Fire Regimes of Western Boreal Canada and the Foothills of Alberta

A Discussion Document and Literature Review for the LANDWEB Project

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CONTENTS

INTRODUCTION

This literature review is designed to be a discussion document for the LANDWEB Project workshop, being held February 19-20, 2014 in Edmonton Alberta. It is not intended to be an exhaustive literature review with every paper related to fire regimes covered, however this is a comprehensive review of the vast majority of literature related to fire regimes in the study area. Contained within this report are the key papers and findings, as determined by this author. Any interpretation of these papers is entirely my own, and others may disagree with the key findings, or know of other papers that should have been included in this review. However, bearing in mind that the key purpose of this document is to generate discussion and provide workshop attendees with some key figures at their fingertips, it is my honest hope that this paper serves such a purpose. It is a living document, and a final version will be distributed following the workshop with additional refinements.

The literature review was initially populated with papers contained within the Foothills Research Institute's OnFire Database (http://www.encaps.com/onfire/), which itself was a review of the literature pertaining to fire regimes strictly within the province of Alberta at the time (2009). From that database, 64 papers were chosen for further review in this document. Since 2009, however, new papers have emerged, and the LANDWEB study area encompasses a broader geographic area than just the province of Alberta. The Web of Science database was accessed via the University of Alberta library between November 20-30, 2013. Search terms included combinations of the following keywords:

- Fire, wildfire, forest fire
- Regime, history, records
- Severity, intensity, frequency, return interval, size, shape, trends, cause
- Boreal, Rocky Mountains, Foothills, Canada, Alberta, Saskatchewan, Northwest Territories
- Grassland, grass, shrub, stand dynamics

Most of the papers found in these searches are included in this review. In addition to these papers, references within those papers were followed to yield the current total contained in this document of 175.

Some subject areas that are not extensively covered in this review are papers related to predicting future fire regimes. These were largely left out because the primary purpose at this stage of the project is to create a common understanding of the past and present state of fire regimes. Also, many papers relating climate to fire regimes are not discussed in detail as this subject area is a massive field of its own and would require resources well beyond the current scope of this literature review.

THE LANDWEB STUDY AREA

The study area contains 115 million hectares of the Canadian boreal forest. The western limit of the study area is the Rocky Mountains, and it extends east to the Manitoba border. The northern limit is described by the 62nd parallel in the Northwest Territories, and the southern limit is the boreal-grassland interface. See figure 1 for a map of the study region.

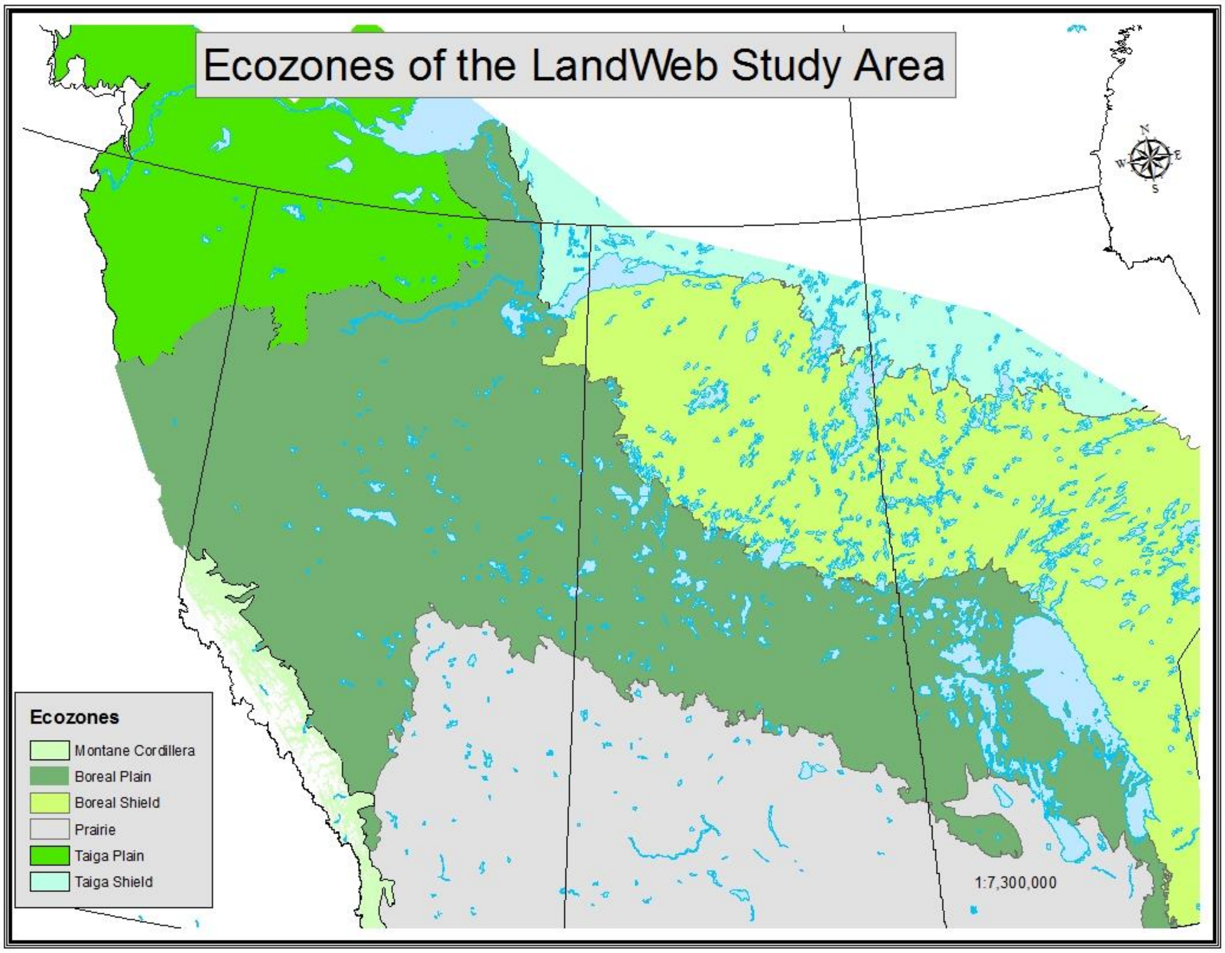

Figure 1: The LANDWEB Study Area showing ecozones. The montane cordillera ecozone has the Alpine Natural Subregion removed as this area is not included in the study.

