bowman, D., J. Balch, P. Artaxo, W. Bond, M. Cochrane, C. M. D'Antonio, R. Defries, et al. 2011. "The Human Dimension of Fire Regimes on Earth." *Journal of Biogeography* 38 (12) (December): 2223–2236.
- Brunelle, A., and C. Whitlock. 2003. "Postglacial Fire, Vegetation, and Climate History in the Clearwater Range, Northern Idaho, USA." *Quaternary Research* 60 (3) (November): 307–318.
- Brunelle, A., C. Whitlock, P. J. Bartlein, and K. F. Kipfmüller. 2005. "Holocene Fire and Vegetation along Environmental Gradients in the Northern Rocky Mountains." *Quaternary Science Reviews* 24 (20-21) (November): 2281–2300.
- Campbell, C. 1998. "Late Holocene Lake Sedimentology and Climate Change in Southern Alberta, Canada." *Quaternary Research* 49: 96 - 101.
- Campbell, I., and M. D. Flannigan. 2000. "Long-Term Perspectives on Fire-Climate-Vegetation Relationships in the North American Boreal Forest." In *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, edited by Eric S. Kasischke and Brian J. Stocks, 151–172. New York: Springer-Verlag.
- Carcaillet, C., Y. Bergeron, P. Richard, B. Fréchette, S. Gauthier, and Y. T. Prairie. 2001. "Change of Fire Frequency in the Eastern Canadian Boreal Forests during the Holocene: Does Vegetation Composition or Climate Trigger the Fire Regime?" *Journal of Ecology* 89: 930–946.
- Carter, V., A. Brunelle, T. Minckley, P. E. Dennison, and M. J. Power. 2013. "Regionalization of Fire Regimes in the Central Rocky Mountains, USA." *Quaternary Research* 80 (3) (November): 406–416.
- Chandler, C., P. Cheney, P. Thomas, L. Trabaud, and D. Williams. 1983. *Fire in Forestry*. John Wiley & Sons, Ltd.
- Clark, J. S. 1988. "Particle Motion and the Theory of Charcoal Analysis: Source Area, Transport, Deposition, and Sampling." *Quaternary Research* 30 (1) (July): 67–80.
- Clark, J. S., J. Lynch, B. J. Stocks, and J. G. Goldammer. 1998. "Relationships between Charcoal Particles in Air and Sediments in West-Central Siberia." *The Holocene* 8 (1): 19–29.
- Clark, J. S., and P. D. Royall. 1996. "Local and Regional Sediment Charcoal Evidence for Fire Regimes in Presettlement North-Eastern North America." *Journal of Ecology* 83 (3): 365–382.

- Clark, T. L., L. Radke, J. Coen, and D. Middleton. 1999. "Analysis of Small-Scale Convective Dynamics in a Crown Fire Using Infrared Video Camera Imagery." *Journal of Applied Meteorology* 38: 1401–1420.
- Conedera, M., W. Tinner, C. Neff, M. Meurer, A. F. Dickens, and P. Krebs. 2009. "Reconstructing Past Fire Regimes: Methods, Applications, and Relevance to Fire Management and Conservation." *Quaternary Science Reviews* 28 (March): 555–576.
- Connor, S. E., J. F. N. van Leeuwen, T. M. Rittenour, W. O. van der Knaap, B. Ammann, and S. Björck. 2012. "The Ecological Impact of Oceanic Island Colonization - a Palaeoecological Perspective from the Azores." *Journal of Biogeography* 39 (6) (June 23): 1007–1023.
- Courtney Mustaphi, C. J. 2013. "A landscape-scale assessment of Holocene fire regime controls in south-eastern British Columbia, Canada". Department of Earth Sciences, Carleton University.
- Courtney Mustaphi, C. J., and M. F. J. Pisaric. 2013. "Varying Influence of Climate and Aspect as Controls of Montane Forest Fire Regimes during the Late Holocene, South-Eastern British Columbia, Canada." Edited by Jack Williams. *Journal of Biogeography* 40 (May 3): 1983–1996. doi:10.1111/jbi.12143. <http://doi.wiley.com/10.1111/jbi.12143>.
- Courtney Mustaphi, C. J., and M. F. J. Pisaric. 2014. "Holocene Climate–fire–vegetation Interactions at a Subalpine Watershed in Southeastern British Columbia, Canada." *Quaternary Research* 81 (2) (January): 228–239.
