A Multiproxy Reconstruction of Mixed-severity Wildfire Dynamics in the Foothills of the Rocky Mountains, Alberta, Canada

by

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ABSTRACT

A MULTIPROXY RECONSTRUCTION OF MIXED-SEVERITY WILDFIRE DYNAMICS IN THE FOOTHILLS OF THE ROCKY MOUNTAINS, ALBERTA, CANADA

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Fire history reconstructions are key to contextualizing the recent and future impacts of humans and climate on changing wildfire regimes. The eastern Foothills of the Rocky Mountains in west-central Alberta, Canada, represent an ecotone between the montane cordillera and the boreal plains. While fire regimes of both biomes have been historically described as infrequent and high-severity, recent fire history studies in the montane cordillera have found historical evidence of mixed-severity fire regimes. The broad aim of this research was to reconstruct and contextualize the historical wildfire regime of this transitional landscape.

Modern wildfire records are often limited in length and may be misrepresentative of the natural disturbance regime due to management and fire exclusion practices. Because different paleoecological proxies record unique information about wildfire characteristics at different spatial and temporal scales, this research used a combination of tree-ring stand initiation, fire scar, and macroscopic sedimentary charcoal fire records to reconstruct the wildfire regime.

Results revealed historical regional evidence of mixed-severity fire regimes. Multi-scale evidence of high-severity fire, including regional pulses in establishment and stand-level cohort initiation, were found, as well as an abundance of fire scar evidence, suggesting low-severity fires were also present. Results indicated that many fire events were small and localized, sometimes affecting as little as a single tree. These results suggest a mixed-severity fire regime classification for this region. Evidence for large and severe fires was broadly coherent between tree-ring and sedimentary records, but was
less coherent for smaller and low severity fires.

This research concludes that typical fire event detection criteria bias fire history records against mixed-severity fire. In regions experiencing complex and variable fire activity, all fire evidence should be included in regime classification. Furthermore, this research concludes that climate is a weak driver of wildfire in this region, and local landscape characteristics that mediate fuel moisture are more important. This research also demonstrates the value of macroscopic sedimentary charcoal records to fire histories in the region. While macroscopic sedimentary charcoal records are not spatially explicit and have a coarse temporal resolution, they do provide a good indication of regional fire activity prior to the start of the tree-ring fire record in this region. This is especially important in mixed-severity regimes where the record of fire is often destroyed by subsequent high-severity fires.
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CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................ iv

CONTENTS .......................................................................................................................... v

LIST OF FIGURES .................................................................................................................. viii

LIST OF TABLES ..................................................................................................................... ix

CHAPTER 1: INTRODUCTION ................................................................................................. 1

1.1 Introduction ....................................................................................................................... 1
  1.1.2 Importance of fire history .......................................................................................... 2
  1.1.3 Role of climate ......................................................................................................... 4
  1.1.4 Role of landscape characteristics............................................................................. 4
1.2 Methodologies: Proxies ..................................................................................................... 5
  1.2.1 Tree-rings ............................................................................................................... 5
  1.2.2 Macroscopic sedimentary charcoal ....................................................................... 6
1.3 Study area: Rocky Mountain Foothills, Alberta, Canada .............................................. 6
1.4 Aim & hypotheses ............................................................................................................. 7
  1.4.1 Definitions of scale ................................................................................................. 8
1.5 Dissertation organization ................................................................................................. 8
1.6 References ....................................................................................................................... 9

CHAPTER 2: SENSITIVITY OF TREE-RING RECONSTRUCTED FOREST FIRE REGIMES TO DETECTION CRITERIA IN MIXED-SEVERITY LANDSCAPES ........................................................................................................... 15

2.1 Introduction ....................................................................................................................... 15
2.2 Methods ............................................................................................................................ 18
  2.2.1 Case study area ....................................................................................................... 18
  2.2.2 Site and sampling selection ............................................................................... 20
  2.2.3 Tree-ring data collection and analysis ................................................................ 20
  2.2.4 Fire regime classification ..................................................................................... 21
2.3 Results ............................................................................................................................... 22
LIST OF FIGURES

1.1 A schematic of landscape pattern of fire regimes ..................................................3

2.1 Study area, Eastern Foothills of the Rocky Mountains, Alberta, Canada ............19
2.2 Variability in mFRIs based on different detection criteria/filters ......................24
2.3 Regional binned stand establishment estimated dates .....................................25
2.4 Fire event detection filters & classification of fire regime ...............................27

3.1 Study area, eastern foothills of the Rocky Mountains, Alberta, Canada ..........40
3.2 Fire demography diagram ..............................................................................46
3.3 Regional static age-class distributions, stratified by species into 10-year bins ....47
3.4 Selected superposed epoch analysis (SEA) results ........................................49
3.5 Mean fire return intervals (mFRIs) versus sampling size (number of plots) ....51

4.1 Study area, eastern foothills of the Rocky Mountains, Alberta, Canada ..........66
4.2 Sampled lakes and surrounding landscape ......................................................67
4.3 Age-depth models of A) Lake PC and B) Lake ZS ........................................70
4.4 A) PC site and B) ZS site fire records .............................................................71
LIST OF TABLES

2.1 Number of fire events and mean fire return intervals (mFRIs) calculated for different event detection filters .................................................................................................................... 23
2.2 Tabulation of fire severity evidence for fire regime classification .......................... 26
3.1 Fire events, record length and mFRIs divided by sites and landscape controls ....... 49
4.1 Correspondence between proxy records ................................................................... 72
CHAPTER 1:
INTRODUCTION

1.1 Introduction
Landscapes are inherently heterogeneous and dynamic. Heterogeneity is a depiction of pattern that is influenced by many processes (Delcourt and Delcourt 1988, Forman 1995a, Lertzman and Fall 1998, Turner 2005, Wu and Hobbs 2007). Disturbance is a key process creating differential patterns on landscapes. Evidence of previous disturbances (pattern) left on the landscape can also influence future disturbances (Risser 1987, Turner 1989, Baker 1992, Forman 1995a&b). Together, these disturbance patterns and processes create landscape heterogeneity over time and space (Forman 1995a&b, Gustafson 1998, Kent 2007). Disturbances also vary over time and space; therefore disturbances are best described as regimes, descriptive sets of typical disturbance characteristics (e.g. frequency, extent, intensity, severity) (Agee 1998, Baker 2009b).

Wildfire is a prominent and important ecological disturbance in many landscapes (Falk et al. 2007, McKenzie et al. 2011). Wildfire changes species composition, cycles soil nutrients, and creates habitat for many species (Johnson 1992, Agee 1993, Brown 2000). Wildfire also impacts human landscapes and is thus actively managed in many regions (Bergeron et al. 1999, DeLong and Kessler 2000, Fenton et al. 2009). However, the stochastic nature of wildfire, as well as its temporal and spatial variability, makes understanding controlling mechanisms, and ultimately managing it, difficult. Historical fire records have been used to analyze fire controls and relationships, however, land management and fire exclusion have made the recent record of fires unrepresentative of the natural disturbance regime in many areas (Hunter 1993). Combined with the anticipated impacts of climate change on wildfire, managing wildfire-prone landscapes is difficult.

Fire regimes are most often classified according to their frequency and severity, a measure of the ecological impact of fire on an ecosystem (Agee 1998). High-severity fires are typically stand-replacing and have high mortality. At the stand scale, low-
severity fires impart minimal physical damage to mature trees and remove small and understory vegetation (Agee 1997 & 1998). Traditionally, fire research and management has been based on either stand origin or fire scar methods. Most commonly, stand origin and/or time-since-fire (TSF) maps have been used to estimate the fire cycle (frequency), and assume that all fires are high-severity. Fire scar based fire histories are used to reconstruct low-severity fires and are used to estimate the fire return interval. As a result, management of fire-prone ecosystems has discretely classified fire regimes as frequent, low-severity or infrequent, high-severity (Bergeron et al. 2004). However, more recent research shows that many wildfire regimes are mixed in severity.

Halofsky et al. (2011) highlight the difficulty in defining mixed-severity fire regimes. While mixed-severity fire regimes may experience both high- and low-severity fires, they may also be unique regimes that experience moderate-severity fires (Arno et al. 2000, Agee 2005), and these are often difficult to differentiate. For example, if a forest is composed of multiple species, which contains a fire adapted species (e.g. Douglas-fir (Pseudotsuga menziesii)), as well as non-fire adapted species, evidence of both low-severity and high-severity fire may be present for a single fire event of moderate-severity (Agee 2005). Furthermore, a single fire event does not burn homogeneously, but rather differential severity effects can be present across its extent (McKenzie et al. 2011). Partial stand replacement, with more than one post-fire cohort, is also possible. Mixed-severity fire regimes create unique landscape patterns; they contain patches of different shapes, sizes, and ages, with differing degrees of stand mortality (Figure 1.1) (Agee 1998). Because the fire regime concept is now understood as a spectrum from high-severity to low-severity, incorporating fire severity variation into fire histories is essential (Baker 2009a, Conedera et al. 2009, Whitlock et al. 2010).

1.1.2 Importance of fire history

Fire regimes are not static and vary over both time and space (Agee 1998, Baker 2009a, Conedera et al. 2009, Whitlock et al. 2010). Understanding how and why fire regimes have changed in the past is important for understanding how landscapes will respond to changes in the future (Bergeron et al. 2004, Baker 2009a). Paleoecological fire histories
provide information about the historical range of variability (HRV) of wildfire (Baker 2009a, Whitlock et al. 2010). It is imperative to know what drives variation in fire to anticipate the future.

Knowledge of the HRV and disturbance regimes, combined with modelling, will help to anticipate the ecological effects of fire and climate change (Delcourt and Delcourt 1988, Morgan et al. 2001, Bergeron et al. 2004). Ecosystems have experienced great changes in climate over the Earth's history (e.g. the Little Ice Age and Medieval Warm Period of the Holocene) and these periods act as analogues for current and future changes (Carcailllet et al. 2001, Hallett and Hills 2006). Paleoecological data contain examples of past parameterized relationships that can be used to model future changes.

![Figure 1.1](image.png)

**Figure 1.1** A schematic of landscape pattern of fire regimes. Black dots in low-severity fire regimes are very old patches of large, old trees being killed by insects and decomposed by fire, and grey dots are emerging pole-size stands that have less-defined edge. The moderate-severity fire regime is typically a complex mosaic of larger patches of the three fire severity levels, while the high-severity fire regime has large stand replacement patches (Adapted from Agee 1998, p.30).

HRVs also exemplify how adaptive fire-prone systems are and identify generalizable directions of future change (Hessl 2011). Historical analyses of disturbance regimes provide a long-term context for evaluating slow-operating processes and unusual or cyclical patterns, as well (Schoonmaker and Foster 1991). The HRV, prior to the
human-induced changes of the last ~100 years, exemplifies responses to natural changes; however, including human impacts on the HRV over the last century, which has pushed many HRVs to new boundaries, is imperative for understanding future changes to the HRV (Gavin et al. 2007). Therefore, paleofire reconstructions, including the most recent century, are needed.

1.1.3 Role of climate
Under future climate scenarios, the relationship between fire and climate will be important. Climate is a prominent top-down control on wildfire. Warm, dry, and windy conditions are ideal for the spread of fire, over short timescales (Agee 1993, Gedalof 2011), and climate also plays an important role in the availability (production) and flammability of fine and coarse fuels, over longer timescales (Carcaillet et al. 2001, Trouet et al. 2006, Meyn et al. 2007, Higuera et al. 2009, McWethy et al. 2013). For example, damp fuels will hinder fire spread and intensity and/or may prevent ignition events (Gedalof 2011). Climate is also a well-known driver of global fire activity and area burned and has been associated with recurring patterns of ocean-atmosphere climate variability, such as the Pacific Decadal Oscillation (PDO), for example (Grissino Mayer and Swetnam 2000, Beaty and Taylor 2001, Carcaillet et al. 2001, Fulé et al. 2003, Hallett et al. 2003, Buechling and Baker 2004, Gedalof et al. 2005, Whitlock et al. 2008, Trouet et al. 2010, Littell and Gwozdz 2011). As the severity and frequency of extreme weather are expected to increase under future climatic scenarios, an increase in fire activity is likely (Bessie and Johnson 1995, Carcaillet et al. 2001, Bergeron et al. 2004, Flannigan et al. 2005, Hessl 2011). How these changes in climate will combine with management impacts in forested regions is yet to be understood, but the historical context of past climatic changes and fire activity provides some insight (Hunter 1993).

1.1.4 Role of landscape characteristics
Also complicating wildfire dynamics is the role of bottom-up controls. Bottom-up controls on fire regimes are local- and landscape-scale physical environmental characteristics that inhibit or promote fire activity (Gavin et al. 2006). While the availability and abundance of fuels are strongly linked to climate, the temporal and
spatial heterogeneity of fuels is also linked to the landscape characteristics, such as elevation, slope, and aspect. Asynchronicity in fire behaviour across regions is often associated with these local controls of wildfire, which are poorly understood (Heyerdahl et al. 2002, Gavin et al. 2006 & 2007). Differing land uses, such as logging, agriculture, and conservation, can also influence the fire regime (Schoennagel et al. 2004, McWethy et al. 2013). Analyses of the role of landscape characteristics on fire regime variability are needed, particularly in mixed-severity fire regimes where they are suspected to play a key role and/or may interact with climatic influences (Agee 1998).

1.2 Methodologies: Proxies
Paleoecological records provide us with unique environmental information about vegetation, fire, and climate interactions beyond instrumental and historical records (Schoonmaker and Foster 1991, Smol 2002). Paleoecological proxies can be used to infer changes in fire regimes over both space and time, as each proxy records different information about fire activity at differing spatial and temporal scales (Smol 2002, Birks and Birks 2006). A hybrid fire history approach is thus ideal for reconstructing fire dynamics (Schoonmaker and Foster 1991, Smol 2002).