The area can be broken down as follows:

- Boreal Plain: 63,000,000 Ha
- Taiga Plain: 25,000,000 Ha
- Boreal Shield: 20,000,000 Ha

The distribution of vegetation is an important component to understanding fire regime dynamics. Vegetation is a key driver of fire behavior (as fuel). Vegetation is also the long term expression of climate. Climate is a primary driver of fire regimes. Where large scale differences are seen in vegetation due to climate, one should expect to see differences in fire regime as well. Therefore as climate changes into the future, it is expected that the concurrent disturbance regimes will also be altered.

TERRESTRIAL ECOZONES OF THE LANDWEB PROJECT AREA

The Terrestrial Ecozones of Canada divides Canada into 15 separate ecozones. Within the LANDWEB Project Area, only three of these zones are present and are described below, however the borders of these regions are affected by their neighbouring ecozones. These primary ecozones are the Boreal Plains, Boreal Shield, and the Taiga Plains. Transitional ecozones under consideration are the Montane Cordillera, Prairie, Boreal Cordillera and Taiga Shield.

An ecotone is generally considered a boundary between adjacent ecosystems, however they can be examined at variety of scales. At the level of biomes, ecotones are broad boundaries that often measure in the tens of kilometres. On a landscape scale, the ecotones are the edges of the mosaic pattern. At the forest stand level, the ecotones are between the various vegetation patches. And, at the population level, the ecotones are between plant groups and even individuals (Risser, 1995).

At the Natural Subregion scale there are ecotones between each Natural Subregion, and this is also true of any classification scheme. An ecotone can be a distinct line (such as that between a stand of trees and a meadow, which in itself also depends upon the scale with which it is examined), or can be very broad. The entire Aspen Parkland Terrestrial Ecoregion is an ecotone between the Boreal Plains to the north and the grasslands to the south. A similar broad ecotone exists in the lower foothills, dividing the grasslands from the forests.

In some cases ecotones are distinct, and their location moves very little. This usually occurs in areas with distinct changes in surficial materials that create fundamentally different soil types. These types of ecotones move very slowly over geological time scales. Other ecotones shift significantly because they are regulated by climate, interspecies competition and disturbance dynamics, all of which are themselves mobile on observable timescales. Ecotones that are due to fire activity are dynamic in space and time. Keep the dynamic nature of ecotones in mind, as many studies will stratify the landscape based on ecozones or natural subregions and attempt to define the fire regimes within them. Over short periods of time (decades) this is not a problem, however, when studies span centuries or millennia, the very boundaries of the strata have likely changed over the course of that time span.

REPORT OVERVIEW

Section 1 will describe fire regimes, discuss the components of fire regimes, classification systems and methods of measuring them.

Section 2 will summarize the specific research studies that have been done on these fire regimes and controlling factors within and near the LANDWEB study region. Some research studies from outside the region are included due to their general utility. This section will discuss some of the primary drivers that influence fire regimes of ecosystems represented within the LANDWEB study region.

Section 3 will provide both a general discussion about the research described in section 2 and a conclusion.

SECTION 1: FIRE REGIMES

FIRE REGIMES DEFINED

There are many definitions of fire regimes, but the simplest description is that a fire regime is the measure of the general pattern of wildfire's interaction with the landscape over time. As Moritz *et al.* (2011) describe, the controls on fire vary depending on the spatial and temporal scale of interest. The primary drivers of flames over seconds and meters are oxygen, heat and biomass. For a given wildfire, occurring at the scale of hours to days, and over tens of meters to kilometers, the primary drivers are weather, fuel and topography. The fire regime is that which occurs over multiple fires over decades to centuries and across large landscapes to ecozones, and the primary drivers are vegetation, climate and ignitions. Figure 2 shows this scalar relationship: combustion occurs at a small spatial scale and over short periods of time, whereas fire regimes are a measure of many fires occurring over a long period of time across a wide region of space.

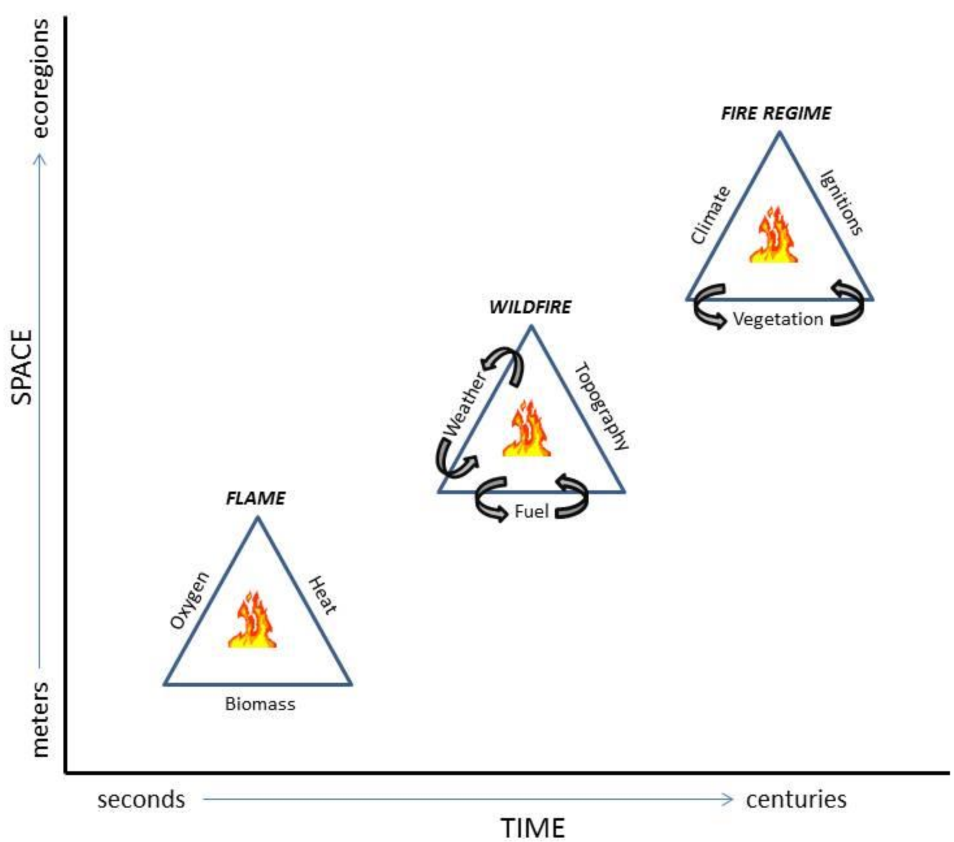

Figure 2: Controls on fire at different scales of space and time. Arrows represent feedbacks between fire and the forces controlling fire at different scales. Figure from Moritz *et al.* (2011).