- Cumming, B. F., K. R. Laird, J. R. Bennett, J. P. Smol, and A. K. Salomon. 2002. "Persistent Millennial-Scale Shifts in Moisture Regimes in Western Canada during the Past Six Millennia." *Proceedings of the National Academy of Sciences of the United States of America* 99 (25) (December 10): 16117–116121.
- Cwynar, L. C. 1978. "Recent History of Fire and Vegetation from Laminated Sediment of Greenlead Lake, Algonquin Park, Ontario." *Canadian Journal of Botany* 56: 10–21.
- Cyr, D., S. Gauthier, Y. Bergeron, and C. Carcaillet. 2009. "Forest Management Is Driving the Eastern North American Boreal Forest Outside Its Natural Range of Variability." *Frontiers in Ecology and the Environment* 7 (10) (December): 519–524.
- Dale, V. H., L. A. Joyce, S. McNulty, R. P. Neilson, M. P. Ayres, M. D. Flannigan, P. J. Hanson, et al. 2001. "Climate Change and Forest Disturbances." *BioScience* 51 (9): 723–734.

- Davis, M. B. 2000. "Palynology After Y2K — Understanding the Source Area of Pollen in Sediments." *Annual Review Earth Planetary Science* 28: 1–18.
- Day, R. J. 1972. "Stand Structure, Succession, and Use of Southern Alberta's Rocky Mountain Forest." *Ecology* 53 (3): 472–478.
- Dean, W. E. Jr. 1974. "Determination of Carbonate and Organic Matter in Calcareous Sediments and Sedimentary Rocks by Loss on Ignition: Comparison with Other Methods." *Journal of Sedimentary Petrology* 44 (1): 242–248.
- Dearing, J. A. 1983. "Changing Patterns of Sediment Accumulation in a Small Lake in Scania, Southern Sweden." *Hydrobiologia* 103: 59–64.
- Edwards, T. W. D., B. H. Luckman, and G. M. MacDonald. 2008. "Climatic and hydrologic variability during the past millennium in the eastern Rocky Mountains and northern Great Plains of western Canada." *Quaternary Research* 70: 188–197.
- Enache, M., and B. F. Cumming. 2006. "Tracking Recorded Fires Using Charcoal Morphology from the Sedimentary Sequence of Prosser Lake, British Columbia (Canada)." *Quaternary Research* 65 (2) (March): 282–292.
- Enache, M., and B. F. Cumming. 2007. "Charcoal Morphotypes in Lake Sediments from British Columbia (Canada): An Assessment of Their Utility for the Reconstruction of Past Fire and Precipitation." *Journal of Paleolimnology* 38 (3) (April 24): 347–363.
- Enache, M., and B. F. Cumming. 2009. "Extreme Fires under Warmer and Drier Conditions Inferred from Sedimentary Charcoal Morphotypes from Opatcho Lake, Central British Columbia, Canada." *The Holocene* 19 (6) (August 14): 835–846.
- Environment Canada. 2013. "Canadian Climate Normals."
- Fægri, K., and J. Iversen. 1989. *Textbook of Pollen Analysis*. IV. John Wiley & Sons, Ltd.
- Flannigan, M. D., A. S. Cantin, W. J de Groot, M. Wotton, A. Newbery, and L. M. Gowman. 2013. "Global Wildland Fire Season Severity in the 21st Century." *Forest Ecology and Management* 294 (April): 54–61.
- Flannigan, M. D., K. Logan, B. D. Amiro, W. R. Skinner, and B. J. Stocks. 2005. "Future Area Burned in Canada." *Climatic Change* 72 (September): 1–16.
- Flannigan, M. D., B. J. Stocks, M. Turetsky, and M. Wotton. 2009. "Impacts of Climate Change on Fire Activity and Fire Management in the Circumboreal Forest." *Global Change Biology* 15 (March): 549–560.

- Flannigan, M. D., B. J. Stocks, and M. Wotton. 2000. "Climate Change and Forest Fires." *The Science of the Total Environment* 262: 221–229.
- Flannigan, M. D., and C. E. Van Wagner. 1990. "Climate Change in Wildfire in Canada." *Canadian Journal of Forest Research* 21: 66–72.
- Fritts, H. C. 1976. *Tree Rings and Climate*. San Diego, California: Academic.