1.2.1 Tree-rings
However, dendropyrochronological reconstructions can be difficult in regions where the time-since-fire (TSF) exceeds tree-age and/or no fire scars are present (Lorimer 1985). Furthermore, uncertainty associated with high-severity fire detection from stand establishment estimates and low-severity fire detection from fire scars makes classifying mixed-severity fire regimes difficult.

1.2.2 Macroscopic sedimentary charcoal
Macroscopic sedimentary charcoal is defined as charcoal fragments >125-150 microns found in cored lake sediment, and peaks in charcoal accumulation are indicative of local or extralocal fires (Whitlock and Millspaugh 1996, Whitlock and Larsen 2001). Charcoal records are particularly useful in wildfire research as they provide a lengthy temporal record (beyond that of the tree-ring fire record). However, there exists problems with a sole reliance on sedimentary charcoal as a methodological technique in pyrochronology because it is not spatially explicit (the dynamics of charcoal transport are complex), evidence of small or low-severity fires may be limited (limited charcoal production and/or transport of charcoal), and there remain issues with the taphonomy of charcoal and its temporal resolution (Whitlock and Larson 2001, Gavin et al. 2003b, Higuera et al. 2005, Tinner et al. 2006). These issues can be especially amplified in mixed-severity fire regimes. Dendropyrochronological records can thus be used to corroborate and contextualize the location, severity, and resolution challenges of the macroscopic sedimentary charcoal fire record (Millspaugh and Whitlock 1995, Gavin et al. 2003a, Marlon et al. 2012).

1.3 Study area: Rocky Mountain Foothills, Alberta, Canada
The eastern foothills of the Rocky Mountains are characterized as a humid continental climate, receiving on average between 450 and 600 mm of precipitation per year and an average annual temperature of 2.0°C (mean summer temperature of 12.5°C; mean winter temperature of -8.5°C), calculated based on 30-year climate normals (Ecological Stratification Working Group 1996). The foothills near Hinton, Alberta fall into the boreal plains ecozone and the western Alberta upland ecoregion (Ecological Stratification Working Group 1996). This area represents the western edge of the boreal forest of
Canada and is dominated by lodgepole pine (*Pinus contorta*) and black spruce (*Picea mariana*). White spruce (*Picea glauca*), trembling aspen (*Populus tremuloides*), balsam fir (*Abies balsamea*), and western larch (*Larix occidentalis*) are also present.

Hinton Wood Products, A Division of West Fraser Ltd., manages approximately one million hectares of forest in the west-central Alberta region, in the foothills east of Jasper National Park (Hinton Wood Products 2010). The Hinton Wood Products Forest Management Area (HWP FMA) is currently listed at extreme to high risk for wildfire and has not experienced significant fire activity since the 1990s. The HWP FMA has been actively harvested since 1956 and is currently managed for timber, pulp extraction, and oil and gas exploration, with sustainable harvesting operations mimicking natural disturbance processes (*i.e.* wildfire) (Hinton Wood Products 2010).

Canada’s boreal forests are typically described as sustaining high-severity, stand-replacing fire regimes (Hunter 1993). However, evidence of low-severity fire has been found in the HWP FMA (Amoroso *et al.* 2011). Both topographic and structural heterogeneity in the foothills region, combined with evidence of low-severity fire, suggests that this region may historically have sustained a mixed-severity fire regime (Andison 1998, Amoroso *et al.* 2011). HWP FMA represents a transition landscape from montane cordillera to boreal plains (*i.e.* an ecotone), and while many fire history studies have been conducted in these regions (Tande 1979, Johnson *et al.* 1990, Masters 1990, Weir *et al.* 2000, Van Wagner *et al.* 2006, Courtney Mustaphi and Pisaric 2014), little has been carried out in this key transitional area (Amoroso *et al.* 2011). This area is also actively managed for multi-use (harvesting, oil/gas exploration, recreation, and conservation). Therefore, a better understanding of fire dynamics and the fire regime is needed (Hinton Wood Products 2010).

### 1.4 Aim & hypotheses

The aim of this dissertation was to reconstruct the historical wildfire regime of the HWP FMA using a multiproxy approach. Specifically, I tested the following hypotheses (stated as predictions):
1. The fire history and the identified fire regime are sensitive to the selection of fire identification criteria.
2. Stands contain multiple lines of fire evidence, consistent with mixed-severity fire regimes; this evidence will differ according to climate and topography.
3. The macroscopic sedimentary charcoal record is broadly coherent with the tree-ring record of large and/or severe wildfires.

1.4.1 Definitions of scale
This dissertation repeatedly references three spatial scales related to sampling plots, study sites and the study area. Hereafter, local scale refers to the plot-level; regional scale refers to the site-level; and, landscape scale refers to the study area as a whole.

1.5 Dissertation organization
This dissertation is comprised of three research papers to be submitted for publication. I am the first author on all three manuscripts, and I provided the bulk of the intellectual effort. My co-authors assisted in developing the experimental design, guiding the analysis, and contributed small written sections.

Chapter 2, titled “Sensitivity of reconstructed forest fire histories to detection criteria in mixed-severity landscapes”, submitted to Forest Ecology & Management, presents the results of a sensitivity analysis of fire event detection criteria and the effects on fire regime classification in a mixed-severity landscape. Chapter 3, titled “Climatic and landscape controls on fire in the Rocky Mountain Foothills, Hinton, Alberta, Canada”, submitted to International Journal of Wildland Fire, describes the fire history of the HWP FMA using tree-ring proxies (fire scars and stand establishment estimates), as well as an analysis of fire regime controls. Finally, Chapter 4, titled “Corroborating lake sediment charcoal records with tree-ring derived fire scar and stand initiation records in complex fire regimes: A case study in the Rocky Mountain Foothills of Alberta, Canada” to be submitted to The Holocene, presents a corroboration of macroscopic sedimentary charcoal fire records with tree-ring fire records in the Alberta Foothills and
demonstrates the potential use of multi-proxy research in mixed-severity fire regimes. Chapter 5 highlights the important findings of this research and introduces areas for future research.

1.6 References


CHAPTER 2:  
SENSITIVITY OF TREE-RING RECONSTRUCTED FOREST FIRE REGIMES TO DETECTION CRITERIA IN MIXED-SEVERITY LANDSCAPES

Vanessa Stretch, Ze’ev Gedalof, Michael F.J. Pisaric, Jaclyn Cockburn

In heterogeneous forest landscapes prone to wildfires, accurate classification of the fire regime beyond direct observations and records is difficult. This is in part due to the methods used to reconstruct historical fires in complex, heterogeneous landscapes with varying fire severities. Mixed-severity fire regimes, defined as variations in wildfire severity over time and/or space, have important implications for ecosystem functioning and forest management. Fire event detection is used to reduce uncertainties in historical tree-ring proxy records. The number of fire events considered in fire regime classification varies based on detection criteria (filters) that are researcher-selected, such as number of trees or plots recording fire. Here we analyzed the sensitivity of fire regime classification to common detection criteria in a mixed-severity fire regime in the eastern foothills of the Rocky Mountains, Alberta, Canada. We found that detection criteria bias records toward high-severity events and against potentially ecologically significant low-severity fires in mixed-severity regimes, ultimately classifying them as higher severity. We conclude that detection criteria methods must address the scale that is relevant to the ecological or management questions being addressed.

2.1 Introduction

Climatic change impacts wildfire activity globally (Gillett et al. 2004, Flannigan et al. 2005, Krawchuk et al. 2009, Hessl 2011, Jolly et al. 2015). More frequent extreme weather events, such as drought, can lead to increased fire susceptibility. Specifically, in Canada’s boreal forest, Gillett et al. (2004), Flannigan et al. (2005), and Price et al. (2013) predict increases in the expected area burned under multiple future climatic scenarios, both with increased frequency and severity effects. In order to anticipate how ecological communities will be impacted and respond to changes to fire regimes in the future, we must understand how they have responded to regime shifts in the past (Conedera et al. 2009). Reconstructing fire regimes is important for understanding and anticipating changes in fire frequency and severity in the future (Bergeron et al. 1999, DeLong and Kessler 2000, Fenton et al. 2009). Intensive forest and fire management
have altered natural regimes (Bergeron et al. 2004, Conedera et al. 2009, McWethy et al. 2013). With future intensive forest management and development planned in many landscapes, consideration of recent human impacts on fire regimes is imperative (Conedera et al. 2009, McWethy et al. 2013). Therefore, we can use historical fire regime reconstructions as models for managing forests now and into the future (Hunter 1993, Swetnam et al. 1999). Managers can interpret the expected fire characteristics to anticipate, plan, and forecast fire occurrence in these landscapes, set conservation and restoration goals, and develop multi-value forest management plans (Hunter 1993, Bergeron et al. 2004, Brown et al. 2004, McKenzie et al. 2004, Conedera et al. 2009).

Fire provides nutrients to soil, creates habitat, and initiates successive processes for many flora species (Johnson 1992, Agee 1993, Conedera et al. 2009); and the impacts and benefits of fire vary with severity. Because fire has an important ecological effect, fire regimes are generally discussed in terms of severity, a measure of the impact of fire intensity on forest ecosystems. Severity falls along a continuum, with possibilities of mixed effects. A single fire event may result in spatial patches of high-, moderate-, or low-severity, if microsite (plot-level) characteristics dictate the fire regime (Andison 1998). Fire regimes can be described at a range of spatial scales, from the site- or stand-level up to the regional- or landscape-level (usually desired for management) (Peterson 1998). Fire can also be mixed in severity over time (e.g. depending on fire weather, time-since-last-fire, and rates of fine fuel production).

A variety of evidence is retained from differing fire events over time and space in any particular regime, thus complicating the classification of fire regimes. For example, low-frequency, high-severity fires kill the majority of vegetation and leave a signature mark on the landscape (Turner and Romme 1994, Peterson 1998, Meyn et al. 2007). Subsequent forest regeneration in the years following fire sometimes results in an even-aged tree cohort. Previous fire evidence may be lost. Reconstructing these regimes is complicated by the criteria used to identify post-fire cohort dates. Post-fire cohort detection is researcher-defined, usually with consideration of species time-to-coring height. However, this detection is complicated furthermore by the uncertainty in the
cause of establishment (e.g. another form of high-severity disturbance, such as an insect outbreak). Higher frequency, low-severity fires kill understorey vegetation and/or leave fire scars on mature trees (McBride 1983, Williams and Baker 2012). Reconstructing these regimes is complicated by differential preservation of fire by species, as well as minimum numbers of replicate scars found on other trees. These challenges are typically addressed by using post-sampling fire event detection criteria (filters) to increase certainty that these events represent fire activity.

Reconstructing fire regimes is challenging, but has been carried out in many well-studied fire-prone regions. In areas where fire regimes are well understood, researchers often target sample for fire evidence. For example, in Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) forests in the US Midwest and Pacific-Northwest, fire scarred trees are purposely selected for analysis (Baker and Ehle 2001). It was well established that these regions have been characterized by low-severity, surface fire regimes. More recently, with multiproxy reconstruction methods, this region is believed to have sustained a broad range of fire regimes in the past. In the Canadian boreal forest, a high-severity, crown fire regime presumably exists and stand establishment data have been collected and time-since-fire maps created (Lynch *et al.* 2004). However, in more complex, or understudied areas where an assumption of the fire regime (i.e. assuming a regime based on forest type or a neighbouring regime) is made, we propose sampling for fire evidence should take an unbiased approach in order to ascertain an accurate fire regime representation. Targeted sampling areas of a single, known severity will bias the regime classification to either end of the classification continuum (Heinselman 1973, Agee 1993, Swetnam *et al.* 1999, Van Wagner *et al.* 2006), while completely random sampling in large, heterogeneous areas may also miss important mixed-severity information.

Boreal forests have historically been managed with the assumption of infrequent, high-severity, stand-replacing fires being the dominant disturbance agent (Johnson 1992). However, Amoroso *et al.* (2011) found evidence for mixed-severity fire regimes in the Rocky Mountain Foothills. A probable explanation for this regime is the degree of
topographic variability that may result in mixed-severity fire effects, as both even-aged stands and fire scars were found (Amoroso et al. 2011). Similarly, recent studies found evidence of mixed-severity fire in the montane cordillera directly adjacent to the Foothills (Davis 2014, Dinh 2015, Chavardes and Daniels 2016), but categorizing mixed-severity regimes without consistent event detection criteria prevents comparisons between regions.

Here, we present a case study outlining a common bias of fire regime classifications in the eastern foothills of the Rocky Mountains in Alberta, Canada. Topographic variability in this area controls fire activity, regardless of large-scale climate patterns at the landscape scale (Chapter 3). Our objectives were: 1) to incorporate multiple forms of tree-ring fire evidence to reconstruct fire regimes in complex landscapes with little-to-no known fire histories in order to classify the fire regime and 2) to analyze the impact of post-sampling detection criteria on the final fire regime classification, in order to ensure that the ecological and/or management questions being asked can be addressed at a relevant scale.

2.2 Methods

2.2.1 Case study area
In this case study we analyze two sites (ZS and PC) in the northern portion of the Hinton Wood Products Forest Management Area (HWP FMA) in the eastern foothills of the Rocky Mountains near Hinton, Alberta, Canada (Figure 2.1). HWP manages approximately one million hectares of land extending east from the Rocky Mountains into the boreal plains ecozone. Here the eastern foothills are considered part of the Alberta upland ecoregion (Ecological Stratification Working Group 1996), which is classified as the western edge of the boreal forest in Canada. The forests are dominated by lodgepole pine (Pinus contorta) and black spruce (Picea mariana), with lesser amounts of white spruce (Picea glauca), trembling aspen (Populus tremuloides), balsam fir (Abies balsamea), and western larch (Larix occidentalis).
The HWP FMA has had minimal fire activity since the 1990s and is therefore classified as extreme to high risk for wildfire in current management planning. It is believed that about 44,000 ha (<5% of the managed area) have burned since the 1930s, with most events being small (<1-10 ha) in size (Hinton Wood Products 2010). Harvesting (pulp and timber extraction) activities have been ongoing since 1956, with a current sustainable harvesting management plan in place that involves mimicking the natural wildfire disturbance regime by using variable cutblock sizes and shapes and retaining remnant stands, as well as burning harvest waste in situ. Prior to 1956, there was minimal known activity in the area; it was used mostly as hunting and camping grounds for nearby settlements.