Fire interacts dynamically with the landscape, and is a primary determinant of present and future vegetation composition. These resulting patterns of vegetation affect future fire, insect and disease activity, and many other ecosystem processes in a constant cycle of interactions and feedback loops (Turner, 1989). Conversely, by studying vegetation patterns information about past fire activity can be determined.

FIRE REGIME COMPONENTS

Agee (1993) defines the characteristics of fire regimes as the following (see Table 1):

Table 1: Common fire regime parameters and definitions, modified from Agee (1993).

DESCRIPTOR	DEFINITION
FREQUENCY	The mean number of events per time period. This can be expressed in several ways: PROBABILITY: A decimal fraction of events per year. RETURN INTERVAL: The inverse of probability; years between events. ROTATION/CYCLE: Time needed to disturb an area equal in size to the study area.
PREDICTABILITY	A scaled function of the variation in frequency. Sometimes referred to as periodicity.
EXTENT	Area disturbed per time period or event. Often referred to as size, and can be represented by a distribution of size classes. Shape can be viewed as a subcomponent of extent.
MAGNITUDE	Described variously as: INTENSITY: Physical force, or energy released per unit area and time for a fire. SEVERITY: A measure of the effect on organisms or ecosystems. Often measured by mortality, depth of burn, consumption of duff.
SYNERGISM	Effect on the occurrence of the same or other disturbances in the future.
TIMING	The seasonality of the disturbance, linked to differential susceptibility of organisms to damage based on phenology.

There is considerable variation in how to parameterize fire regimes, and what the definitions mean. Agee's table above is not a definitive source, but is included as a starting point. The reader is referred to CIFFC (2002), Johnson and Gutsell (1994), and Barrett et al. (2010). Many factors influence the various fire regime properties. As described by Falk *et* al. (2007), many of the drivers of fire regime parameters are shown in table 2.

Table 2: Drivers of fire regime attributes. From Falk *et al*. (2007)

Properties	**Drivers**		
	Climate/Weather	Vegetation/Fuels	Landform
Temporal Distribution			
Frequency or Interval	Spatial and temporal coincidence of ignitions and flammable fuels; extended droughts and pluvials	Rates of post-fire vegetation recovery and fuel accumulation; fuel type	Topographic influences on ignition probability, vegetation types
Duration	Fuel moisture and fire propagation conditions, length of fire season	Fuel mass, continuity, consumption rate	Microclimate influences on fuel moisture and fire spread
Seasonality	Temporal patterns of ignition, precipitation, humidity	Timing of greenup, leaf fall	Spatial patterns of ignition, fuel moisture
Spatial Distribution			
Extent (fire size)	Climatic regulation of fuel accumulation, fire spread, length of fire season	Landscape scale extent and connectivity of flammable fuels	Physiographic barriers to fire spread
Pattern (patch size, aggregation)	Orographic atmospheric instability, wind vectors	Spatial heterogeneity of flammable fuels within burn perimeter	Mesotropographic influences of terrain roughness and slope wind vectors
Intensity and severity	Seasonal influences on fuel moisture, fire behavior, synchronization of fire weather conditions	Fuel mass, density, moisture, vertical continuity	Slope/aspect effects on fuel moisture and fire behavior
The collective properties of disturbance multiple events and their associated drivers. Fire regimes reflect the distribution of each property derived over multiple individual events in space and time.			

Agee's breakdown of fire regimes (Table 1) misses a critical component: cause. Fires can be ignited by lightning, or by people. Humans have a long history of fire use (Bowman *et al.* 2011; Coughlan and Petty, 2012; Marlon *et al.* 2008), and in the foothills regions and grasslands, human fire use has been common for millennia (see section on cause below), while in the boreal regions fire use by first nations was practiced (Lewis, 1988), it was perhaps less common, and its influence is debated {Clark and Royall, 1995; Campbell and McAndrews, 1995). Nonetheless, whether a fire is ignited by humans or lightning is an important distinction, as it affects the timing, location, size, vegetation association, and frequency of fire.

For the purposes of this literature review, the following fire regime parameters will be discussed (Table 3).

Table 3: Fire regime parameters and definitions for this literature review.

DESCRIPTOR	DEFINITION
CAUSE	Anthropogenic or lightning initiated fire?
FREQUENCY	How frequently fire occurs. Expressed as return intervals, cycles, probability
TIMING	Time of year that fires occur, how long a fire season is
SIZE	How large fires are on the landscape
SEVERITY/ INTENSITY	Level of vegetation mortality that occurs, and long term effects of fires, which includes their shape, pattern, and vegetation composition. INTENSITY (the amount of energy released by the fire) will be discussed with severity, as there is a cause and effect relationship between the two

FIRE REGIME CLASSIFICATION

As per ecosystem and vegetation classification schemes, fire regimes can also be classified into general categories. The most common classification methods use variation in frequency and severity (Agee, 1993; Arno *et al.* 2000). Frequency and severity are continuous variables, and delineations for the purpose of categorization are arbitrary and done solely for the purpose of easing our understanding of the phenomenon. The fire regimes of Alberta have not been subjected to a rigorous classification scheme to date.

For a general classification scheme, a useful place to start is with one created by Heinselman (1973), and reproduced in Agee (1993). The numbers used by Heinselman to represent the actual return intervals in years have been removed as they are not necessarily relevant in the Alberta context. See Table 4.

Table 4: Fire Regime Classification Scheme (Heinselman, 1973, in Agee, 1993)

FIRE REGIME TYPE	DESCRIPTION OF THE REGIME
0	No natural fire
1	Infrequent light surface fire
2	Frequent light surface fire
3	Infrequent, severe surface fire
4	Short return interval crown fires
5	Long return interval crown fires and severe surface fires in combination
6	Very long return interval crown fires and severe surface fires in combination

The Heinselman classification system results in seven categories of fire regimes. This has been simplified in recent years to a five class system, used in the Fire Regime Condition Class (FRCC) system (Barrett et al, 2010) which is commonly used in the United States. Rogeau (2007) reviewed the FRCC system and its applicability to Alberta forests, and modified these classes to better suit Alberta's fire history and ecosystems. The FRCC (unmodified) and Rogeau's modifications are shown in table 5.