- Gavin, D. G., F. S. Hu, K. P. Lertzman, and P. Corbett. 2006. "Weak Climatic Control of Stand-Scale Fire History during the Late Holocene." *Ecology* 87 (7): 1722–1732.
- Gedalof, Z., D. L. Peterson, and N. J. Mantua. 2005. "Atmospheric, Climatic, and Ecological Controls on Extreme Wildfire Years in the Northwestern United States." *Ecological Applications* 15 (1): 154–174.
- Gillett, N. P., A. J. Weaver, F. W. Zwiers, and M. D. Flannigan. 2004. "Detecting the Effect of Climate Change on Canadian Forest Fires." *Geophysical Research Letters* 31 (L18211): 1–4.
- Glew, J. R., J. P. Smol, and W. M. Last. 2001. "Sediment Core Collection and Extrusion." *Tracking Environmental Change Using Lake Sediments*: 73–105.
- Grimm, E. C. 1987. "CONISS: A Fortran 77 Program for Stratigraphically Constrained Cluster Analysis by the Method of Incremental Sum of Squares." *Computers & Geosciences* 13 (1): 13–35.
- Grissino-Mayer, H. D. 2001a. "FHX2- Software for Analyzing Temporal and Spatial Patterns in Fire Regimes from Tree Rings." *Tree-Ring Research* 57 (1): 115–124.
- Grissino-Mayer, H. D. 2001b. "Evaluating Crossdating Accuracy: A Manual and Tutorial for the Computer Program COFECHA." *Tree-Ring Research* 57 (2): 205–221.
- Gutsell, S. L., and E. A. Johnson. 1996. "How Fire Scars Are Formed: Coupling a Disturbance Process to Its Ecological Effect." *Canadian Journal of Forest Research* 26: 166–174.
- Hall, R. I., and J. P. Smol. 1993. "The Influence of Catchment Size on Lake Trophic Status during the Hemlock Decline and Recovery (4800 to 3500 BP) in Southern Ontario Lakes." *Hydrobiologia* 269/270: 371–390.
- Hallett, D. J., and L. V. Hills. 2006. "Holocene Vegetation Dynamics, Fire History, Lake Level and Climate Change in the Kootenay Valley, Southeastern British Columbia, Canada." *Journal of Paleolimnology* 35 (February): 351–371.

- Hallett, D. J., R. W. Mathewes, and R. C. Walker. 2003. "A 1000-Year Record of Forest Fire, Drought and Lake-Level Change in Southeastern British Columbia, Canada." *The Holocene* 13 (5): 751–761.
- Hallett, D. J., and R. C. Walker. 2000. "Paleoecology and Its Application to Fire and Vegetation Management in Kootenay National Park , British Columbia." *Journal of Paleolimnology* 24: 401–414.
- Heiri, O., A. Lotter, and G. Lemcke. 2001. "Loss on Ignition as a Method for Estimating Organic and Carbonate Content in Sediments: Reproducibility and Comparability of Results." *Journal of Paleolimnology* 25: 101–110.
- Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2001. "Spatial Controls of Historical Fire Regimes: A Multiscale Example From the Interior West, Usa." *Ecology* 82 (3): 660–678.
- Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2002. "Annual and Decadal Climate Forcing of Historical Fire Regimes in the Interior Pacific Northwest, USA." *The Holocene* 12 (5) (September 1): 597–604.
- Heyerdahl, E. K., R. F. Miller, and R. A. Parsons. 2006. "History of fire and Douglas-fir establishment in a savanna and sagebrush-grassland mosaic, southwestern Montana, USA." *Forest Ecology and Management* 230: 107-118.
- Heyerdahl, E. K., K. P. Lertzman, and C. M. Wong. 2012. "Mixed-Severity Fire Regimes in Dry Forests of Southern Interior British Columbia, Canada." *Canadian Journal of Forest Research* 42: 88–98.
- Higuera, P. 2009. "CharAnalysis 0.9 : Diagnostic and Analytical Tools for Sediment-Charcoal Analysis - User's Guide."
- Higuera, P., L. B. Brubaker, P. M. Anderson, F. S. Hu, and T. A. Brown. 2009. "Vegetation Mediated the Impacts of Postglacial Climate Change on Fire Regimes in the South-Central Brooks Range, Alaska." *Ecological Monographs* 79 (2): 201–219.
- Higuera, P., D. G. Gavin, P. J. Bartlein, and D. J. Hallett. 2010. "Peak Detection in Sediment–charcoal Records: Impacts of Alternative Data Analysis Methods on Fire-History Interpretations." *International Journal of Wildland Fire* 19: 996–1014.