Figure 2.1 Study area, Eastern Foothills of the Rocky Mountains, Alberta, Canada. A) Hinton Wood Products Forest Management Area (HWP FMA) outlined in white. B) Two study sites north of Hinton. Black dots represent sampling plots at each site. DEM source: Shuttle Radar Topography Mission, NASA.
2.2.2 Site and sampling selection

Using a combination of random and condition-based sampling techniques, we reconstructed wildfire activity at two sites. Working in a large potential sampling area (almost one million hectares), we focused our sampling on areas of suspected mixed-severity concerns based on historical landscape knowledge of ecological professionals from HWP. With the purpose to incorporate multiple lines of fire evidence, we also surveyed the landscape at more than 30 sites looking for signs of historical evidence of fire occurrence since at least the mid-1900s to suggest mixed-severity before selecting our final two study sites. These sites were selected because they contained evidence of a potential mixed-severity regime (fire scars, even-aged cohorts, and/or multiple canopy layers).

To select specific plots for sampling within each study site (~10,000 ha), we used a condition-based selection approach. To facilitate a multi-century reconstruction, we used Alberta Vegetation Index (AVI) stand age polygons to eliminate stands less than 100 years old (Environment and Sustainable Resource Development 2008). By excluding these stands, we are not biasing the record against recent high-severity fires; most of the excluded stands were harvested, and large, stand-replacing fires were relatively rare during the past 100 years (Hinton Wood Products 2010). We then randomly selected six accessible stand polygons from each cardinal direction (24 plots at each site), in order to assure sampling was dispersed across the site (Figure 2.1). Sampling plots were established in the centre of each polygon and permanently staked (plot sizes ranged from 0.0019 to 0.0716 ha).

2.2.3 Tree-ring data collection and analysis

To capture the high-severity fire record, canopy and subcanopy trees (if present) were sampled for tree establishment estimation (Barrett and Arno 1988, Baker and Ehle 2001, Heyerdahl et al. 2012). We used an n-tree sampling design that resulted in variable plot sizes. This was done by coring to pith within the lower 30 cm (basal coring) of the 10 closest canopy and 10 closest subcanopy trees (with a DBH > 5cm) to plot centre.
Because post-fire cohorts on their own do not represent all fire activity (Lorimer 1985), and to capture the low-severity fire record, cross-sectional and partial cross-sectional sampling was carried out at sites where visual fire evidence existed (McBride 1983, Lorimer 1985, Rist et al. 2011). Fire-scarred trees within the plot were sampled; as well, downed wood was cut into to examine for evidence of buried fire scars and sampled if appropriate (Agee 1993; 1998, Swetnam et al. 1999, Niklasson and Drakenberg 2001). To reduce sampling redundancy, at most five samples were selected from both dead and live trees.

All samples were returned to the laboratory and processed using standard dendrochronological techniques (Stokes and Smiley 1996). Samples were visually crossdated, measured in WinDendro (v.2008a) (Regent Instruments Inc. 2009), and the crossdating was confirmed using COFECHA (v. 6.04P) (Grissino-Mayer 2001a). Crossdating of dead material was accomplished using COFECHA and suggested dates were then confirmed using visual crossdating techniques. Fire scars were assigned event years from the crossdated chronology. Geometric pith estimation techniques were used on any tree-ring samples with missing piths (Applequist 1958, Duncan 1989). Because samples were taken within the lower 30 cm of the trunk-ground interface (Barrett and Arno 1988, Amoroso et al. 2011), and with consideration of the time to coring height of lodgepole pine and black spruce, no correction factors were applied to pith dates (Johnson and Fryer 1989, Nyland 1998, Antos and Parish 2002, Axelson et al. 2009). Fire scar dates were then entered into FHAES (Brewer et al. 2014) and FHX2 (Grissino-Mayer 2001b) for compilation and analysis of mean fire return intervals (mFRIs). High-severity fire, even-aged cohorts were identified by 60% of trees in the canopy or subcanopy having pith dates within 10 years of each other, with no live samples older than the earliest cohort date. No exact fire years for high-severity events were assigned in this analysis, but rather the number of likely events was tabulated.

2.2.4 Fire regime classification

In order to classify the fire regime at a regional scale, we analyzed evidence from each plot to classify the two study sites. This allowed us to evaluate spatial patterns in
classification within each site. We classified each plot based on the severity evidence found. Low-severity fire evidence was tabulated from the fire scar record, and high-severity estimates were calculated based on cohort establishment detection at each plot.

Filters for detection and inclusion of low-severity fire evidence were analyzed to identify any underrepresentation or exaggeration of fire activity. The filters assessed here included all fire scar evidence at all plots, a minimum of two trees recording fire at each plot, and 10% of trees recording fire at each plot. Both minimum and percentage filters were assessed to analyze differences in event detection stemming from varying sample sizes at each plot. Filters were also spatially scaled up to include all plots recording any fire scar event and minimum two plots recording an event, as well as across sites (regional scale).

To examine the influence of detection criteria on high-severity events, all individual tree establishment dates at each study site were combined to show regional pulses in establishment. Establishment dates were binned at different bin widths to further demonstrate the under- or over-representation of establishment pulses that may be related to high-severity fire at the site-level. Bins of 1-, 5-, 10-, 20-, and 25-years were analyzed here.

2.3 Results

2.3.1 Records of low-severity fire
In total, 188 fire scars were dated from 29 plots containing low-severity fire evidence. Of these, 77% of scars were found at the PC site with the remainder at the ZS site. From these fire scars, 76 fire events were recorded on at least one tree. Fire events were detected in 71% of PC plots (n = 54 events); while only 50% of plots in ZS had scars (n = 38 events).
Plot-scale comparisons

To examine event detection within each plot, we applied two filters (10% of trees at a plot & 2 trees at a plot recording fire). We found more fire events were detected when applying a 10% of trees at a plot recording fire filter (with n ranging from 15-25 trees) than the 2 trees at a plot filter, with a single fire scar constituting an event by this criterion (Table 2.1).

Table 2.1 Number of fire events and mean fire return intervals (mFRIs) calculated for different event detection filters.

<table>
<thead>
<tr>
<th>Filter</th>
<th>PC # Events</th>
<th>mFRI (years)</th>
<th>ZS # Events</th>
<th>mFRI (years)</th>
<th>Landscape # Events</th>
<th>mFRI (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All trees at plots</td>
<td>54</td>
<td>2.2</td>
<td>38</td>
<td>5.2</td>
<td>76</td>
<td>2.6</td>
</tr>
<tr>
<td>10% trees/plot</td>
<td>49</td>
<td>2.4</td>
<td>14</td>
<td>7.2</td>
<td>56</td>
<td>2.1</td>
</tr>
<tr>
<td>2 trees/plot</td>
<td>17</td>
<td>4.0</td>
<td>0</td>
<td>N/A</td>
<td>17</td>
<td>4</td>
</tr>
<tr>
<td>2 plots</td>
<td>25</td>
<td>2.2</td>
<td>4</td>
<td>17.3</td>
<td>34</td>
<td>2.6</td>
</tr>
<tr>
<td>2 plots &amp; 10% trees</td>
<td>24</td>
<td>2.3</td>
<td>1</td>
<td>N/A</td>
<td>27</td>
<td>2</td>
</tr>
<tr>
<td>2 plots &amp; 2 trees</td>
<td>4</td>
<td>8.7</td>
<td>0</td>
<td>N/A</td>
<td>4</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Note: Site and landscape mFRIs are calculated as averages of composite intervals from relevant plots (Agee 1993). mFRIs here are biased by the different sample sizes (number of plots) and areas of each filter.

Site-scale comparisons

To detect potential larger-scale events, events that were recorded at two or more plots were tabulated. Only 34 events were recorded at two or more plots across sites, with 25 in PC plots only and four in ZS plots (Table 2.1).

Cross-scale comparisons

Combining the large-scale and small-scale detection filters, 27 fire events across both sites were detected at two plots, with 10% of trees at each plot recording fire (24 events in the PC site only and one in the ZS site). Only four events were recorded at two or more plots across sites with each plot having at least two trees recording the event (all of these events were in the PC site) (Table 2.1).
We calculated mFRIs for each of our filters to investigate the potential bias of detection filters (Reed and Johnson 2004). When calculating composite mFRIs for sites (all plots at a site) and the landscape (all plots across both sites), we averaged the number of years between fire events. Scaling up with this method can decrease the overall mFRI at larger scales, however our purpose was to analyze the influence of all individual fire events on the fire regime and denote how often any fire activity was occurring anywhere on the landscape (Agee 1993). The mFRI for at least one plot detecting a fire event at site PC was 2.2 years and 5.2 years at site ZS. When filtering to at least two plots recording, mFRIs at PC remained the same (2.2 years), but increased at ZS to 17.3 years (see Table 2.1 for all calculated mFRIs). Overall, mFRIs do not change significantly with different filters in this landscape as fire return intervals are variable (Figure 2.2), but the number of detected fire events varies greatly.

Figure 2.2 Variability in mFRIs based on different detection criteria/filters. A) ZS site and B) PC site.
Figure 2.3 Regional binned stand establishment estimated dates. A) ZS site and B) PC site.

2.3.2 Stand establishment

From the groupings of establishment (Figure 2.3), multiple pulses are evident at smaller bin sizes, which become masked as bin size increases. Larger bin sizes show two main
establishment pulses at the regional-level, one at the end of the 1800s that is predominantly lodgepole pine and another beginning in the 1920s that is predominantly black spruce. These patterns are seen at both sites, demonstrating landscape-scale pulses in establishment.

Canopy cohorts were detected at 14 plots (58%) at the PC site and at only nine plots (38%) at the ZS site. Subcanopy cohorts were detected at 4/9 plots and 3/11 plots, respectively. For those plots with subcanopies, significant differences between canopy and subcanopy ages were detected at 18/20 plots.

Table 2.2 Tabulation of fire severity evidence for fire regime classification.

<table>
<thead>
<tr>
<th>Fire evidence</th>
<th># PC Plots</th>
<th># ZS Plots</th>
<th># Plots on Landscape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-severity</td>
<td>16</td>
<td>13</td>
<td>29</td>
</tr>
<tr>
<td>High-severity canopy</td>
<td>14</td>
<td>9</td>
<td>23</td>
</tr>
<tr>
<td>High-severity subcanopy</td>
<td>4</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>High-severity subcanopy only</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>High-severity &amp; low-severity</td>
<td>14</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>Low-severity only</td>
<td>3</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>High-severity canopy only</td>
<td>3</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>

2.3.3 Fire regime classifications

Based on the inclusion of all fire evidence, the number of plots exhibiting different fire regime evidence was tabulated in order to conceptualize fire regimes across the landscape, as well as at the site-level (Table 2.2). The majority of fire evidence was low-severity (fire scars), found at 29 plots (60%). Cohort detection at plots revealed evidence of high-severity fire at 26 plots (54%), with moderate-severity evidence inferred from a subcanopy cohort at seven plots (15%). Overall, 44% of plots had evidence of mixed-severity fire events, resulting in an overall mixed-severity fire regime classification. The remaining landscape is classified as 21% low-severity fire regime and 13% high-severity fire regime (with the remaining 23% of the landscape showing no fire evidence over the length of the record – approximately the last 150 years). More mixed-severity plot-level classifications were found at PC (14/24 plots) than at ZS (7/24).
Figure 2.4 Fire event detection filters & classification of fire regime. A) All events at all plots filter, B) two trees per plot filter, and C) 10% of trees per plot filter. Green plots have no detected fire events, yellow plots have low-severity regimes, red plots have high-severity regimes, pink plots have a subcanopy cohort (moderate-severity fire) only, and orange plots have mixed-severity regimes.
However, when applying detection criteria/filters within plots, plot-level fire regime classification changes (Figure 2.4). Low-severity regimes decrease in number when 10% of trees at a plot and 2 trees per plot filters are applied. Filters also decrease the amount of overall fire evidence by classifying some plots as having no evidence of fire.

2.4 Discussion

2.4.1 Fire histories from multiple lines of evidence
Analyzing the stand establishment data, we found more plot-level high-severity fire evidence in site PC than in site ZS. Site PC is characterized as a drier area based on vegetation composition and site characteristics (e.g. higher-elevation, plateau). We also detected subcanopy cohorts at the plot-level, which may indicate moderate- or mixed-severity fire. When analyzing the site-level high-severity fire evidence, we found two pulses in establishment, one in the late 1800s and one in the 1920s (Figure 2.3). However, when the data are filtered into establishment bin widths, the pulses merge into a single pulse at 25-year bins. Binning at different researcher-selected bin widths can thus overlook potential small, higher-severity fire events happening at the site- or plot-scale. Overall, we found that the study sites experience high-severity fire at both the plot- and site-level, but have not experienced much high-severity fire since harvesting activities began (in the mid 1950s).

Our fire scar data demonstrates that this region experiences variable, but frequent low-severity fire as well (Table 2.1). Site PC, which is located on a higher-elevation plateau, experiences low-severity fire more frequently than site ZS, based on mFRIs (Table 2.1). We also found that due to the high number of low-severity fire events, when applying detection criteria filters, including or excluding a few events does not alter the mFRI significantly but biases it toward more infrequent fire (Table 2.1). The largest discrepancy in mFRI occurs at ZS, which has overall less fire evidence (across all severities). Applying spatial filters for event detection reduces the number of fire events, ultimately biasing the mFRIs toward a more infrequent fire regime, as well.
An important implication of our event detection analysis is that we are confident that all events indicate a fire that affected at least one tree (scar) or stand (cohort). In the case of scars, we were careful to exclude scars that were not unambiguously fire (e.g. mechanical or insect scars) (Gutsell and Johnson 1996), meaning that from an ecological perspective they represent a disturbance event that creates structural complexity. Many traditional approaches to fire reconstructions have focused on events that scar multiple trees, and exclude these single scar events, which bias regime classification toward more infrequent fire. However, from a conservation perspective, they are potentially quite ecologically important. For example, changes in fire activity at multiple scales can result in changes in biodiversity by altering species composition, age distributions, and habitat (Odion and Sarr 2007). Therefore, it is imperative to select criteria that represent fire at a relevant ecological or management scale.