Table 5: Fire Regime Condition Classes (Barrett et al, 2010) and Alberta Fire Regime Classes (Rogeau, 2007)

FIRE REGIME	FRCC (FIRE CYCLE)	AB FIRE REGIME CLASS (FIRE CYCLE)	AB FIRE REGIME CLASS (MEAN FIRE RETURN INTERVAL)
I	0-35 years low-mixed severity	0-50 years low-mixed severity	0-35 years
II	0-35 years high severity	51-100 years mixed severity	36-75 years
III	36-200 years mixed severity	101-150 years high severity	36-150 years
IV	36-200 years high severity	151-200 years mixed to high severity	151-200 years
V	200+ years high severity	250+ years high severity	250+ years

Low severity = surface fire | mixed severity = < 75% canopy removal | high severity = >75% canopy removal

Boulanger *et al.* (2012) conducted an analysis of fire records across Canada, and created a map of 33 Homogenous Fire Regimes for Canada, which is the first attempt to define Canadian fire regimes at such a scale. The attributes that were used to conduct this analysis were the lightning and anthropogenic burn rates, the number of fires per unit area per year (by lightning and human cause), the mean day of burning, and the fire return interval. While the spatial extent over which this study was conducted is large, the temporal depth is quite shallow, and embedded within a highly altered fire regime. As the fire frequency measures discussed below show, in some areas the fire frequency has been affected (reduced) by orders of magnitude from its natural condition.

FIRE REGIME METHODS

How fire regimes are measured has a significant influence on the outcomes of a given study. Given that fire regimes are a suite of statistics and observations over space and time, there can be considerable variability in estimates of frequency, size, severity, cause, timing and intensity depending on how the spatial unit of study is bounded, the source of data used, and the temporal depth over which the phenomenon is studied. While there are many variations on the categories below, fire regime studies can be conducted by (adapted from Tymstra *et al,* 2005):

1. Field studies
    a. Point sampling
    b. Stand origin mapping
2. Fire records analysis
    a. Fire occurrence record analysis
    b. Lightning strike data
3. Modelling
    a. Predictive modeling
    b. Wildfire simulations

All of these methods have their strengths and weaknesses, and are well discussed by Tymstra *et al* (2005). Field studies of point sampling are limited to the researcher's ability to find fire scars on trees, which limits the temporal depth of analysis to the maximum lifespan of trees in the forest (~200 years in the boreal, ~400 years in the foothills). Evidence of older records is "erased" by newer fires. How researchers account for these missing records is a current area of debate. Stand origin mapping also has the same problem of missing older events that have been erased by subsequent disturbance, and assumes stand-replacing fire is the dominant factor (see section on severity). As Gralewicz *et al.* (2012) note "there is a gap in fire research, with few studies conducted at fine spatial scales, over larger areas, and through many time periods".

Fire records analysis is limited to an even shorter time frame than field based fire history studies, as studies can only examine records from 1931 in Alberta. Even over this time period, analysis is complicated as standards of data acquisition over this period have changed, and fire records from the 1930's do not correspond directly with fire records today, as different size limits and attributes have been used over the years. These fire records are largely within the era of "active fire suppression", and cannot be assumed to represent the "natural order", however this point is debated (Cumming, 2005; Weir *et al.,* 1995; Johnson *et al.,* 2001).

Modelling is only as strong as the assumptions and knowledge used to calibrate them, and by definition models are a simplification of reality. As our limited measures of fire regimes are themselves a simplification of the complex interaction of fire with the landscape over time, and if models are a simplification of the fire regime, then models are orders of magnitude simpler than reality. While models have utility, a quote attributed to statistician George Box says "all models are wrong, but some are useful".

The spatial scale over which each of these approaches varies. Morgan *et al.* (2001) provide an excellent overview of the advantages and disadvantages of using various derivations of fire regime data, and as Gavin *et al.*(2007) show in figure 3 below, each type has a spatial and temporal scale over which it is best suited.

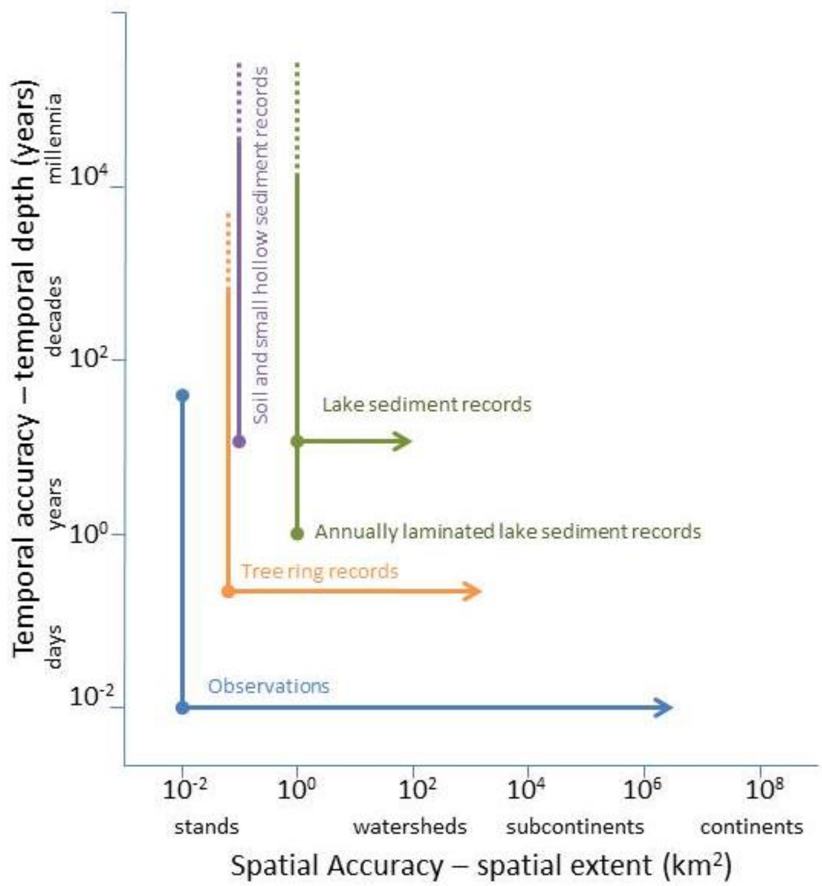

Figure 3: Spatial and temporal domains of fire history methods span several orders of magnitude. Vertical lines extend from the finest temporal accuracy to the maximum temporal depth of a particular method. Horizontal lines extend from estimates of the finest spatial accuracy of individual records to the combined spatial extent of all existing North American records. A terminal circle represents an insurmountable constraint on a particular method. Dashed lines represent the potential to extend fire history further back in time, although this is contingent upon discovering such records. Arrows represent the potential for more spatial coverage with future work. From Gavin *et al.* (2007).