- Higuera, P., C. Whitlock, and J. A. Gage. 2010. "Linking Tree-Ring and Sediment-Charcoal Records to Reconstruct Fire Occurrence and Area Burned in Subalpine Forests of Yellowstone National Park, USA." *The Holocene* 21 (2) (October 15): 327–341.

- Hilton, J. 1985. "A Conceptual Framework for Predicting the Occurrence of Sediment Focusing and Sediment Redistribution in Small Lakes." *Limnology and Oceanography* 30 (6): 1131–1143.
- Holmes, R. L. 1983. "Computer-Assisted Quality Control in Tree-Ring Dating and Measurement." *Tree-Ring Bulletin* 43 (1): 69–78.
- Jackson, S. T. 1990. "Pollen Source Area and Representation in Small Lakes of the Northeastern United States." *Review of Palaeobotany and Palynology* 63: 53–76.
- Jensen, K., E. A. Lynch, R. Calcote, and S. C. Hotchkiss. 2007. "Interpretation of Charcoal Morphotypes in Sediments from Ferry Lake, Wisconsin, USA: Do Different Plant Fuel Sources Produce Distinctive Charcoal Morphotypes?" *The Holocene* 17 (7): 907–915.
- Johnson, E. A., and G. I. Fryer. 1989. "Population Dynamics in Lodgepole Pine-Engelmann Spruce Forests." *Ecology* 70 (5): 1335–1345.
- Johnstone, J. F., F. S. Chapin, J. Foote, S. Kemmett, K. Price, and L. Viereck. 2004. "Decadal Observations of Tree Regeneration Following Fire in Boreal Forests." *Canadian Journal of Forest Research* 34: 267–273.
- Johnstone, J. F., E. J. B. McIntire, E. J. Pedersen, G. King, and M. F. J. Pisaric. 2010. "A Sensitive Slope: Estimating Landscape Patterns of Forest Resilience in a Changing Climate." *Ecosphere* 1 (6) (December): 1–21.
- Kasischke, E. S. 2000. "Boreal Ecosystems in the Global Carbon Cycle." In *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, edited by Eric S. Kasischke and Brian J. Stocks, 19–30. New York: Springer-Verlag.
- Kasischke, E. S., and M. Turetsky. 2006. "Recent Changes in the Fire Regime across the North American Boreal region—Spatial and Temporal Patterns of Burning across Canada and Alaska." *Geophysical Research Letters* 33 (9): L09703 1–5. doi:10.1029/2006GL025677. <http://doi.wiley.com/10.1029/2006GL025677>.
- Kelly, R., M. L. Chipman, P. Higuera, I. Stefanova, L. B. Brubaker, and F. S. Hu. 2013. "Recent Burning of Boreal Forests Exceeds Fire Regime Limits of the Past 10,000 Years." *Proceedings of the National Academy of Sciences of the United States of America* 110 (32) (August 6): 13055–60.
- Kelly, R., P. Higuera, C. M. Barrett, and F. S. Hu. 2011. "A Signal-to-Noise Index to Quantify the Potential for Peak Detection in Sediment–charcoal Records." *Quaternary Research* 75 (1) (January): 11–17.

- Kipfmüller, K. F., and W. L. Baker. 1998. "A Comparison of Three Techniques to Date Stand-Replacing Fires in Lodgepole Pine Forests." *Forest Ecology and Management* 104: 171–177.
- Kitzberger, T., P. M. Brown, E. K. Heyerdahl, T. W. Swetnam, and T. T. Veblen. 2007. "Contingent Pacific-Atlantic Ocean Influence on Multicentury Wildfire Synchrony over Western North America." *Proceedings of the National Academy of Sciences of the United States of America* 104 (2) (January 9): 543–548.
- Kozak, S. A. 1998. "Lightning Strikes in Alberta Thunderstorms: Climatology and Case Studies". Department of Earth and Atmospheric Sciences, University of Alberta.
- Kug, J., S. An, Y. Ham, and I. Kang. 2010. "Changes in El Niño and La Niña Teleconnections over North Pacific–America in the Global Warming Simulations." *Theoretical and Applied Climatology* 100 (3-4) (August 12): 275–282.