2.4.2 Classifying fire regimes
Senici et al. (2013) discuss how spatial or landscape differences can impact fire frequencies, creating different regimes at local spatial scales. Here, we found that applying common event detection filters resulted in different plot-level fire regime classifications (Figure 2.4). As a whole, this area, as well as each site, is classified as mixed-severity based on multiple lines of fire evidence (Table 2.2), but at the plot-level there is high spatial variability in the regime, which is further complicated by researcher-selected fire event detection. As can be seen in Figure 2.4, applying common event detection filters biases fire regimes towards high-severity. This is particularly troubling when we have purposely collected multiple lines of mixed-severity fire evidence.

Another important consideration for fire regime classification is the non-static nature of fire regimes over time (Lertzman et al. 1998, Beaty and Taylor 2001, Carcaill et al. 2001). For example, a high-severity, stand-replacing fire regime may experience intermittent small, low-severity, surface fires; this ‘new’ regime may return to the stand-replacing regime after the next stand-replacing fire. Here we found that while no large, landscape-level fires have been present in this landscape since at least the mid-1800s (Figure 2.3), many small, low-severity fires have occurred since. We also found
subcanopy trees established in cohorts, potentially indicating moderate-severity events. However, if the well-documented boreal forest fire regime also persists in this transition landscape, a few hundred years may pass between high-severity, landscape-scale fire events. Two temporal regimes operating simultaneously are possible (Barrett et al. 1991). For example, Masters (1990) found that while a climate-dominated fire regime, characterized by infrequent fires, has existed in the Kootenays of southern British Columbia, Canada since the early 1500s, a more frequent regime post-1919 resulting from anthropogenic sources, now co-exists.

The difficulty with the mixed-severity classification is that it can encompass a range of definitions (Agee 2005). It can be a static regime that experiences moderate-severity fires with varying effects across space, it can be a landscape that experiences different severity regimes at the site-plot-level, or it can be temporally a stand or landscape that moves from low- to moderate- to high-severity regimes over time as relationships with fire controls change (Lertzman et al. 1998, Arno et al. 2000, Agee 2005, Amoroso et al. 2011, Halofsky et al. 2011). The latter is most likely in highly topographically diverse landscapes. The landscape presented here may be a combination of these, as we have presented evidence of changes in fire activity and establishment over time and variations in fire evidence and severity across space. With all criteria analyzed here, this landscape is classified as patchy. We conclude that in mixed-severity regimes such as these, defining fire events using stricter criteria biases results against low-severity fire in general, and mixed-severity fire in particular. According to Whitlock et al. (2010), fire reconstructions and regime classifications should involve a reconceptualization of the fire regime concept as more variable to encompass the scale of concern. We propose here that fire reconstructions in similar landscapes be comprised of multiple lines of evidence and analyzed using different detection criteria in order to assure that the classification captures the scale that is most appropriate to the questions being addressed (Arno et al. 2000, Fulé et al. 2003, Agee 2005, Falk et al. 2007, Conedera et al. 2009, Whitlock et al. 2010, Halofsky et al. 2011). These analyses are crucial for studies of mixed-severity fire regimes.
2.5 Conclusions

Historical fire reconstructions in complex landscapes or in landscapes with unknown fire histories are ultimately difficult. We have demonstrated here how multiple lines of evidence collected using a condition-based random sampling of sites can provide a detailed reconstruction in a complex and understudied system. In a suspected mixed-severity fire regime area, we analyzed the interspersion of cohorts with fire scars. We conclude that the decisions made during the analysis stages of tree-ring based fire reconstructions are crucial to fire regime classification. One decision may exaggerate or underestimate mFRIs that are critical to ecologically understanding or managing these landscapes. Specifically, strict detection criteria bias fire records against low and mixed-severity events.

2.6 References


Variability in climate and topography has resulted in areas of complex wildfire dynamics in many forest management areas in western North America. The implications of wildfire variability in managed forests are numerous and thus a comprehensive knowledge of mixed-severity wildfire dynamics is essential. Using dendropyrochronological techniques, we reconstructed ~150 years of wildfire variability in the eastern foothills of the Rocky Mountains near Hinton, Alberta, Canada. This is an area where little fire research has been conducted, but is currently considered to be at high risk of fire and is intensively managed for multiple resource values. We combined fire scar (a proxy for low-severity fire) and stand establishment records (a proxy for high-severity fire) to reconstruct wildfire history and evaluate the mixed severity nature of fire history in this landscape. The wildfire record shows no evidence of landscape-scale fire events over the last ~150 years. Instead, we found evidence of frequent, low-severity fire activity in the early 1900s that is not explained by climate, as well as establishment pulses associated with these fire periods. Overall, our research shows the foothills experienced variability in fire severity over both time and space, which has resulted in small, cool weather fire events that are associated with landscape heterogeneity. Climate, on its own, is not an overarching control on wildfire in this region. We have found evidence for connections between the complex landscape characteristics (bottom-up controls), landscape preconditioning, and climate trends that drive wildfire activity in this unique and understudied landscape. These connections are ecologically important for forest gap dynamics and management within the region.

3.1 Introduction

In Canada, the boreal forests of the western Cordillera depend on wildfire to drive changes in species composition, cycle nutrients, create habitat for species, and ultimately create forest complexity (Johnson 1992, Agee 1993, Brown 2000). Wildfires are part of the natural history of these landscapes; however, wildfire activity does not occur spatially or temporally at consistent frequencies, extents, intensities, or severities. These heterogeneous landscapes may result in dynamic, mixed-severity fire regimes that are difficult to understand, as these regimes experience a range of low- to high-severity fire

As management of forested landscapes intensified over the last century (e.g. for harvest, insect control, and fire suppression), some forests have structurally changed and limits of the natural historical range of variability (HRV) of wildfire have been altered (Bergeron et al. 1999, DeLong and Kessler 2000, Fenton et al. 2009). The HRV of wildfire, in some cases, may exceed the bounds of natural variability seen in the previous centuries and the consequences of fire exclusion on these forests are now being experienced (Hunter 1993). For example, in some forest types, years of effective fire exclusion in the early part of the 20th century resulted in large buildups of fuels that have, in many cases, resulted in increased fire activity and/or extents (Hessburg et al., 2000). Similarly, exclusion of only those fires that burned under suboptimal climatic conditions or on sites where suppression is comparatively easy may have altered stand structure and composition outside their historical ranges (Cumming et al. 2000). Understanding how changes to the HRV will ultimately impact ecosystems is imperative because climate change, which will bring about inherent influences on fire activity globally, will also add to the changes already observed due to management strategies (Hunter 1993, McKenzie et al. 2004).

Climate is an overarching driver of wildfire activity at regional to landscape scales and can influence fire activity via multiple mechanisms (Gedalof 2011). Temperature and precipitation regimes help determine the composition and abundance of vegetation growing in an area (i.e. fuels). Increasing temperatures and a lack of precipitation, combined with lightning, also determine when and where fires ignite and how rapidly they spread (Gedalof 2011). Multi-scale changes in temperature and precipitation regimes in western North America and the boreal forests are expected in the next century (Bessie and Johnson 1995, Carcaillet et al. 2001, Bergeron et al. 2004, Flannigan et al. 2005, Hessl 2011) and a thorough understanding of how these changes might combine with management plans to alter the HRV are uncertain (Hunter 1993).
Managing wildfire-prone regions requires a thorough understanding of how these systems interact with climate to influence fire activity. Low-frequency (decadal and multi-decadal) climatic patterns are understood to be important controls of fire activity in western North America via landscape preconditioning (i.e. fuel availability and flammability) (McKenzie et al. 2004, Gedalof et al. 2005). However, high-frequency, extreme climatic conditions may also be associated with ignition sources and fuel flammability (Agee 1997, McWethy et al. 2013). Although climatic factors may be conducive to wildfire, topographic complexity or microsite characteristics may impede or promote fire activity (Beaty and Taylor 2001, Heyerdahl et al. 2001, Gavin et al. 2006, Lentile et al. 2006, Dillon et al. 2011). For example, mesic forest stands, which experience saturated soils for long portions of the year, may require extreme and prolonged drought to be conducive to wildfire (Senici et al. 2013, Lynch et al. 2014). In topographically complex landscapes, we hypothesize that mesic areas normally burn at low-severities, except during periods of drought years when they burn at higher severity; and more xeric areas burn at moderate- or high-severity regardless of climate. Thus, heterogeneous landscapes may experience historically mixed-severity fire regimes.

Canadian fire histories in the Rocky Mountains are numerous (Tande 1979, Johnson et al. 1990, Masters 1990, Weir et al. 2000, Van Wagner et al. 2006, Cochrane 2007, Da Silva 2009, Nesbitt 2010, Courtney Mustaphi & Pisaric 2014, Davis 2014, Dinh 2015, Chavardes and Daniels 2016), where relations between fire, climate, and landscape controls tend to be pronounced (Antos and Parish 2002, Axelson et al. 2009). Few reconstructions of fire history have been done in the Foothills of the Rocky Mountains and the boreal plains, where topographic and structural variation is also high (Beckingham et al. 1996, Andison 1998). This area forms an ecotone between the boreal forest, where stand-replacing fires dominate (Hunter 1993), and the dry intermountain cordillera, where surface fires dominate (Heyerdahl et al. 2012). This ecotone is also a region of high biodiversity on a landscape that is heavily modified and intensively managed (Amoroso et al. 2011). Using fire-scarred trees and stand establishment records, the objectives of this study were: 1) To reconstruct the fire history of the eastern foothills of the Rocky Mountains, near Hinton, Alberta; 2) To analyze temporal variability in fire
activity in relation to climatic influences; and 3) To assess the role of topographic and structural complexity on fire activity.

3.2 Methods

3.2.1 Study area
The eastern foothills of the Rocky Mountains near Hinton, Alberta fall into the boreal plains ecozone and the western Alberta upland ecoregion (Ecological Stratification Working Group 1996). This area is the western edge of the boreal forest of Canada and is dominated by lodgepole pine (Pinus contorta) and black spruce (Picea mariana). White spruce (Picea glauca), trembling aspen (Populus tremuloides), balsam fir (Abies balsamea), and western larch (Larix occidentalis) are also present, but their dominance is less. The eastern foothills of the Rocky Mountains are characterized as a humid continental climate, receiving on average between 450-600 mm of precipitation per year (with snow accounting for approximately 24%) and an average annual temperature of 2.0°C (mean summer temperature of 12.5°C; mean winter temperature of -8.5°C) (Ecological Stratification Working Group 1996).

Hinton Wood Products, A Division of West Fraser Ltd., manages approximately one million hectares of forest in the west-central Alberta region, in the foothills east of Jasper National Park (Hinton Wood Products 2010). This study was carried out in two sites (hereafter denoted as PC and ZS) in the northern portion of the Hinton Wood Products Forest Management Area (HWP FMA) (Figure 3.1). These sites were selected because they represent typical forests of the region based on local knowledge and vegetation maps, and they contain trees old enough to span the pre-fire suppression and modern eras, so evidence of the HRV should be possible to detect. Site ZS ranges in elevation between 1000 and 1200 m and contains many wetlands and fens. Site PC ranges in elevation between 1200 and 1400 m and is located on a prominent plateau. Site PC is drier than site ZS based on topographic and vegetation composition characteristics.
Figure 3.1 Study area, eastern foothills of the Rocky Mountains, Alberta, Canada. A) Hinton Wood Products Forest Management Area (HWP FMA) highlighted in white. B) Study sites located north of Hinton. Black dots represent sampling plots at each site. DEM source: Shuttle Radar Topography Mission (SRTM), NASA.

The HWP FMA is currently listed at extreme to high risk for wildfire and has not experienced significant fire activity since the 1990s. Since the 1930s, it is believed that approximately 44,000 ha has burned, with only 2% of this having burned since 2000 in 41 small (<110 ha) fire events (Hinton Wood Products 2010). The HWP FMA has been actively harvested since 1956 and is currently managed for timber, pulp extraction, and oil and gas exploration, with sustainable harvesting operations aimed at mimicking natural disturbance processes (i.e. wildfire). Mimicking of natural disturbance processes is done with variable cutblock sizes and shapes, as well as retaining remnant forest stands and the burning of harvesting waste on site (Hinton Wood Products 2010). Prior to the establishment of the HWP FMA, the area was used for hunting and camping by nearby settlements.
3.2.2 Sampling, data processing & compilation

We used existing data sampled from each study site, ZS and PC (Chapter 2). A 113 km$^2$ area (radius = 6 km) was divided into quadrants (N, E, S, W) and outlined for potential sampling. Stand age polygon data from the Alberta Vegetation Index (Environment and Sustainable Resource Development 2008) were superimposed over each sampling site. Stands less than 100 years old were eliminated, and 6 random polygons from each of the quadrants were selected and polygon centres were used as sampling plots. A total of 48 plots were sampled (24 plots at each site). Plots ranged in elevation from 1000 to 1400m a.s.l, represented both cool and warm aspects, and sloped between 0 and 40°.