Before delving into the specifics of what has been found regarding fire regimes in the study area, it is important to discuss why many studies will seem to disagree. As Gedalof (2011) describes, our records of fire history are short, usually lack detailed location information, and fire regime estimates are not easily reconciled.

Many of these disagreements are due to a moving window of analysis. As the spatial unit of analysis changes, AND as the temporal depth changes, the fire "regime" will also change. This is a phenomenon known as the Modifiable Areal Unit Problem (MAUP), which is a well understood problem in geography and spatial analysis (Jeliniski and Wu, 1996). Keeping this problem in mind, if one researcher examines fire regimes in the Subalpine, for example, at the exclusion of any other Natural subregion, and another examines a larger area that overlaps the *same Subalpine* region, but also examines the neighbouring Montane and Upper Foothills, they are bound to come up with different measures of fire regime within the Subalpine based solely on differences in what data they have collected and analysed. This is not even taking into account that there is also variation in how different researchers calculate statistics such as Annual Area Burned, or Mean Fire Return Interval, or how they deal with the fact that recent fires hide evidence of earlier fires. Rather than focusing on which one is right and which one is wrong, it is more appropriate to focus on which one is most *applicable* to a given problem.

Fire regimes are a set of *statistics* to help us measure how fire interacts with a given piece of ground. They are not "inherent characteristics" of an ecosystem (Johnson *et al*., 1998). Fire regimes are a complex expression of the interactions between fire and short term weather, climate, soils, topography, human history, grazing, browsing, and vegetation succession. No two are the same, they are like fingerprints. And this fingerprint changes as the scale changes.

SECTION 2: FIRE REGIMES OF THE LANDWEB PROJECT AREA

Considerable research has been done throughout North America on fire regimes throughout the boreal forest, the east slopes of the Rocky Mountains, and at the forest-grassland interface. These cannot all be described in detail, however this review aims to be as thorough as possible. Numerous large scale studies have been done that cover a larger area than the LANDWEB project will be dealing with. There have also many fine-grained studies within the area.

In the Rocky Mountains (Eastern Continental Cordillera ecoregion), many studies have been done within Banff National Park, Kananaskis Country, Spray Lakes Forest Management Area, Jasper National Park, and the Foothills Model Forest landscape. In the Boreal forest regions there have been numerous studies in Alberta, Saskatchewan, the Northwest Territories, and across the entire boreal forest.

The LANDWEB Project area includes the Boreal Plains, Boreal Shield, and the Taiga Plains, Montane Cordillera, Prairie, Boreal Cordillera and Taiga Shield. The mixedwood subregions represent the southernmost fringe of the Boreal Plains ecozone, and the ecoregion is the Boreal Transition. There is not a large body of research that has been conducted on fire regimes in the Dry Mixedwood and Central Parkland Natural Subregions. While the Central Mixedwood represents a larger area in the study region than the Montane or Northern Fescue Natural Subregions, it likely will be *less* important over time than the other two due to projected shifts in Natural Subregions northward due to climate change. Weber and Flannigan (1997) suggest that under climate change scenarios that fire activity in the boreal forest will increase substantially due to longer burning seasons, lower moisture, and higher variability in weather. Soja *et al*. (2007) demonstrate that *globally* the boreal forest is undergoing rapid change due to climate change. Forecasts include significant dieback of *Picea glauca*.

Rather than describe what is known about the fire regimes of the region study by study, this document will discuss what is known about each fire regime attribute, and within each attribute, variability within the various ecozones will be discussed. Finally, overarching trends in fire regimes will be addressed separately. All fire regime attributes have feedbacks and interactions with each other, some research is targeted at specific attributes of fire regimes, and some is broader in scope. The following tables have duplicate records within them: some studies only examine fire frequency, others only examine fire timing, some studies look at all elements of fire regimes. Those that look at more than one element appear in more than one table. These tables are designed to be used in discussion so that pertinent facts and general assumptions relevant to each fire regime attribute will be at all workshop participant's fingertips.

FIRE IN FORESTED ECOSYSTEMS

The range in fire regimes presented in the previous tables (4 and 5) express themselves in particular ways in forested ecosystems. Each attribute (Table 3) will be discussed in regards to the LANDWEB Project Area.

CAUSE

Cause can be considered the highest level, or first order attribute of fire regimes. This is because cause defines WHEN, WHERE, and HOW OFTEN fires burn on the landscape. Lightning fires are driven by fundamentally different parameters than are anthropogenic fires: they burn at different frequencies, in different places, and start at different times of year. The papers relevant to cause are cited within this discussion, but a table has not been developed as there is no real "data" to discuss for this fire regime attribute, the reasons for which will become clear below.

The primary historic cause of fire in the boreal regions of the study area was lightning, with some degree (largely unknown) of anthropogenic burning. In the foothills regions, and in the prairie complexes within the boreal the historic causes of fires have a more anthropogenic component, however, it is not known the degree to which this occurs. While there are many modern statistics showing in great detail the breakdown between anthropogenic versus lightning caused fire (Tymstra *et al.* 2005, among others) in the modern era, these ratios are meaningless in terms of historical conditions.

There are several descriptive accounts of First Nations fire use in the specific (Lewis, 1978; Lewis, 1988) and general area (Coughlan and Petty, 2012; Marlon *et al.* 2008; Clark and Royall, 1995; Kay 1994), however, none are quantitative in nature, and these studies cannot be used to determine what proportion of fires can be attributed to what cause. Only modern fire records can be partitioned by cause. Tymstra *et al.* (2005) show that between 1961-2002, humans were responsible for 48.3% of all fires, which account for 25% of the area burned.

Most studies do not bother to differentiate between causes when it comes to analyzing fire regime parameters. Should it matter? I would argue "yes". In the south of the study region, there is no shortage of evidence that First Nations people used fire to manage the landscape. The Blackfoot First Nations included the Peigan, the Kainai (Blood), and Siksika. They are rumoured to have been named "blackfoot" due to their frequent use of fire on the prairies (Francis, 1989), hence having black feet from walking through the ashes. These First Nations used a large expanse of the prairie region of western Canada and the United States, and were the tribes encountered by David Thompson on his journey through the North Saskatchewan Landscape across the Kootenay Plains (Thompson, 1801, in Tyrell, 1916). Some view these people as landscape level ranchers, controlling the movement of animals through the use of fire, herding, hunting (Kay, 1994; Boyd 2002).