- Larsen, C. 1996. "Fire and Climate Dynamics in the Boreal Forest of Northern Alberta, Canada, from AD 1850 to 1989." *The Holocene* 6 (4) (January 1): 449–456.
- Larsen, C. 1997. "Spatial and Temporal Variations in Boreal Forest Fire Frequency in Northern Alberta." *Journal of Biogeography* 24 (5): 663–673.
- Larsen, C., and G. M. Macdonald. 1993. "Lake Morphometry, Sediment Mixing and the Selection of Sites for Fine Resolution Palaeoecological Studies." *Quaternary Science Reviews* 12: 781–792.
- Lertzman, K. P., J. Fall, and B. Dorner. 1998. "Three Kinds of Heterogeneity in Fire Regimes: At the Crossroads of Fire History and Landscape Ecology." *Northwest Science* 72: 4–23.
- Long, C. J., Cathy W., P. J. Bartlein, and S. H. Millsbaugh. 1998. "A 9000-Year Fire History from the Oregon Coast Range, Based on a High-Resolution Charcoal Study." *Canadian Journal of Forest Research* 28 (5): 774–787.
- Lotan, J. E., J. K. Brown, and L. F. Neuenschwander. 1985. "Role of Fire in Lodgepole Pine Forests." In *Lodgepole Pine the Species and Its Management*, edited by D. Baumgartner, 133–152. Pullman: Washington State University.
- Luckman, B. H. 1986. "Reconstruction of Little Ice Age Events in the Canadian Rocky Mountains." *Géographie Physique et Quaternaire* XL (1): 17–28.
- Luckman, B. H., K. R. Briffa, P. D. Jones, and F. H. Schweingruber. 1997. "Tree-Ring Based Reconstruction of Summer Temperatures at the Columbia Icefield." *The Holocene* 7 (4): 375–389.

- Luckman, B. H., and M. S. Kearney. 1986. "Reconstruction of Holocene Changes in Alpine Vegetation and Climate in the Maligne Range, Jasper National Park, Alberta." *Quaternary Research* 26 (2) (September): 244–261.
- Luckman, B. H., and G. D. Osborn. 1979. "Holocene Glacier Fluctuations in the Middle Canadian Rocky Mountains." *Quaternary Research* 11: 52-77
- Luckman, B. H., and R. J. S. Wilson. 2005. "Summer Temperatures in the Canadian Rockies during the Last Millennium: A Revised Record." *Climate Dynamics* 24 (2-3) (January 21): 131–144.
- Lynch, J., J. S. Clark, and B. J. Stocks. 2004. "Charcoal Production, Dispersal, and Deposition from the Fort Providence Experimental Fire: Interpreting Fire Regimes from Charcoal Records in Boreal Forests." *Canadian Journal of Forest Research* 34 (8) (August): 1642–1656.
- MacDonald, G. M., C. Larsen, J. M. Szeicz, and K. A. Moser. 1991. "The Reconstruction of Boreal Forest History from Lake Sediments: A Comparison of Charcoal, Pollen, Sedimentological, and Geochemical Indices." *Quaternary Science Reviews* 10 (1991): 53–71.
- Mann, M. E. 2002. "Little Ice Age." In *Encyclopedia of Global Environmental Change*, edited by Dr. Michael C. MacCracken and Dr. John S. Perry, Volume 1 -, 1:504–509. Chichester: John Wiley & Sons, Ltd.
- Mantua, N. J., and S. R. Hare. 2002. "The Pacific Decadal Oscillation." *Journal of Oceanography* 58: 35–44.
- Marcoux, H. M., S. E. Gergel, and L. D. Daniels. 2013. "Mixed-Severity Fire Regimes : How Well Are They Represented by Existing Fire-Regime Classification Systems ?" *Canadian Journal of Forest Research* 43: 658–668.
- Marlon, J. R., P. J. Bartlein, C. Carcaillet, D. G. Gavin, S. P. Harrison, P. Higuera, F. Joos, M. J. Power, and I. C. Prentice. 2008. "Climate and Human Influences on Global Biomass Burning over the Past Two Millennia." *Nature Geoscience* 1 (10) (September 21): 697–702.
- Marlon, J. R., P. J. Bartlein, A. Daniau, S. P. Harrison, S. Y. Maezumi, M. J. Power, W. Tinner, and B. Vanni re. 2013. "Global Biomass Burning : A Synthesis and Review of Holocene Paleofire Records and Their Controls." *Quaternary Science Reviews* 65: 5–25.