To determine tree establishment dates, dendrochronological sampling at each plot consisted of a modified $n$-tree sampling design (Lessard et al. 1994). The 10 closest live canopy and 10 closest live subcanopy trees (if present) to plot centre were sampled by basal increment coring within <30 cm to the root-shoot interface (Barrett and Arno 1988, Amoroso et al. 2011), with replacement for centre rot. This sampling method resulted in variable plot sizes (ranging from 0.0019 to 0.0716 ha) due to differing stand densities. If visual signs of fire were present in the plot (i.e. triangular basal scars, charred wood or snags), up to five samples (cross sections or partial cross sections) were taken from a combination of live, dead, or downed trees (McBride 1983, Barrett and Arno 1988, Rist et al. 2011).

All samples were processed using standard dendrochronological techniques (Stokes and Smiley 1996) and analyzed using WinDendro Imaging Software (v.2008a) (Regent Instruments Inc. 2009). COFECHA (v. 6.04P) (Holmes 1983, Grissino-Mayer 2001a) was used to verify the dating of all samples both within and between plots and divided by canopy and subcanopy strata. A geometric arc method (Applequist 1958, Duncan 1989) was used to estimate the distance to any missing piths and correct for the number of rings (years) to pith in the increment cores. In total, 74% of piths were corrected, with an average of 4 rings corrected ($\delta = 4$). Because increment cores were collected as close to the root-shoot interface as possible and average age to coring height for the dominant species (lodgepole pine) is greater than half the coring height in this
study, we did not apply any correction factors to the existing age data (Wong and Lertzman 2001). Knowing that regeneration times vary by species and samples were collected from multiple species, we used a conservative approach to compile age-class data across the two sites to reconstruct high-severity fire (Crotteau et al. 2013). We compiled individual sample establishment dates and grouped them into 10-year age bins (allowing for species-specific post-fire regeneration) in order to examine regional pulses (i.e. across both sites) in regeneration following wildfire activity (Johnson and Fryer 1989, Nyland 1998, Antos and Parish 2002, Axelson et al. 2009, Amoroso et al. 2011, Heyerdahl et al. 2012). We also examined age-class data at the plot level for cohort detection using a modified method from Heyerdahl et al. (2012). For this analysis, we defined the presence or absence of cohorts at each plot as 60% of trees at a plot establishing within 10 years of each other.

To reconstruct low- to moderate-severity fires, we identified fire scars on partial and full cross-sections by the presence of charcoal and/or open or formerly open catfaces and/or defined scar tips and assigned event years to scars. We used a combination of WinDendro and microscopic verification to assign each scar to an intra-ring position (if possible). We then compiled fire history data and calculated composite mean fire return intervals (mFRIs) from fire scars for each site, excluding pith-to-scar and the most recent fire-free interval, using FHAES (v. 2.0.0β) (Brewer et al. 2014). While we did define cohorts, we did not assign fire dates to stand-initiating events, as these represent minimum times-since-disturbance and the precise date is presumed to be some years prior to the earliest ring detected in the cohort.

3.2.3 Climatic & landscape associations
In western North America, the most important large-scale modes of climatic variability affecting winter and spring temperatures and precipitation (variables associated with fire season activity) are the El Niño Southern Oscillation (ENSO) (Wang et al., 1999), the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997), and the Atlantic Multidecadal Oscillation (AMO) (Kerr 2000). These climatic patterns are associated with temperature and precipitation regimes, which are influential on fire activity. Because the influences of
low-frequency climate variability on wildfire may span multiple years (fuel production) to single years (fuel flammability), climatic patterns are often compared to wildfire events over a window of time. Here, we used a superposed epoch analysis (SEA) to analyze climate-fire relations at the landscape scale over the length of our fire record (1808-2003) in seven-year windows (four years prior to the event, the event year, and two years following the event) using FHX2 (v. 3.2) (Grissino-Mayer 2001b, Schoennagel et al. 2007). This window size allows for associations between climate variability and fuel preconditioning to be detected, as well as associations with extreme climatic events in the year of fire. We used the ENSO 3.4 reconstruction by Cook (2000), the PDO reconstruction from Gedalof and Smith (2001), and the AMO reconstruction from Gray et al. (2004) for this analysis. We also used the Palmer Drought Severity Index (PDSI), gridpoint 52, from Cook and Krusic (2004), and a local lodgepole pine drought reconstruction from the Hinton/Entrance region from Daniels (Personal Communication, 2014) to detect any local, small-scale, annual drought signals. We calculated Monte Carlo simulations ($n = 1000$) to detect significance levels ($\alpha < 0.05$) for all SEAs. There remains disagreement on how to account for the inherent autocorrelation in climate time-series (Box and Jenkins 1970). However, given that the effects of autocorrelation may be associated with the likelihood of fire activity (e.g. lack of precipitation in the previous year), autocorrelation in this analysis was not removed.

While the former SEA analysis accounts for climatic preconditioning, it calculates significance based on individual year index values from the respective reconstructions, which are largely seasonal to annual in nature. However, synoptic climate variability may influence fire activity at longer time scales. We hypothesized that the occurrence of a fire event may therefore be related to the presence of a particular phase of a synoptic climate variable. We therefore carried out an analysis of the occurrence of fire events during positive or negative phases (of differing lengths) of the modes of variability, as they are known to alter the frequency of synoptic modes favorable to wildfire (Johnson & Wowchuk 1993, Gedalof 2011). Large-scale climatic patterns also do not operate independently but occur simultaneously, so we performed chi-square contingency analyses to determine if there is a dependence on phase presence or phase direction, as
well as any teleconnections between indices (Gershunov and Barnett 1998, Trouet et al. 2006).

Landscape controls have historically been analyzed as a means to help explain discrepancies between sites in their fire history. Differences in elevation, aspect, and slope between plots may result in microclimatic conditions that do not promote wildfire, despite the regional climate signal. To analyze the influences of landscape controls on fire activity, we used Kurskall-Wallis H-Tests to statistically ($\alpha < 0.05$) compare mFRIs between plots of differing microsite conditions, such as aspects (filters = cool [270-90°] and warm [90-270°]) (Masters 1990, Heyerdahl et al. 2001; 2007), elevations (filters = low (<1300 m) and high (>1300 m)) (Masters 1990, Agee 1991, Turner and Romme 1994, Fulé et al. 2003, Heyerdahl et al. 2007), slopes (filters = flat (<10°) and steep (>10°)) (Lentile et al. 2006), and structural complexity (filter = simple (one dominant canopy layer), complex (>1 canopy layer)) (Oliver and Larsen 1996, Agee 1998, Lertzman et al. 1998, Franklin et al. 2002). Structural complexity may result from moderate-severity fire events and was thus tested here. We also used bottom-up filters in an ad hoc SEA to examine complex associations between fire, climate, and landscape controls. For example, to see if fires on warm aspects with steep slopes are significantly associated with climate patterns. Fire events included in this analysis were filtered by landscape control.

To spatially analyze fire events, we classified events as either single plot, scattered plot, or clustered plot events. We defined single plot events as a fire event that occurred only at a single plot, scattered events as fire events that occurred at more than one plot that was not a nearest neighbour, and clustered events as fire events that occurred at more than one plot which also occurred at a neighbouring plot. We used ArcMap 10 (ArcGIS 2010) for this analysis.
3.3 Results

3.3.1 Fire history

In total, we collected 690 cores and 121 partial or full cross sections from 48 plots. Analyses of the stand-age polygons provided by the Alberta Vegetation Index (AVI) indicated that approximately 50% of the polygons within the two study sites are older than 200 years. We found that while a few stands at site PC originated in the early- to mid-1700s, most established in the 1875 to 1900 period. Site ZS had a similar establishment history, with a few stands establishing in the early- to mid-1700s and most of the stands establishing within the last 150 years, however there is less synchrony in establishment dates post-1850 at site ZS (Figure 3.2). In the regional age-class distributions (Figure 3.3), we see two large establishment periods; the first spans from the late 1800s into the 1920s and the second spans from the 1940s into the 1960s. In an analysis of the age-class distributions between the two study sites, we found more obvious establishment pulses at site PC, whereas more continuous establishment was prominent at site ZS. We found that the regional establishment pulse that spans the late 1800s into the 1920s was dominated by lodgepole pine, whereas the second establishment pulse in the 1940s was dominated by black spruce. We found that no balsam fir has established since before 1910 and white spruce has only more recently established (post-1910).

We found evidence of low- to moderate-severity fire, as evidenced by fire scars, at 31 of the 48 plots (64.6%), and no significant difference in the proportion of plots recording this evidence of fire between the two study sites (PC = 62.5% and ZS = 66.7%, \( p = 0.764 \)). However, the mean occurrence of fire between the two sites did significantly differ (Mann-Whitney U test, \( p = 0.018 \)); 144 instances (including open or buried fire scars and external char evidence) were recorded from 64 samples at PC plots and only 44 scars were recorded from 28 samples at ZS plots. Fire dates ranged from 1808 to >2003 (we also found externally charred samples with outer rings dating to 2003 but no specific fire dates could be assigned to these events due to missing bark and possibly outer rings) across both sites (Figure 3.2). In total, we were able to record 76 event years across both sites. The composite site mean fire return interval (mFRI) at PC was 2.2 years and at ZS
Figure 3.2 Fire demography diagram. Chronology lengths are exemplified by lines. Plus signs (+) indicate fire scars and dark triangles represent cohort initiation. The histogram at the bottom represents regional fire scar frequency (synchrony).
Figure 3.3 Regional static age-class distributions, stratified by species into 10-year bins.

was 5.2 years (which are significantly different based on a Mann-Whitney U test; \( p = 0.000 \), with a regional mFRI of 2.6 years.

We found that 55.3% of fire evidence was represented by fire events at a single plot \((n = 42)\), while 44.7% \((n = 34)\) of events were recorded at two or more plots. However, only four of these multiplot events were recorded at site ZS. Our spatial analyses of fire evidence revealed that 39.5% of fire events were scattered across the study area, while 4% were clustered, indicating either larger fire events or multiple ignitions within a small area. The remaining 56.5% of fire event years were restricted to a single plot. Our fire demography diagram (Figure 3.2) shows the high degree of variability of fire throughout the region and between sites and plots.
We found evidence of high-severity, stand-replacing fire at approximately 54% (26/48) of plots, *i.e.*, cohorts with no trees establishing prior to the cohort. We assumed here that a high-severity fire event initiated the oldest cohort; however, we also recognize that the cohort initiation could be caused by other factors, such as insect outbreaks. However, if we have multiple species forming the same cohort that are unlikely to be attacked by the same insect, it is unlikely that the cohort is insect-initiated. The remaining plots lacked cohorts.

Of the 48 plots we sampled across the study area, only 20 plots (41.7%) had multiple canopy layers (at PC $n = 9$; at ZS $n = 11$), a typical mixed-severity structural characteristic. In most cases (90%), we found that the subcanopies were significantly younger than the canopies. We also differentiated canopies and subcanopies by species and found that lodgepole pine typically characterized the canopy and black spruce the subcanopy. We only detected cohorts in seven subcanopies across both sites (four in PC and three in ZS).

Of the 77% of fire scars to which we could assign an intra-ring position, 91% were in the earlywood or late earlywood of the rings, suggesting they were created by spring or early summer fire events. The remaining 9% were in the latewood and represent mid- to late-summer burning. We were unable to determine the termination position of the scar tips in the remaining samples. We found no obvious spatial pattern to scars found in the latewood; these plots were scattered across sites. We also found no temporal trends in the distribution of latewood scars. Latewood scars were scattered throughout the record.

### 3.3.2 Climate influences on the fire regime

Our SEAs between climate indices and fire years across all plots revealed few significant associations between climate and the years prior to or of the fire event (Figure 3.4). Across both sites and analyzing all fire events, we found the PDO consistently remained positive throughout the seven-year window analyzed, with significant associations four and two years prior to the event and during the event year ($n = 65$). We also found that
the PDSI was consistently negative for the duration of the window around the fire event (n = 65), but significance was not reached; and the local lodgepole pine drought reconstruction was significantly negative the year prior to the fire event (n = 76), indicating a year of decreased growth and/or drought stress. When analyzing fire events that occurred at two or more plots (n = 33), we found a significantly negative correlation with PDSI the year before fire.

**Figure 3.4** Selected superposed epoch analysis (SEA) results. A) Fire events (n = 65) versus Gedalof and Smith (2001) PDO reconstruction, B) Fire events (n = 76) versus Daniels (Personal Communication, 2014) local drought reconstruction and C) Fire events (n = 65) versus Cook and Krusic (2004) PDSI reconstruction. Grey bars represent the index deviation from the mean in the years surrounding fire events. Bars that cross the horizontal black lines are significant (p < 0.05, based on 1000 Monte Carlo simulations). Year 0 represents the year of a fire event. Negative years are those preceding the event and positive years are those following the fire event.

We found that fire events occur in both phases (positive and negative) of all of the climatic patterns analyzed here, but appear to occur more when the climatic indices are not near average. We also found significant associations between the phase (multi-year interval) of ENSO and the PDO and the occurrence of wildfire (p = 0.001), indicating a potential interaction in the teleconnections of these climatic regimes and fire occurrence.

### 3.3.3 Landscape heterogeneity & fire

Our analysis of the fire return intervals between plots with differing elevations, aspects and slopes revealed few overarching significant influences. The mFRIs of plots with cool versus warm aspects did not differ significantly. We found no significant differences in mFRIs between low and high elevation plots. We did find that mFRIs between flat and
steep slopes were significantly different ($p = 0.008$), with longer mFRIs on steeper slopes. We found no significant differences in mFRIs between plots with simple or complex structural complexity (Table 3.1). Correcting for the sampling bias of plots in each landscape category, we found that warm, low elevation, and complex structured plots have higher mFRIs than would be expected (Figure 3.5).

Table 3.1 Fire events, record length and mFRIs divided by sites and landscape controls.