It was widely believed that First Nations people were responsible for the presence of the Great Plains, which delimits the southern boundary of this study area. Hind (1860) declared “the extension of the prairies into the aspen parkland is evidently due to fires, and the fires are caused by Indians for the purpose of telegraphic communication or to divert the buffalo”. In 1838, Nicolett (in Boyd, 2002) observed that the great grasslands of the Great Plains (“all the land watered by the Mississippi and Missouri”) were chiefly the work of natives who burned the rich vegetative cover for the purposes of providing forage for game. In his opinion, if the people were removed (and therefore the fires) the land would revert to forest.

The use of fire by First Nations peoples was neither accidental, nor random. Nelson and England (1971) document numerous uses of fire in the early 1800s by aboriginals for game management, warfare and other purposes. Nor was fire use restricted to Plains tribes. It was a common tool used by First Nations in the forested regions to the north in the boreal regions of Alberta and Saskatchewan (Lewis, 1982), and in the hardwood forests of Ontario and Quebec (Clark and Royall, 1995).

Human fire use is so influential that Sauer (1950, cited in Axelrod, 1985) noted there was little evidence globally for a *climate* driven grassland climax. Grasslands occur globally with a range in precipitation of less than ten inches of rain annually, to more than a hundred. Grasslands occur with long dry seasons and short dry seasons. What grasslands all have in common is the presence of fire and grazers. The amount of fire derived from lightning, and contributed by humans varies from region to region, but there is significant evidence of continual human burning around the world. Archer (1999) also concludes that fire and human use are major drivers of the grassland biome.

Although lightning has historically been a major cause of fire throughout the region, there is mounting evidence that native peoples were responsible for many fires not only regionally and continentally, but also globally (Nelson and England, 1971; Lewis, 1982; Kay, 1984; Arno, 1985; Gruell, 1985; Boyd, 2002). Boyd (2002) has proposed a new method of analyzing paleo fire regimes. By analyzing grass silicophytoliths rather than using pollen, researchers can document fire records throughout the Holocene. Silicophytoliths are small, hard, rock-like bodies formed in the spaces between the living cells of a plant through the structured accumulation of silica brought into the cells with water. The identification of phytoliths from different plants preserved in archaeological material can provide an indication of the local vegetation over time. Silicophytoliths are more readily identified than pollen, and it is also easy to determine whether they have been exposed to fire, as carbon is incorporated into the molecular structure of the phytoliths (Boyd, 2002). Pollen, in contrast tends to be consumed by fire, and cannot be used to identify whether or not fire has occurred.

If it were not for historical cultural use of fire, the southern margin of the LANDWEB study area would likely extend even further south: the cutoff for the study area is the southern margin of the boreal forest/aspen parkland. This ecotone is quite possibly only where it is today due to a long history of human fire use on the prairie.

FREQUENCY

Fire frequency is one of the most studied attributes of fire regimes. A thorough review on definitions of fire frequency is provided by Agee (1993). Reed (2006) makes an interesting argument that rejects the use of the term Fire Cycle (the amount of time required to burn an area equivalent to the study area), however, this is one of the most widely used frequency metrics.

Much of the literature in this review pertains to fire frequency (see Table 6 for an overview). There are more than 50 studies included in this table, with key findings related to fire frequency presented. This is not an exhaustive list of all studies relevant to fire frequency in the region, however it does represent the majority, and also represents the range in types of studies that have been done. Some of the studies included in the following tables were done outside of the area of interest, but they are included because they have relevant findings germane to a discussion on the Natural Range of Variability concept, or may help explain the variation in the numbers we see.

Given the vast area covered by the LANDWEB study region, we need to pay attention to where and how fire regime studies are done. As discussed previously, there are many ways to analyze and measure a fire regime. In this region there are fire history studies, fire records analyses, and exercises in modeling. The field studies that have been done tend to cover very small areas (relative to the project area), which can make interpolation quite challenging. Fire regime studies over larger areas tend to be done using fire records analyses, and many of the studies have used the same datasets (Canadian Large Fire Database, Alberta ESRD Fire Records), many of the differences in outcomes are due to the method of analysis. Models tend to be based on statistics obtained from either the field studies or the fire records analyses.

Table 6: Research papers relevant to fire frequency for the study area and key findings

Lead Author	Year	Title	Grain/Extent	Time	Location	Method	Findings
Adams	2013	Mega-fires, tipping points and ecosystem services: Managing forests and woodlands in an uncertain future	N/a	N/a	global	Literature review	Trends in postfire revegetation suggest that conifers may be in decline and deciduous on the rise. This is due to increased fire activity, but will result in lowered fire activity due to lower flammability
Andison	1998	Temporal patterns of age-class distributions on foothills landscapes in Alberta.	Stand/NSR	N/A	Foothills Model Forest	Modelling, derived from Stand Origin Map	Cycles: Lower Foothills 80 yrs, Subalpine 125, Upper Foothills 100
Andison	2000	Landscape-level fire activity on foothills and mountain landscape of Alberta.	Stand/Mgmt Unit	1800-2000	Foothills Model Forest	Field study Stand origin mapping	Burn rates: range 4.6%/20years Upper Subalpine JNP – 29.1%/20years Lower Foothills Hinton WP FMA
Andison	2003	Natural levels of forest age-class variability on the Alberta-Pacific FMA.	Stand/Mgmt Unit	1911-1970	AlPac FMA	Modelling, rollback from current inventory	Cycle: 48 years (range 40-60).
Armstrong	1999	A stochastic characterization of the natural disturbance regime of the boreal mixedwood forest with implications for sustainable forest management.	Landscape 8.6*10^6 Ha	1961-1995	~AlPac FMA	Modelling, Canadian Large Fire Databse	Burn rates: ~1.1%/year with wide confidence intervals (.01%-9.78 over 5 year simulation/ .74-1.55% over 1000 year simulation
Arno	1980	Forest fire history in the Northern Rockies.	Landscape/Ecozone	1665-1980	Montane Cordillera + others	Field study Fire scar studies	Re-reported figures from other reports (Hawkes, Tande)
Arno	2000	Mixed-severity fire regimes in the northern Rocky Mountains: consequences of fire exclusion and options for the future.	Landscape/ecozone	1500-1900	Wyoming and Montana	Literature review	Discussion and definitions of mixed severity fire regimes
Belleau	2007	Using spatially explicit simulations to explore size distribution and spacing of regenerating areas produced by wildfires: recommendations for designing harvest agglomerations for the Canadian boreal forest.	Ecozone	Var. lit review	Boreal forest	Modelling	Repeats info from other studies
Bergeron	2004	Past, current and future fire frequency in the Canadian boreal forest: implications for sustainable forest management.	National	Var. lit review	Boreal forest, foothills, montane	Modelling, values derived from Canadian Large Fire Database, lit review	Burn rates (current/historical%/yr): Jasper .0271/ 1.04; Kananaskis .0503/ 0.76%; Northern AB: .2223/no value WestCentral AB 0.0194/2.0 Wood Buff: 0.6603/1.41