- Marlon, J. R., P. J. Bartlein, D. G. Gavin, C. J. Long, R. S. Anderson, C. E. Briles, Kendrick J Brown, et al. 2012. "Long-Term Perspective on Wildfires in the Western USA." *Proceedings of the National Academy of Sciences of the United States of America* 109 (March 28): 535–543.

- Marlon, J. R., P. J. Bartlein, and C. Whitlock. 2006. "Fire-Fuel-Climate Linkages in the Northwestern USA during the Holocene." *The Holocene* 16 (8) (December 1): 1059–1071.
- Mcbride, J. R. 1983. "Analysis of Tree Rings and Fire Scars to Establish Fire History." *Tree-Ring Bulletin* 43: 51–67.
- McKenzie, D. M., Z. Gedalof, D. L. Peterson, and P. Mote. 2004. "Climatic Change, Wildfire, and Conservation." *Conservation Biology* 18 (4): 890–902.
- Mertens, K. N., A. M. Price, and V. Pospelova. 2012. "Determining the Absolute Abundance of Dinoflagellate Cysts in Recent Marine Sediments II: Further Tests of the Lycopodium Marker-Grain Method." *Review of Palaeobotany and Palynology* 184 (September): 74–81.
- Meyer, G. A., J. L. Pierce, S. H. Wood, and A. J. Jull. 2001. "Fire, Storms, and Erosional Events in the Idaho Batholith." *Hydrological Processes* 15 (October 30): 3025–3038.
- Millsbaugh, S. H., and C. Whitlock. 1995. "A 750-Year Fire History Based on Lake Sediment Records in Central Yellowstone National Park, USA." *The Holocene* 5 (3): 283–292.
- Moore, P. D., and J. A. Webb. 1978. *An Illustrated Guide to Pollen Analysis*. London: Hodder and Stroughton.
- Morris, J. L., A. Brunelle, R. J. Derosé, H. Seppä, M. J. Power, V. Carter, and R. Bares. 2013. "Using Fire Regimes to Delineate Zones in a High-Resolution Lake Sediment Record from the Western United States." *Quaternary Research* 79: 24–36.
- Murphy, P., J. Mudd, and B. J. Stocks. 2000. "Historical Fire Records in the North American Boreal Forest." In *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, edited by Eric S. Kasischke and Brian J. Stocks, 274–288. New York: Springer-Verlag.
- Nigh, G. D., and B. A. Love. 1999. "A Model for Estimating Juvenile Height of Lodgepole Pine." *Forest Ecology and Management* 123 (2-3) (November): 157–166.
- Ohlson, M., and E. Tryterud. 2000. "Interpretation of the Charcoal Record in Forest Soils: Forest Fires and Their Production and Deposition of Macroscopic Charcoal." *The Holocene* 10 (4): 519–525.
- Oliver, C., and B. C. Larson. 1996. *Forest Stand Dynamics*. John Wiley & Sons, Ltd.

- Osborn, G., and B. H. Luckman. 1988. "Holocene glacier fluctuations in the Canadian Cordillera (Alberta and British Columbia)." *Quaternary Science Reviews* 7: 115-128.
- Parks Canada. 2013. "Parks Canada - Jasper National Park." <http://www.pc.gc.ca/eng/pn-np/ab/jasper/visit/info-jasper.aspx>.
- Patterson, W. A., K. J. Edwards, and D. J. Maguire. 1987. "Microscopic Charcoal as a Fossil Indicator of Fire." *Quaternary Science Reviews* 6: 3–23.
- Payette, S. 1992. "Fire as a Controlling Process in the North American Boreal Forest." In *Systems Analysis of the Global Boreal Forest*, edited by Herman Shugart, Rik Leemans, and Gordon Bonan, 144–169. Cambridge University Press.
- Perry, D. A., P. F. Hessburg, C. N. Skinner, T. A. Spies, S. L. Stephens, A. H. Taylor, J. F. Franklin, B. McComb, and G. M. Riegel. 2011. "The Ecology of Mixed Severity Fire Regimes in Washington, Oregon, and Northern California." *Forest Ecology and Management* 262 (5) (September): 703–717.
- Peters, M. E., and P. Higuera. 2007. "Quantifying the Source Area of Macroscopic Charcoal with a Particle Dispersal Model." *Quaternary Research* 67: 304–310.