<table>
<thead>
<tr>
<th></th>
<th># Plots</th>
<th># Events</th>
<th>Date range</th>
<th>mFRI (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>29</td>
<td>76</td>
<td>1808-2003</td>
<td>2.6</td>
</tr>
<tr>
<td>PC</td>
<td>16</td>
<td>54</td>
<td>1888-2003</td>
<td>2.2</td>
</tr>
<tr>
<td>ZS</td>
<td>13</td>
<td>38</td>
<td>1808-2002</td>
<td>5.2</td>
</tr>
<tr>
<td>Aspect:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm (90-270°)</td>
<td>21</td>
<td>55</td>
<td>1808-2003</td>
<td>3.6</td>
</tr>
<tr>
<td>Cool (270-90°)</td>
<td>27</td>
<td>53</td>
<td>1888-2002</td>
<td>2.2</td>
</tr>
<tr>
<td>Elevation:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low (&lt;1300 m)</td>
<td>17</td>
<td>49</td>
<td>1808-2003</td>
<td>4.1</td>
</tr>
<tr>
<td>High (&gt;1300 m)</td>
<td>12</td>
<td>48</td>
<td>1888-2000</td>
<td>2.4</td>
</tr>
<tr>
<td>Slope:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat (&lt;10°)</td>
<td>24</td>
<td>69</td>
<td>1808-2002</td>
<td>2.9</td>
</tr>
<tr>
<td>Steep (&gt;10°)</td>
<td>5</td>
<td>28</td>
<td>1900-2003</td>
<td>3.8</td>
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<tr>
<td>Structure:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simple</td>
<td>16</td>
<td>50</td>
<td>1888-2003</td>
<td>2.4</td>
</tr>
<tr>
<td>Complex</td>
<td>13</td>
<td>49</td>
<td>1808-2002</td>
<td>4.0</td>
</tr>
</tbody>
</table>

3.3.4 **Interactions between top-down and bottom-up controls**

Our analyses of interacting associations between top-down and bottom-up controls revealed interesting patterns. We found that ENSO was significantly positively correlated with fire events on warm aspects in the year prior and the year of fire. We also found a significantly positive association between growth (local lodgepole pine reconstruction) and fire two years prior to fire on warm aspects, and negatively correlated the year prior to fire on cool aspects. Overall, we found that lower elevation (<1200 m) and steeper sloped plots have more significant associations with climate variables than higher elevation or flatter plots and stand structure differences were not significantly or consistently related to climate and fire activity.
3.4 Discussion

3.4.1 Fire history & stand dynamics
The fire history of the Hinton area is best categorized as spatially and temporally variable. Fire is an active and crucial part of the foothills landscape (Andison 1998), but is not characterized by low-frequency, high-severity fires similar to the neighbouring mountain slopes (Johnson et al. 1990, Masters 1990, Weir et al. 2000, Van Wagner et al. 2006). The tree-ring record of fire in this study provides insights regarding the frequency of fire and establishment pulses over the last ~150 years. A large number of trees appear to have established in the mid- to late-1800s, suggesting a large-scale fire prior to or around this time. Reconstructions in neighbouring areas show large-scale fire activity during this time (Amoroso et al. 2011, Chavardes and Daniels 2016). Frequent low-
severity fires characterized the end of the 1800s (Figure 3.2). In addition, an establishment pulse of lodgepole pine persisted into the 1920s (Figure 3.3). Lodgepole pine is a post-fire regenerator, and we suspect this pulse is an indicator of regional-scale, high-severity fire activity just prior to this time (Amoroso et al. 2011). The 1920s were also characterized by frequent fire events, followed by a decrease in the 1930s. We found another pulse in establishment in the 1940s that was dominated by the establishment of black spruce. We hypothesize that this may be the result of low- to moderate-severity fire events in the 1920s that opened the landscape for spruce subcanopy establishment. In most cases, we found that the canopy was dominated by shade-intolerant lodgepole pine, while shade-tolerant black spruce was in the subcanopy. Of the plots that exhibited complex structure, which are believed to be indicative of mixed-severity fire regimes, we found significant differences between the ages of the canopy and subcanopy. Since the 1950s, we found a decrease in establishment and fire activity that can be explained by the onset of active management and harvesting of the region for timber purposes beginning in the late 1950s (MacLaren et al. 2007).

The intra-ring positions of fire scars (Section 3.3.1) suggest that fires in this area are predominantly spring and early summer events and this does not appear to have changed over the length of the record. The amount of snowpack and type of precipitation falling in the spring determine if and when the landscape is dry enough to burn (Morgan et al. 2008, Lutz et al. 2009) and these influences can be further magnified or minimized based on regional or local landscape differences. Furthermore, the pulse of understory plants in the spring provides fuel if and when conditions are ideal for ignition. Lightning events that are more likely to increase ignition probabilities also increase in the late spring and early summer (Romme 1982, Gedalof et al. 2005, Gedalof 2011, Hessl 2011), which together help to explain our seasonal findings.

Results from the spatial analysis (Section 3.3.1) suggest that very few fire events were spatially clustered (i.e. regional events). Scattered fire events were more common, but single plot events were the most dominant. Scattered fire events demonstrate the interaction we found between bottom-up controls and climate, suggesting that fires in
certain areas of the region with unique landscape controls also respond to climate controls (Morgan et al. 2001). We further hypothesize that the dominance of single plot events demonstrates the high degree of topographic and structural complexity found in the region.

3.4.2 Fire regime complexity in the Foothills

We found that fires in this region tend to occur under a wide range of climatic conditions and in a range of landscape characteristics. The fire regime in the foothills does not appear to be controlled by any single factor. While this finding may be atypical of fire studies in western Canada and the western United States (Hessl et al. 2004, Schoennagel et al. 2005, Trouet et al. 2006, Schoennagel et al. 2007, Sherriff and Veblen 2008), this area is uniquely located at the interface of an important ecotone between two well-defined fire regimes. The surface fire regime of the dry intermountain cordillera (Heyerdahl et al. 2012) and the stand-replacing regime of the boreal plains (Hunter 1993) have dominant controls, but being located between these two regimes, the fire regime in the foothills appears to be a combination of the two regimes and their respective controls (fuel- and moisture-driven) at the scale of analysis, as well as land management.

Although we found fire activity occurs under a range of climatic conditions in this region, we did find a consistent association between fire and prolonged drought periods (Figure 3.4). Though not consistently significant, prolonged periods of positive PDO and negative PDSI were associated with fire activity. We suspect that this indicates an important association between multi-year drought and fire preconditioning in this region (Westerling and Swetnam 2003), and that due to the mesic nature of many plots, a persistent and prolonged drought is necessary for fire. For example, an abnormally long positive PDO phase from 1902-1950 occurred simultaneously with increased fire frequency (Figure 3.2). We found that local drought reconstructions detect significant short-term preconditioning relationships between drought and fire, such as a decrease in growth associated with drought conditions in the year before fire (Figure 3.4). We also found that slope is most often significantly related to fire activity, however counter-intuitively. Steeper slopes, which are presumably drier than flatter slopes, have longer
mFRIs. Therefore, we suspect interactions between these plot-level landscape characteristics and climate may best explain fire activity (Morgan et al. 2001). For example, under drought conditions, a flat plot located on a plateau will burn most frequently. Climatic influences on fire regimes are well established and the significance of these relationships are not questioned here (Hessl et al. 2004, Schoennagel et al. 2005, Trouet et al. 2006, Schoennagel et al. 2007, Sherriff and Veblen 2008). Instead, we suggest that the overarching climatic influences interact with the finer scale spatial heterogeneity in this landscape to create unique fire events that result in a range of fire characteristics that are best defined as mixed-severity.

Definitions of mixed-severity vary. Mixed-severity is defined as a fire event of moderate-severity or a fire event that results in varying fine-scale spatial severity differences (Barrett et al. 1991, Arno et al. 2000, Fulé et al. 2003, Brown et al. 2004, Buechling and Baker 2004, Agee 2005). We have defined this region as a mixed-severity fire regime according to the latter. We found mixed-severity evidence at single plots where a single tree succumbed to fire and a neighbouring tree was simply scarred. Groundtruthing of aerial photographs during the 1960s confirmed the presence of single trees scarred or killed by lightning, with a small burn area affecting adjacent trees (Murphy, Personal Communication, 2013). These small events may be ecologically important for gap dynamics in these regions and are important for management by means of their cumulative effects over time (Cumming et al. 2000). Mixed-severity fire regimes may also be represented by HRVs that represent temporal shifts in severity. While we were only able to reconstruct the fire history of the HWP FMA over the last ~150 years, and found evidence of mostly low- or moderate-severity fire events, we conclude that high-severity fire events in the mid-1800s were likely responsible for the establishment of many of these stands.

3.5 Conclusions
Understanding the controlling mechanisms of fire regimes in areas where active forest management and mixed-severity wildfire intersect, specifically timber harvesting regions, is imperative for the maintenance of ecological integrity in these ecosystems under future
management and climate change scenarios (Swetnam et al. 1999, Conedera et al. 2009). This study demonstrates the complex nature of mixed-severity regimes in a heterogeneous and understudied region of the eastern Foothills of the Rocky Mountains. We reconstructed the fire history of the HWP FMA and conclude that 1) fire occurs under a range of climatic and landscapes conditions and that fire is not controlled by a single mechanism, but is likely rather an interaction of multi-scale controls (Heyerdahl et al. 2001, Morgan et al. 2001, Falk et al. 2007) and 2) the presence of both fire scars and cohorts over time and space indicate that this region operates under a mixed-severity fire regime. While we found that large-scale fire events have been rare in this region over the last ~150 years, we have highlighted the role of low-severity, high-frequency events in regulating stand structure and composition. We have also highlighted the role of management and fire exclusion in altering stand structure and fire activity outside of the HRV (Hunter 1993), as seen by shifts in species composition and decreased fire activity that coincides with 20th-century forest management.

### 3.6 References


CHAPTER 4: CORROBORATING LAKE SEDIMENT CHARCOAL RECORDS WITH TREE-RING DERIVED FIRE SCAR AND STAND INITIATION RECORDS IN COMPLEX FIRE REGIMES: A CASE STUDY IN THE ROCKY MOUNTAIN FOOTHILLS OF ALBERTA, CANADA

Vanessa Stretch, Ze’ev Gedalof, Michael F.J. Pisaric, Jaclyn Cockburn

Macroscopic sedimentary charcoal preserved in lake sediment has the potential to extend records of historical wildfires. However, charcoal records cannot be used to infer spatial locations or severity of wildfire. Tree-ring records of fire developed from the eastern foothills of the Rocky Mountains, Alberta, Canada, provide high-resolution reconstructions of fire and were used to corroborate overlapping lake sediment charcoal records. Here, we collected 1 m cores from 2 small lakes in the foothills and compared peaks in charcoal accumulation with fires found in the tree-ring record. We found a high level of correspondence between tree-ring records (fire scars and stand establishment estimates) and peaks in charcoal in the sediment record. We found that peaks in charcoal are synchronous with periods of increased low-severity fire (fire episodes), but peaks do not capture all low-severity fires due to location and constraints of production and deposition of charcoal. We hypothesize that charcoal peaks not found in the tree-ring record may represent higher-severity fire events that are missing in the tree-ring record due to subsequent events. Overall, we found that the macroscopic sedimentary charcoal record preserved in small lakes in the foothills captures a consistent but longer record of historical wildfires than tree rings, and can be used in reconstructing historical wildfire regimes.

4.1 Introduction

With fire activity expected to increase under future climatic scenarios, management of fire-prone landscapes in the coming decades will rely on our understanding of the relationship between climate, vegetation, and fire activity (Flannigan et al. 2005). Knowledge of how fire-prone systems have responded to climatic changes in the past can provide us with an understanding of how these systems may respond to future changes (Agee 2000). Recent records of fire activity help to highlight the role of management in these relationships, as well. However, landscape management in many regions, such as fire exclusion and forest harvesting, has altered natural fire regimes and moved some
forest systems outside of their natural range of variability of wildfire over the last century (*i.e.* the span of the observational record) (Agee 1998, Whitlock *et al.* 2010).

Paleoecological records provide us with unique environmental information about vegetation, fire, and climate interactions beyond instrumental and historical records, and they can be used to reconstruct the natural range of variability of wildfire and contextualize anticipated changes under future climate scenarios (Schoonmaker and Foster 1991, Smol 2002). Paleoecological proxy records have been used to infer fire activity in fire prone landscapes, including tree rings and sedimentary charcoal (Clark 1990, Millspaugh and Whitlock 1995, Whitlock and Larsen 2001, Whitlock *et al.* 2004, Higuera *et al.* 2005, Gavin *et al.* 2006). These records provide unique information concerning fire activity at differing spatial and temporal resolutions. Tree rings can provide seasonal or annual temporal resolutions at fine spatial scales, which are used to infer fire frequency and severity, but are limited in temporal length to the age of the oldest intact sample. In industrially managed landscapes, this often limits the length of the records to ~100 years.

Sedimentary charcoal collected from lake sediment can be used to extend the temporal record of fire activity beyond the dendrochronological record (Gavin *et al.* 2007, Whitlock *et al.* 2008), however charcoal is often not enumerated at annual resolution, and the resolution varies with sediment accumulation in lakes (Whitlock and Larsen 2001, Gavin *et al.* 2003a, Tinner *et al.* 2006). Charcoal may also represent fire activity over large spatial scales (regional to landscape) and it is therefore difficult to spatially locate fire activity (Gavin *et al.* 2003b). Both of these proxies have advantages and limitations and historically have been studied individually, but more recently we have seen that combining data across proxies can provide a better, long-term understanding of the associations between fire, vegetation and climate (Long *et al.* 1998, Walsh *et al.* 2010, Marlon *et al.* 2012).

Charcoal is produced from incomplete combustion of material during a fire and can thus be indicative of vegetation biomass and fire intensity (Lynch *et al.* 2004b).
Charcoal particles also vary in size. Microscopic charcoal (<50-100 microns) can be carried far from fire locations (tens to hundreds of kilometers) due to its small and light nature (Whitlock and Larsen 2001, Peters and Higuera 2007); macroscopic charcoal (>125-150 microns) represents larger, heavier pieces that fall out of the atmosphere over shorter distances (meters to tens of kilometers) (Pisaric 2002) and are indicative of local or extralocal fires (Whitlock and Millspaugh 1996, Whitlock and Larsen 2001). Macroscopic charcoal is thus more often used to study local fire events within a few kilometers or less of the sampling location (Gavin et al. 2003a).