							Also burn rates under elevated CO2 scenarios
Boulanger	2012	An alternative fire regime zonation for Canada	Fire/nation	1980-1999	Forested Canada	Fire records analysis	Divides the Boreal study region (this project area) into 12-13 distinct Homogenous Fire Regimes.
Burton	2008	Large fires as agents of ecological diversity in the North American boreal forest.	ecozone	1959-2008	Boreal Forest	Fire records analysis (>200ha)	#Fires/year = 42 (Boreal plains) 75 (B Shield West) 29.6 (Taiga Plains) #/fires/yr/10,000km2 = 0.723 (Boreal Plains) = 0.894 (B Shield W) = .568 (Taiga Plains)
Campbell	2000	Late Holocene vegetation and fire history at the southern boreal forest margin in Alberta, Canada.	Fire/management Unit	1500-2000	Elk Island National Park (Aspen Parkland)	Field study Charcoal and pollen analysis	No hard numbers, discusses relative changes in fire frequency over time and shows shifting vegetation composition due to disturbance regime shifts
Cumming	1997	Landscape dynamics of the boreal mixedwood forest.	Stand/Landscape	1940-1990	~AlPac FMA	Modelling	Burn rate: Total area .281%/year shows varying rates by species. estimates effect of fire suppression
Cumming	2000	A synopsis of fire research in the boreal mixedwood forest.	Stand/Landscape	Var.	AlPac FMA	Modelling, Fire records analysis	Burn rate (as per above), but corrected for suppression = .41%/year
Cumming	2001	Forest type and wildfire in the Alberta boreal mixedwood: what do fires burn?	Stand/Ecozone	1961-1994	~AlPac FMA	Modeling	Burn Rate = .21%/year total rates included by species
Gavin	2007	Forest fire and climate change in western North America: insights from sediment charcoal records	Biome/Continent	10,000 years	Western North America	Field studies (lit review) Charcoal	No absolute numbers, shows high variability in burning over 10KY. Links fire frequency changes to vegetation composition. Huge uptick in fire frequency 6KYA due to arrival of Black Spruce in record
Girardin	2008	Three centuries of annual area burned variability in northwestern North America inferred from tree rings.	Tree/Biome	1700-2000	Western boreal	Field study Dendrochronol ogy	No hard numbers, but shows high variability in Annual Area Burned over the time period. No consistent rate.
Gralewicz	2012	Spatial and temporal patterns of wildfire ignitions in Canada from 1980 to 2006	Fire/Ecozone	1980-2006	Canada	Fire records analysis	Shows variation ignitions Ignition density (#ignitions/km2) variability by Ecozone Defines fire ignition regimes (map fig 6)
de Groot	2013	A comparison of Canadian and Russian boreal forest fire regimes	Fire/Ecozone	1970-2009	Boreal Canada	Fire records analysis	MFRI 179.9 years (2001-2007) MFRI 167.4 (1970-2009) #large fires/year = 93.7/100M Ha (2001-2007) #large fires/year = 74.7/100M Ha (1970-2009)
Hawkes	1979	Fire history and fuel appraisal of Kananaskis Provincial Park.	Tree/Landscape	1586-	Kananaskis	Field study	MFRI = 14 years MFRI (large fires >1000ha) = 21 years

				1978	Provincial Park	Fire history	FRI's broken down by aspect, elevation and valley
Huggard	1999	Comment Reverse cumulative standing age distributions in fire-frequency analysis.	Theoretical paper	n/a	n/a	Modelling	Descriptive paper relating age class distribution to fire frequency rates
Jiang	2012	Modeling large fire frequency and burned area in Canadian terrestrial ecosystems with Poisson models	Fire/Ecozone	1959-2010	Boreal Shield	Fire records analysis	frequency by size classes of fire (2km2 min size) Total = 95.3/year
Johnson	1987	Historical vegetation change in the Kananaskis Valley, Canadian Rockies.	Stand/Landscape	1730-1972	Kananaskis Provincial Park	Fire records analysis, stand reconstruction	Fire return interval = 150 years
Johnson	1991	Climatically induced change in fire frequency in the southern Canadian Rockies.	Stand/landscape	1600-1990	Kananaskis watershed	Field study: stand origin map	1600-1729 AD fire cycle = 50 years 1730-1980 AD Fire cycle = 90 years
Johnson	1985	The theory and use of two fire history models	Theoretical paper	n/a	n/a	Modelling	Presents equations for fire size distributions and frequencies
Johnson	1998	Wildfires in the western Canadian boreal forest: Landscape patterns and ecosystem management.	Fire/Biome	n/a theory	Boreal Western Canada	Literature review	Frequency is a continually varying statistic
Kelly	2013	Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years	Sediment cores/Ecozone	10,000 years	Yukon Flats ecozone AK	Field study, charcoal analysis	Major fluctuations in frequency over 10KY 5.6 fires/KY before 6000 years ago 8.6 fires/KY after 6000 change coincides with increase in Black Spruce on landscape Past 3000 years show relatively consistent vegetation
Krawchuk	2009	Disturbance history affects lightning fire initiation in the mixedwood boreal forest: Observations and simulations	Fire/Natural subregion	1994-2001	AlPac FMA/Boreal Mixedwood	Fire records analysis	Fires burning within 30 years depress the reignition potential Harvesting increases reignition potential
Larsen	1997	Spatial and temporal variations in boreal forest fire frequency in northern Alberta.	Tree/Landscape	1739-1989	Wood Buffalo National Park	Field study, fire scars	Fire Cycle: 38 years (95%CI 34-43) Time period 1750-1859 63 years (95%CI 55-68) Time period 1860-1989 Also presented by distance to waterbreaks (shorter cycle away from water), and by species (stand type)
Larsen	1998	Fire and vegetation dynamics in a jack pine and black spruce forest reconstructed using fossil pollen and charcoal.	Sediment core/Lake drainage	1400-2000	Lake in Wood Buffalo National Park	Field study palynology charcoal assessment	Fire return interval = 34 years
Larsen	1998	An 840-year record of fire and vegetation in a boreal white spruce forest.	Sediment core/Lake drainage	1100-1998	Rainbow Lake, Wood Buffalo	Field study palynology charcoal assessment	Fire return interval 69 years (range 30-130) Mean fire interval 95-185 years
Lauzon	2006	Fire Cycles and Forest Management:	Literature review	Var.	Boreal Biome	Literature	No original data