- Pisaric, M. F. J. 2002. "Long-Distance Transport of Terrestrial Plant Material by Convection Resulting from Forest Fires." *Journal of Paleolimnology* 28: 349–354.
- Power, M. J., C. Whitlock, and P. J. Bartlein. 2011. "Postglacial Fire, Vegetation, and Climate History across an Elevational Gradient in the Northern Rocky Mountains, USA and Canada." *Quaternary Science Reviews* 30 (19-20) (September): 2520–2533.
- Rhemtulla, J. M., R. J. Hall, E. S. Higgs, and S. E. Macdonald. 2010. "Eighty Years of Change : Vegetation in the Montane Ecoregion of Jasper National Park, Alberta, Canada." *Canadian Journal of Forest Research* 32: 2010–2021.
- Rhodes, A. N. 1998. "A Method for the Preparation and Quantification of Microscopic Charcoal from Terrestrial and Lacustrine Sediment Cores." *The Holocene* 8 (1): 113–117.
- Rhodes, T. E., and R. B. Davis. 1995. "Effects of Late Holocene Forest Disturbance and Vegetation Change on Acidic Mud Pond, Maine, USA." *Ecology* 76 (3): 734–746.
- Rodionov, S. N. 2005. "A Sequential Method for Detecting Regime Shifts in the Mean and Variance." In *Large-Scale Disturbances (regime Shifts) and Recovery in Aquatic Ecosystems: Challenges for Management toward Sustainability*, edited by V Velikova and N Chipev, 68–72. Varna, Bulgaria.

- Romme, W. H. 1982. "Fire and Landscape Diversity in Subalpine Forests of Yellowstone National Park." *Ecological Monographs* 52 (2): 199–221.
- Ropelewski, C. F., and M. S. Halpert. 1986. "North American Precipitation and Temperature Patterns Associated with the El Niño/Southern Oscillation (ENSO)." *Monthly Weather Review* 114: 2352–2362.
- Rozas, V. 2003. "Tree Age Estimates in *Fagus Sylvatica* and *Quercus Robur* : Testing Previous and Improved Methods." *Plant Ecology* 167: 193–212.
- Schoennagel, T., T. T. Veblen, and W. H. Romme. 2004. "The Interaction of Fire, Fuels, and Climate across Rocky Mountain Forests." *BioScience* 54 (7): 661–676.
- Schoennagel, T., T. T. Veblen, W. H. Romme, J. S. Sibold, and E. R. Cook. 2005. "ENSO and PDO Variability Affect Drought-Induced Fire Occurrence in Rocky Mountain Subalpine Forests." *Ecological Applications* 15 (5): 2000–2014.
- Seppä, H., T. Alenius, P. Muukkonen, T. Giesecke, P. A. Miller, and A. E. K. Ojala. 2009. "Calibrated Pollen Accumulation Rates as a Basis for Quantitative Tree Biomass Reconstructions." *The Holocene* 19 (2): 209–220.
- Shuman, B. 2003. "Controls on Loss-on-Ignition Variation in Cores from Two Shallow Lakes in the Northeastern United States." *Journal of Paleolimnology* 30: 371–385.
- Speer, J. H. 2010. *Fundamentals of Tree-Ring Research*. University of Arizona Press.
- Stockmarr, J. 1971. "Tablets with Spores Used in Absolute Pollen Analysis." In *Pollen et Spores*, 615–621.
- Stokes, M. A., and T. L. Smiley. 1968. *An Introduction to Tree-Ring Dating*. Chicago: University of Chicago Press.
- Sugita, S. 2007. "Theory of quantitative reconstruction of vegetation II: all you need is LOVE." *The Holocene* 17: 243–257
- Sutherland, E., W. W. Covington, and S. Andariese. 1991. "A Model of Ponderosa Pine Growth Response to Prescribed Burning." *Forest Ecology and Management* 44: 161–173.
- Swain, A. M. 1973. "A History of Fire and Vegetation in Northeastern Minnesota as Recorded in Lake Sediments." *Quaternary Research* 3: 383–396.
- Tande, G. D. 1979. "Fire History and Vegetation Pattern of Coniferous Forests in Jasper National Park, Alberta." *Canadian Journal of Botany* 57: 1912–1934.

- Taylor, A. H., and C. N. Skinner. 1998. "Fire History and Landscape Dynamics in a Late-Successional Reserve, Klamath Mountains, California, USA." *Forest Ecology and Management* 111: 285–301.