Charcoal from fires can blanket landscapes and subsequently be incorporated into both terrestrial and aquatic sediment. Terrestrial soil coring can produce records of charcoal accumulation, however soil records often suffer from low charcoal concentrations, slow sedimentation rates, and periods of erosion that can cause discontinuities in the soil profile (Gavin et al. 2003b, Higuera et al. 2005). Conversely, charcoal captured in lakes or ponds and incorporated into sediment is normally preserved in a continuous and undisturbed manner (Millspaugh and Whitlock 1995, Whitlock and Millspaugh 1996, Whitlock et al. 2004).

Fire is a prominent disturbance in the Rocky Mountains in Alberta, Canada, and multiple paleoecological proxy studies have been conducted in this high elevation, mountainous region (Tande 1979, Johnson et al. 1990, Masters 1990, Weir et al. 2000, Van Wagner et al. 2006, Courtney Mustaphi and Pisaric 2014). However, little research has been conducted in the lower elevation, eastern foothills of the Rocky Mountains. The paucity of fire research from this region has relied exclusively on tree-rings (Amoroso et al. 2011). A longer-term reconstruction of fire activity in this region, incorporating macroscopic sedimentary charcoal, may provide a better understanding of fire dynamics.

The eastern foothills are heterogeneous in terms of their topography and forest cover (Andison 2012) that we hypothesize contributes to variable fire severity over both space and time. This variability has implications for both the relative effectiveness of past fire suppression efforts and future forest management plans in the region. The purpose of
this study is to contextualize the contemporary fire regime within a longer term range of historical variability by 1) reconstructing the fire history in the eastern foothills of the Rocky Mountains using macroscopic sedimentary charcoal and 2) corroborating sedimentary charcoal records with an existing tree-ring record of fire (Chapter 3).

4.2 Methods

4.2.1 Study area
The eastern foothills of the Rocky Mountains, near Hinton, Alberta, is a wildfire-prone forested region that borders the Boreal Plains and Montane Cordillera and is located in the Alberta uplands ecoregion (Ecological Stratification Working Group 1996). Forests here are dominated by fire tolerant, thin-barked lodgepole pine (*Pinus contorta*), with lesser amounts of black spruce (*Picea mariana*), white spruce (*Picea glauca*), trembling aspen (*Populus tremuloides*), balsam fir (*Abies balsamea*), and western larch (*Larix occidentalis*). Fire is a necessary and important component of the regeneration and reproduction of these forests (Agee 1993, Brown 2000). In addition, the landscape is dotted with many small lakes, bogs, wetlands and fens, as well as rolling hills and plateaus (Andison 1998, Amoroso et al. 2011). The high level of topographic variability and potential for aquatic sedimentary charcoal records makes this landscape ideal for reconstructing complex and variable fire regimes from multiple proxies.

Hinton Wood Products, A Division of West Fraser Ltd., has managed a large portion of the forested landscape in the foothills east of Jasper National Park since the mid-1950s (Figure 4.1) (Hinton Wood Products 2010). This study was carried out in the northern portion of the Hinton Wood Products Forest Management Area (HWP FMA). Two small (<1 ha) lakes (hereby denoted Lake PC and Lake ZS) were selected for charcoal analysis in this study. These lakes were selected due to minimal inflows and outflows, a regular shape (circular/oblong), and no visual evidence of disturbance from rockfalls or landslides (Millspaugh and Whitlock 1995, Whitlock and Millspaugh 1996, Whitlock et al. 2004). The lakes were located in documented and expected regions of fire activity within the HWP FMA. Lake PC (53.6635°N, 117.8465°W) is located at ~1400 m
a.s.l., on a plateau (Figure 4.1 and 4.2). A series of random depth measurements revealed Lake PC has flat-bottomed bathymetry with an average depth just over 1 m. Lake ZS (53.8802°N, 117.4300°W) is located approximately 37 km NE of Lake PC and is ~1100 m a.s.l. (Figure 4.1 and 4.2). Lake ZS has a bowl-shaped bathymetry and is 4.75 m deep at its deepest location. Both lakes are surrounded by mats of floating vegetation, which extend a few metres into the lake.

**Figure 4.1** Study area, eastern foothills of the Rocky Mountains, Alberta, Canada. A) Hinton Wood Products Forest Management Area (HWP FMA) highlighted in white. B) Study sites located north of Hinton. White squares highlight the area of the two small sampled lakes. Black circles represent existing tree-ring sampling plots (Chapter 3). DEM source: Shuttle Radar Topography Mission (SRTM), NASA.
Figure 4.2 Sampled lakes and surrounding landscape. A) Lake PC, facing northeast. Lake PC is located on a plateau. B) Lake ZS, facing southeast. Lake PC is located at lower elevation and the surrounding region borders a large river.

4.2.2 Macroscopic sedimentary charcoal records

Since the multi-century tree-ring record of fire is short, we were only concerned with the overlapping portion of the sedimentary charcoal record to corroborate the two proxies. We used a modified Livingstone piston corer to retrieve a ~1 m core from the deepest location in each lake (Wright et al. 1984). We extruded and subsampled each core in the field at contiguous 0.5 cm increments. We removed approximately 1 cm$^3$ of sediment from each subsample and deflocculated it for 24 hours in 30 ml of 5% sodium hexametaphosphate solution (Hallett and Walker 2000, Walker 2001, Whitlock and Larsen 2001). We then wet-sieved the samples through a 150 µm sieve (Whitlock and Larsen 2001) and rinsed the remaining material into a labeled petri dish. We took extra care during the sieving process to ensure that large pieces were not broken during sample handling. We identified charcoal pieces by studying reference photos and by comparison to known charcoal properties (i.e. black colour, opacity, high light reflectivity, and fragile breakage leaving a black powdery track) (Enache and Cumming 2006). We used a 0.5 cm x 0.5 cm grid to help tally macroscopic charcoal pieces in each subsample (Hallett and Walker 2000, Whitlock and Larsen 2001).

We obtained $^{210}\text{Pb}$ dates from the top ~30 cm of each core from MyCore Scientific, Inc. (Dunrobin, Ontario, Canada) and used linear extrapolation to assign dates
to the full length of the core (Nevissi et al. 1989, Higuera et al. 2005). We entered interpolated and extrapolated sediment dates and charcoal counts into CharAnalysis (Higuera et al. 2009) for further statistical analyses and identification of fire events, peak detection, and background charcoal. We then re-interpolated the charcoal series to a common sampling interval (Higuera et al. 2005), and performed a correlation analysis between the two lakes in order to determine if the charcoal records were synchronous across large spatial scales (landscape). We also used a regime-shifting algorithm by Rodionov (2004) to detect significant changes in background charcoal that might be associated with climate or land management practices.

4.2.3 Correspondence with tree-ring records
We used existing tree-ring records collected from stratified randomly sampled plots surrounding each of our lakes (Figure 4.1), up to six km from the lake in all directions, which represents a probable source area for charcoal transport (Whitlock and Millspaugh 1996). From each of the four cardinal wind directions, six plots (minimum 100 years old) from the Alberta Vegetation Index forest polygon data (Environment and Sustainable Resource Development 2008) were selected and sampled, totaling 24 plots surrounding each lake. Data collected included fire scar (a proxy for low-severity fire events) (Agee 1993; 1998, Swetnam et al. 1999) and estimated stand establishment dates (a proxy for the most recent high-severity fire) (Heinselman 1973, Van Wagner et al. 2006) that spanned the last ~200 years, with greater sample depth post-1875. More detailed tree-ring methods are described in Chapter 3.

Due to different spatial and temporal scales represented by tree-rings and lake sediment, corroborating these two proxies can be difficult (Swetnam et al. 1999). Furthermore, the challenges inherent in reconstructing fire from sedimentary charcoal can be exacerbated due to dating errors (Millspaugh and Whitlock 1995, Tinner et al. 1998, Higuera et al. 2005). As such, to corroborate these proxy records of fire that should presumably be documenting the same events, we used a modified method from Higuera et al. (2005) to quantify correspondence for each lake that calculates window lengths for detection based on individual age-depth models. We compared fire scar and stand
establishment dates against initiation dates from statistically significant peaks in charcoal, as well as against dates of significant shifts in background charcoal. We assessed correspondence as the proportion of positive detection rates, i.e. the proportion of charcoal peaks that are associated with fires in the tree-ring record.

4.3 Results

4.3.1 Fire history from charcoal records
Due to a lack of macrofossils, inbuilt age assumptions associated with shells and aquatic vegetation found in our subsamples, and the carbonate base of the underlying geology that prevented confident $^{14}$C bulk sediment dating, we used linear models based only on our $^{210}$Pb results to interpolate and extrapolate dates for each core (Nevissi et al. 1989, Higuera et al. 2005). A lower sedimentation rate (~0.2 cm/yr on average) in Lake PC resulted in a sediment date of 1533 AD at the bottom of the core; a higher sedimentation rate (~0.5 cm/yr on average) resulted in a sediment date of 1745 AD at the bottom of the core in Lake ZS (Figure 4.3). These age-depth models resulted in three-year and one-year resolutions, respectively.

Using $^{210}$Pb dates and charcoal counts, a local peak detection threshold in CharAnalysis was selected that was defined as a percent cutoff (95%) of the noise distribution defined by a Gaussian mixture model with a minimum count probability <10% within 75 years of the peak. We selected a Lowess smoother that was robust to outliers and was smoothed over 100-year windows to detect background charcoal (Higuera et al. 2005). We selected these parameters to help detect relative peaks in charcoal due to the overall lower amount of charcoal found in our lakes than those in montane studies (Gardner and Whitlock 2001, Prichard et al. 2009, Courtney Mustaphi and Pisaric 2014, Davis 2014). This analysis resulted in charcoal accumulation rates, background charcoal, and statistically significant peaks in charcoal that represent fire activity.
Figure 4.3 Age-depth models of A) Lake PC and B) Lake ZS. Dots represent $^{210}\text{Pb}$ dates with 95% error bars. A linear age depth model has been extrapolated to the base of the core.

We found that charcoal accumulation varied over the length of both records (Figure 4.4). Fire peak magnitudes also appear to be higher in the past than in the current century, representing increased charcoal production from either higher-severity fires or more proximate fires. We identified 15 significant peaks in Lake PC and 14 in Lake ZS. The mean fire return interval (mFRI) calculated from the charcoal records is 29.6 years in the Lake PC region (range = six to 57 years) and 16.1 years in the Lake ZS region (range = three to 59 years). The study area as a whole has a mFRI of 15.3 years, with a range of two to 48 years. Using a regime-shifting algorithm from Rodionov (2004), we also found three significant shifts in background charcoal (i.e. a regime shift) in the PC region and six significant shifts in the ZS region (Figure 4.4).
Figure 4.4 A) PC site and B) ZS site fire records. Charcoal accumulation rate (black line), background charcoal (dashed line), and significant charcoal peaks (squares). Tree-ring records of fire include stand establishment dates (grey diamonds) and fire scars (triangles). All fire scar events are depicted as small, light grey triangles. Stepped solid black lines display significant regime shifts in background charcoal.

In order to identify regional trends in fire activity and to help determine if the charcoal records in fact represent only local fire events, we calculated Spearman correlations for the charcoal accumulation rates between lakes, using re-interpolation to match sample resolutions across cores. We found a significantly positive, but weak (rho = 0.139, p = 0.022) correlation. However, given serial autocorrelation in the time series, it is possible that the correlation is spurious and that the two records are statistically independent.
4.3.2 Correspondence between proxies

To assess correspondence between the charcoal record of fire and the tree-ring record of fire, we modified a method of correspondence from Higuera et al. (2005). Our modified method defined correspondence as a charcoal peak occurring five years prior or 10 years post-fire event found in the tree-ring record in the ZS region and as 15 years prior or 30 years post-fire event in the tree-ring record in the PC region. These windows were selected individually for each lake taking into account different age-depth models, potential dating and extrapolation errors, sediment focusing and/or mixing, and potential delayed charcoal transportation processes (Higuera et al. 2005). We also assessed correspondence between fire activity (i.e. fire scars, stand establishment, and charcoal peaks) and shifts in the background charcoal regime, which may represent changes in vegetation biomass and/or landscape-scale fire activity (Rodionov 2004).

Table 4.1 Correspondence between proxy records.

<table>
<thead>
<tr>
<th>Proxies</th>
<th>Correspondence at PC</th>
<th>Correspondence at ZS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire scars &amp; charcoal peaks</td>
<td>40%</td>
<td>43%</td>
</tr>
<tr>
<td>Stand establishment &amp; charcoal peaks</td>
<td>60%</td>
<td>43%</td>
</tr>
<tr>
<td>Fire scars, stand establishment &amp; charcoal peaks</td>
<td>60%</td>
<td>57%</td>
</tr>
<tr>
<td>Charcoal peaks &amp; background charcoal</td>
<td>100%</td>
<td>67%</td>
</tr>
<tr>
<td>Fire scars &amp; background charcoal</td>
<td>0%</td>
<td>50%</td>
</tr>
<tr>
<td>Stand establishment &amp; background charcoal</td>
<td>33%</td>
<td>33%</td>
</tr>
</tbody>
</table>

We found that charcoal peaks correspond well with the tree-ring record of fire, with correspondence rates >40% in most cases (Table 4.1). We found that some, but not all, charcoal peaks are found in the tree-ring record and that higher severity fires in the tree-ring record (stand establishment dates) correspond more strongly to the charcoal record than lower severity fires (fire scar dates) in the PC region. We also found that shifts in background charcoal correspond most with charcoal peaks, and very little with fire scars and stand establishment. Shifts in background charcoal are not synchronous.
across the study area. Instead, background charcoal appears to represent a regional signal of vegetation biomass and/or regional fire activity surrounding each lake.

### 4.4 Discussion

#### 4.4.1 Fire history from charcoal records

We found a high degree of variability in fire frequency in the macroscopic sedimentary charcoal records from two small lakes in the foothills region, consistent with hypothesized paleofire activity in the region (Amoroso et al. 2011, Andison 2012). The two lakes sampled, ZS and PC, each have unique charcoal records (Figure 4.4). Results indicate an overall decline in background charcoal over the 20th-century, what we believe to be the impact of fire exclusion practices in the surrounding regions. Results also show that the highest charcoal accumulations were in the early part of the records. We suspect that these peaks represent the last major fire events before the onset of severe Little Ice Age cooling in the region (Mann 2002). Watson and Luckman (2001) also found drought conditions persisted in the greater study area (Jasper National Park & the foothills) from approximately 1600 AD to 1800 AD. Drier conditions in the region may have resulted in larger burns with greater charcoal accumulations. We also found an increase in fire activity beginning in the 1920s that is consistent with drought conditions in the region (Case & MacDonald 1995, Watson & Luckman 2001). As this region was not actively managed until the mid-1950s, we suspect that prolonged drought was the main driver of fire activity in the 1920s. However, with the creation of Jasper National Park to the west in 1907, an increase in recreational use of the surrounding region may have resulted in increased human ignitions as well (MacLaren et al. 2007).

Given age differences in the two cores, we conclude that fire activity is greater in the ZS region; we found a similar number of peaks over a shorter record in Lake ZS. This contradicts the tree-ring fire evidence from the two sites (Chapter 3). The tree-ring record indicates more fire activity in the PC region (a higher elevation, drier region), and less in the ZS region (a lower elevation, wetter region). The tree-ring records of fire support general fire ecology literature that explains the effects of landscape variability on fire
activity (Agee 1993; 1998). We speculate that the contradiction between the tree-ring and charcoal records of fire may be related to differences in fire severities (Whitlock and Larsen 2001). There were a higher number of fire scars in the PC region, indicative of low-severity events, which were confirmed to be small in extent (Murphy, Personal Communication, 2013). Low-severity events result in less charcoal production due to limited fuels to combust, hence fewer peaks in the lake sediment record (Whitlock and Larsen 2001). Given that this region experiences more frequent low-severity fire, there are less understorey fuels to burn in subsequent fires, which reflect smaller peaks in the charcoal record. Conversely, the ZS region does not easily or as often ignite due to moisture constraints. When triggered by a dry enough climate, the abundance of fuels may result in a moderate to high-severity fire that produces more charcoal. It is hypothesized that more productive (fuel abundant) regions may produce more charcoal more often than less productive (fuel-limited) regions (Meyn et al. 2007, Krawchuk and Moritz 2011). Charcoal peaks may thus represent higher-severity events that are not picked up in the tree-ring record (as found in Lake ZS) or multiple low-severity events occurring over a short period of time (as found in Lake PC).

4.4.2 Correspondence between proxies
Due to the inability to differentiate between a small, proximate, low-severity fire and a larger, higher-severity, distant fire in sedimentary charcoal records (Whitlock and Larsen 2001, Pisaric 2002, Gavin et al. 2003b, Higuera et al. 2005, Tinner et al. 2006), it was not possible to draw conclusions about fire severity from the charcoal record alone. Instead, the charcoal record of fire activity was corroborated with the tree-ring record, which spans the local environment around each lake. Correspondence between all tree-ring records of fire and charcoal peaks across the study area was ~60%. While this figure is not extremely high, it is unlikely that the charcoal records capture fire evidence from every fire in the surrounding landscape. Fire activity that is not detected in the lake sediment charcoal record may represent small or low-severity fire events that do not produce enough charcoal or may be in a location not likely to transport charcoal to the lake (dependent on wind directions at the time of fire) (Clark 1988, Gardner and Whitlock 2001, Lynch et al. 2004a, Whitlock et al. 2004, Tinner et al. 2006, Peters and
Higuera 2007). The tree-ring records also do not capture all fire events burning on the surrounding landscape; they represent fire evidence from only 24 plots. Given that fires reconstructed from the tree-ring record were recorded at only a few plots, it is likely that these events were small in extent. It is also likely that fires burning outside of the tree-ring plots may also be represented here as charcoal peaks.

It is also important to note that stand establishment dates tended to correspond better with charcoal peaks than with fire scars because higher-severity events produce more charcoal and result in charcoal peaks (Meyn et al. 2007, Krawchuk and Moritz 2011). However, this method of correspondence does not consider the cumulative impact of multiple low-severity fire events on the charcoal record. Many low-severity fires over a short period of time may have the same effect on the charcoal record (i.e. a peak in charcoal) as a high-severity, stand-initiating event. Furthermore, because the dates assigned to charcoal peaks indicate the initiation of a peak, and peaks persist over varying lengths of time, charcoal peaks may be better understood as episodes rather than discrete events. The charcoal records developed for the Foothills region seem to support this, as numerous fire episodes in the sediment record are associated with multiple low-severity fire events in the tree-ring record. Therefore, charcoal peaks prior to the start of the tree-ring records likely represent periods of fire activity in the surrounding region as opposed to discrete events. While the record may not provide specific characteristics or locations of these events, it is a glimpse into fire activity prior to the observational and tree-ring records in this area (Andison 2012). Thus charcoal peaks can be confidently used as indicators of local fire activity, however they can result from a range of fire severities that are known to define the fire regime in this region.

4.4.3 Implications for mixed-severity fire regimes

The sedimentary charcoal records used in this study are not typical of those from mountain, high-elevation lakes (Gardner and Whitlock 2001, Prichard et al. 2009, Courtney Mustaphi and Pisaric 2014, Davis 2014). These small lakes have high loads of organic matter, are very productive, and are being overtaken by aquatic vegetation. These lake environments have been largely understudied in the sedimentary charcoal research
community. Despite their comparatively lower concentrations of charcoal, this study has highlighted their potential use to extend tree-ring proxies of fire further back in time in heterogeneous regions with complex, mixed-severity fire histories such as the Foothills. Previous and current understandings of the historical range of variability of wildfire in the area assume a single fire regime that is infrequent and stand-replacing, similar to the nearby mountain slopes (Amoroso et al. 2011). This assumption still underlies management planning in the area. The results show a weak correlation between charcoal records across the region, which suggests that it is unlikely that large-scale fire activity dominates. Instead, each lake has a unique record of fire that has developed due to the high degree of landscape variability in the region. Therefore, more studies of this nature are required in large and topographically diverse areas that are and will be managed for multiple purposes now and in the future.

4.5 Conclusion
We reconstructed the recent macroscopic sedimentary charcoal record of wildfire in the forests of the eastern foothills of the Rocky Mountains, near Hinton, Alberta, and validated the sediment charcoal record with high-resolution tree-ring records of fire (fire scars and stand establishment dates). We found that this area has historically had a mixed-severity fire regime over time. Periods of increased fire activity from 1500 AD to 1800 AD were followed by a decrease in fire activity in the 1800s. Another notable peak in fire activity occurred in the 1920s, which occurs simultaneously with a known period of regional drought, and likely an increase in human use of the landscape. We found that peaks in charcoal are associated with periods of increased low-severity fire, and charcoal peaks not found in the tree-ring record may represent higher-severity fire events not recorded in the tree-ring record because they occurred prior to the start of the record or evidence was lost in subsequent events. Overall, we found that the macroscopic sedimentary charcoal record preserved in small lakes in the foothills complements the tree-ring record of historical wildfire and has the potential to provide wildfire information prior to the start of tree-ring records.
4.6 References


CHAPTER 5: DISCUSSION & CONCLUSIONS

5.1 Summary
The aim of this dissertation was to use a multiproxy, hybrid-methods approach to test the hypothesis that the HWP FMA is characterized by a mixed-severity fire regime. In a heterogeneous, understudied forested region in the HWP FMA in the eastern foothills of the Rocky Mountains in Alberta, Canada, I reconstructed historical fire dynamics using tree-ring and sedimentary charcoal fire records and classified the historical and recent fire regime.

In chapter 2 I examined how fire regimes and fire event detection are influenced by the selection of researcher-defined filters. Both the size of the stand establishment bin and the number/ratio of trees or plots recording fire scars ultimately affect the mean fire return intervals (mFRIs) and the classification of the fire regime based on severity. I found that commonly used detection criteria bias against small, low-severity fires, and against mixed-severity fires in particular. In topographically and/or structurally heterogeneous landscapes, plot-level fire regime classification best defines spatially mixed-severity regimes.

In chapter 3 I presented a detailed fire history reconstruction from the HWP FMA, as well as analyzed the role of top-down (i.e. climate) and bottom-up (i.e. topographic) controls on fire activity. I examined stand establishment (high-severity fire proxy) and fire scars (low-severity fire proxy) at two spatial scales (local and regional). I found that high-severity fire is currently infrequent in this region, but frequent low-severity fire episodes were prevalent prior to active harvesting. Climate is not a dominant control on fire activity in this region. Instead, slope is most strongly associated with fire activity. Fire activity in this region appears to be more controlled by landscape characteristics combined with localized drought, however fire is likely under a range of climatic conditions.
In chapter 4 I assessed the use of macroscopic sedimentary charcoal as a fire proxy in the HWP FMA. Macroscopic charcoal accumulation rates from two lake cores were corroborated with surrounding tree-ring fire records. Peaks in charcoal, which represent fire episodes, corroborated well with tree-ring fire records. Stand establishment records corroborated best, as they represent high-severity events that are likely to produce more charcoal. Frequent, low-severity fire events in the tree-ring fire record were represented in the charcoal record as a single peak. The macroscopic sedimentary charcoal record extended fire records back ~450 years.

5.2 Contributions
The contributions from this research are both practical and scholarly. This fire history reconstruction provides useful information for continued development, industry, and conservation planning and management in the area. My research has provided an idea of the natural HRV of wildfire, including frequency and severity information, as well as how humans have more recently impacted the fire regime in this area. This can be used by HWP to more accurately attempt to mimic natural wildfire with harvesting practices.

A key scholarly contribution presented in this dissertation is how researcher-selected fire event detection criteria affect fire regime classification, specifically biasing against mixed-severity fire. It is important to select detection criteria for fire history studies that are at the appropriate scale to the ecological questions being addressed. I have also demonstrated the importance of scale in reconstructing mixed-severity fire histories and contributed to the development of multiproxy studies by quantitatively corroborating tree-ring and charcoal fire records in a mixed-severity fire regime. Together, this information can be used to model future fire activity under different climatic and management scenarios. Specifically, this research can be used to anticipate the impacts of changes in land cover and management strategies (fire exclusion and/or prescribed burning) on heterogeneous landscapes with mixed-severity fire regimes. An improved understanding of event detection, drivers of fire regime change, effects of management, and multiproxy reconstructions in mixed-severity regimes will allow for better predictions of fire regime changes under future climatic scenarios.
5.3 Limitations & Future Research

This research has its limitations and many areas for continued research. First, further analyses on the effects of detection criteria in other fire regimes and other sources of uncertainty in fire regime reconstructions are necessary. Testing the effects of detection criteria on regime classification in other mixed-severity regimes, as well as in high- and low-severity regimes, is needed to assure correct classification. Second, more research is needed on the interrelationship between climatic and landscape controls on fire activity. Generally, these controls have been statistically associated with fire activity separately (e.g. Heyerdahl et al. 2001, Heyerdahl et al. 2002, Schoennagel et al. 2004, Gedalof et al. 2005, Lentile et al. 2006, Dillon et al. 2011), and while here I found weak interrelated associations, little research has been done on this connection. It is potentially an important association explaining fire activity that crosses scales (local to regional) and may better explain fire activity at both scales. Third, more multiproxy fire history studies are needed (Clark 1988, Tinner et al., 1998, Gavin et al. 2003, Hallett et al. 2003, Higuera et al. 2005, Whitlock et al. 2008, Prichard et al., 2009). While it is difficult to corroborate between proxies due to differing scales, each proxy provides unique fire information that can contribute to an improved overall understanding of the HRV of wildfire in complex, dynamic fire regimes (Schoonmaker and Foster 1991, Smol 2002, Birks and Birks 2006, Baker 2009, Whitlock et al. 2010). Lastly, more fire research is needed in wildfire-prone ecotone regions. Many fire-prone regions have been well-studied and fire regimes have been confidently classified (Hunter 1993, Bergeron et al. 2004). However, in transition and heterogeneous landscapes, fire regime assumptions can be misleading. While these regions present a challenge to fire researchers, they are key regions of complex fire dynamics that may provide important information.

5.4 Conclusions

1. Most of the HWP FMA has experienced a mixed-severity fire regime over the last ~450 years. This regime is spatially and temporally variable. The regime represents a range of fire activity from small, frequent low-severity fires, to moderate- and mixed-severity fires, to infrequent, high-severity fires. Fire activity has decreased in the region
since development in the mid-1950s, and the region has not had any significant high-severity fire activity since at least the mid- to late-1800s.

2. The HWP FMA mixed-severity fire regime is not strongly controlled by climate at the regional scale. Rather, fire activity is likely in this area under a range of climatic conditions. A more important relationship at the scale of analysis appears to be that of moisture-controlled local, topographic characteristics, probably mediated by short-term variations in weather.

3. Mixed-severity fire regimes can be reconstructed using a multiproxy approach. A combination of stand age estimations, fire scars, and macroscopic sedimentary charcoal were used here to infer frequency and severity information and define the regime. Regime classification carried out at local and regional scales helps to spatially define mixed-severity regimes.

4. Fire event detection criteria bias fire regime classifications against small, low-severity fires and mixed-severity fires in particular. This may result in the misclassification of fire regimes. Mixed-severity fire regimes can be mixed across both space and time, complicating the classification. Therefore, classifications should not be considered static or assumptions made.

5.5 References