- Telford, R. J., E. Heegaard, and H. J. B. Birks. 2004. "The Intercept Is a Poor Estimate of a Calibrated Radiocarbon Age." *The Holocene* 14 (2) (March 1): 296–298.
- Terrier, A., M. P. Girardin, C. Périé, P. Legendre, and Y. Bergeron. 2013. "Potential Changes in Forest Composition Could Reduce Impacts of Climate Change on Boreal Wildfires." *Ecological Applications* 23 (1) (January): 21–35.
- Thompson, R., R. W. Battarbee, P. E. O'Sullivan, and F. Oldfield. 1975. "Magnetic Susceptibility of Lake Sediments." *Limnology and Oceanography* 20 (5): 687–698.
- Tinner, W., M. Conedera, B. Ammann, H. W. Gaggeler, S. Gedye, R. Jones, and B. Saggesser. 1998. "Pollen and Charcoal in Lake Sediments Compared with Historically Documented Forest Fires in Southern Switzerland since AD 1920." *The Holocene* 8 (1): 31–42.
- Tinner, W., S. Hofstetter, F. Zeugin, M. Conedera, T. Wohlgemuth, L. Zimmermann, F. Zeu, and R. Zweifel. 2006. "Long-Distance Transport of Macroscopic Charcoal by an Intensive Crown Fire in the Swiss Alps - Implications for Fire History Reconstruction." *The Holocene* 16 (2): 287–292.
- Traverse, A. 1988. *Paleopalynology*. Boston: Unwin Hyman.
- Turner, M. G., W. W. Hargrove, R. H. Gardner, and W. H. Romme. 1994. "Effects of Fire on Landscape Heterogeneity in Yellowstone National Park, Wyoming." *Journal of Vegetation Science* 5 (5): 731–742.
- Umbanhowar, C. E. Jr., and M. J. Mcgrath. 1998. "Experimental Production and Analysis of Microscopic Charcoal from Wood, Leaves and Grasses." *The Holocene* 8 (3): 341–346.
- Vance, R. E., R. W. Mathewes, and J. J. Clague. 1992. "7000 year record of lake-level change on the northern Great Plains: A high-resolution proxy of past climate." *Geology* 20: 879 - 992
- Viau, A. E., and K. Gajewski. 2009. "Reconstructing Millennial-Scale, Regional Paleoclimates of Boreal Canada during the Holocene." *Journal of Climate* 22: 316-330.
- Walsh, M. K., C. A. Pearl, C. Whitlock, P. J. Bartlein, and M. A. Worona. 2010. "An 11 000-Year-Long Record of Fire and Vegetation History at Beaver Lake, Oregon, Central Willamette Valley." *Quaternary Science Reviews* 29 (May): 1093–1106.

- Ward, P., and W. Mawdsley. 2000. "Fire Management in the Boreal Forests of Canada." In *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, edited by Eric S. Kasischke and Brian J. Stocks, 66–84. New York: Springer-Verlag.
- Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. "Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity." *Science* 313 (5789) (August 18): 940–943.
- Whitlock, C., and C. Larsen. 2001. "Charcoal as a Fire Proxy." In *Tracking Environmental Change Using Lake Sediments*, edited by John P. Smol and H.J.B. Birks, 3:75–97. Dordrecht, The Netherlands: Kluwer Academic Publishers.
- Whitlock, C., P. Higuera, D. B. McWethy, and C. E. Briles. 2010. "Paleoecological Perspectives on Fire Ecology : Revisiting the Fire-Regime Concept." *The Open Ecology Journal* 3: 6–23.
- Whitlock, C., and S. H. Millspaugh. 1996. "Testing the Assumptions of Fire-History Studies: An Examination of Modern Charcoal Accumulation in Yellowstone National Park, USA." *The Holocene* 6 (1): 7–15.
- Whitlock, C., S. L. Shafer, and J. Marlon. 2003. "The role of climate and vegetation change in shaping future fire regimes in the northwestern US and the implications for ecosystem management." *Forest Ecology and Management* 178: 5-21.
- Winkler, M. G. 1985. "Charcoal Analysis for Paleoenvironmental Interpretation: A Chemical Assay." *Quaternary Research* 23: 313–326.
- Wright, H. E., H. D. Mann, and H. P. Glaser. 1984. "Piston Corers for Peat and Lake Sediments." *Ecology* 65 (2): 657–659.