		An Alternative Approach for Management of the Canadian Boreal Forest.			Canada	review	
Lewis	1988	Yards, corridors, and mosaics: how to burn a boreal forest.	None/ethno study	1800's – 2000	No specific area	Ethnographic study	2-3% of Fort Vermillion area regularly burned by First Nations 30-40% of Peace River/Grande Prairie region regularly burned by First Nations Doesn't specify time period over which this is done.
Li	2000	Reconstruction of natural fire regimes through ecological modelling.	Fire/Management unit	1700-2000	Hinton Wood Products FMA	Modelling	Describes approaches to calculating "natural" fire cycles free from suppression influence
Li	2002	Estimation of fire frequency and fire cycle: a computational perspective	Fire/Management unit	1700-2000	Hinton Wood Products FMA	Modelling	Fire cycle ~ 130 years
MacDonald	1991	The reconstruction of boreal forest fire history from lake sediments: A comparison of charcoal, pollen, sedimentological, and geochemical indices.	Sediment core	1800-1991	Rainbow Lakes, Wood Buffalo National Park	Field study, charcoal analysis	Poor correlation between charcoal measures and other measures of fire history, however the local fire history was obtained within 2km radius, which might be a poor resolution. Does provide large area wide measures.
Macias Fauria	2008	Climate and wildfires in the North American boreal forest.	Fire/Biome	1900-2010	Boreal north America	Fire records analysis	Discussion relating fire cycles to climate cycles
McIntire	2005	Seed and bud legacies interact with varying fire regimes to drive long-term dynamics of boreal forest communities	Tree/Ecozone	n/a	Boreal Cordillera, BC	Modelling	Conversion to deciduous with frequent (<75 year), high severity fire. Maintenance of pine with moderate frequency (75-125 year), high severity fire
Parisien	2004	Saskatchewan fire regime analysis	Fire/Province	1945-2000	Forested Saskatchewan	Fire records analysis	Large fires only >200ha Frequency (cycle) Boreal Plain = 263 years, Boreal Shield = 104 years, Taiga Shield = 112 years Frequency (#/fires/1M ha), BP = 1.5, BS = 3.34, TS = 4.88
Reed	1998	Estimation of temporal variations in historical fire frequency from time-since-fire map data.	Fire/Landscape	1600-1990	Kananaskis Provincial Park	Modelling, based on Field data	Post 1730 fire cycle = 144.6 years (95% confidence interval = 99.2-222.3) pre 1730: fire cycle = 46.6 years (95% confidence interval 19.9 - 151.2)
Rogeau	1999	Fire history study of the central Rockies. Ecosystem InterAgency North Saskatchewan Unit.	Tree/Landscape	1700-1999	Upper North Saskatchewan River watershed	Field study Stand origin mapping fire scars	Cycle: Fire cycles are longer in small valleys compared to large ones MFRI: <20 years Along North Saskatchewan Basin (main valley), evidence of fires every 20 years or less between 1800-1910
Rogeau	2005	Fire history study Kananaskis District, Alberta 2004 field results.	Tree/Landscape	1500's to pres.	Spray Lakes Sawmills FMA	Field study Stand origin map, fire scars	Detailed fire frequency measurements (from scars) provided by each watershed across the district MFRI Upper Foothills = 9 years, Montane = 7.6 years, 1850-1942

							Stand origin map developed for the area
Rogeau	2004	Fire regime study of Kananaskis district, Alberta. Part 1.	Fire/Landscape	1800-2004	Spray Lakes Sawmills FMA	Fire records analysis	1961-2002 = 1,457 years; 1930-1950 = 104 years total area estimate Fire Cycles (NRV): From StandOr Modeling Subalpine N 149 (121-177), Subalpine S 93 (76-93), Montane 41 (30-52), Upper Foothills 37 (28-45), Lower Foothills N 111 (89-133), Lower Foothills S 111 (92-130)
Rogeau	2005	Fire regime study of C5 FMU.	Stand/Landscape	1800-2000	C5 FMU	Fire records analysis AVI analysis	Cycle 402 years (AVI derived) Cycle 78 years (range 49-196) Fire Size method Cycle 85 years (1930-1950) Air photo screening Cycle Subalpine 116 (93-139) STANDOR Cycle Montane 92 (76-108) STANDOR
Rogeau	2008	Fire regime analysis of the Chinchaga River Basin (FMUs P8-P15).	Fire/Landscape	Late 1800's – 2008	P8 and P15 FMU	Fire records analysis	Fire Cycle (1961-2006) Lower Boreal Highlands = 92 years Upper Boreal Highlands = 104 years #fires/year/1Mha = Central mixedwood = 8.5 Dry mixedwood = 18.6 Lower Boreal Highlands = 9.0 Upper Boreal Highlands = 8.9
Rogeau	2009	Fire regime study FMU R11: Part 1.	Fire/Landscape	1961-2008	R11 FMU	Fire records analysis	Current fire cycles are extremely long due to suppression Subalpine 1,055 years, Montane 3,590 Upper Foothills 51,772
Rogeau	2010	Fire regime departure R11 FMU: Part 3.	Tree/Landscape	1700's to pres.	R11 FMU	Modelling and Field study fire scar	Modeled cycles: 50 yrs NSask Other valleys range 78-180 years Modeled MFRI 63 NSask Other valleys 98-230 years
Rogeau	2010	Fire history study 2009 field results, R11 FMU: Part 2.	Tree/Landscape	1700's to pres.	R11 FMU	Field study fire scar	MFRI: Saskatchewan river 22-34 years Other river valleys = 54-84 years
Senici	2010	Spatiotemporal variations of fire frequency in central boreal forest	Fire/Landscape	1921-2008	Lake Nipigon, Ontario	Fire records analysis and field study	Fire Cycle = 158 years 1921-2008 295 years prior to 1921
Senici	2013	Multi-millennial fire frequency and tree abundance differ between xeric	Sediment cores/Lake region	10,000 years	Lake Ben, Lake Small, Ontario	Field study, charcoal and	FRI range from 40-820 years (mean 186 +/- 23 years) Median FRI = 140

		and mesic boreal forests in central Canada				pollen analysis	FRI shortest between 4,000-5,000 YBP
Stelfox	2007	Chapter 5: The fire regime. Daishowa-Mirubeni Detailed Forest Management Plan	Fire/Landscape	1961-1995	Mirubeni Daishowa FMA	Fire records analysis	Cycle = Upper Foothills 78, Subarctic 195, Boreal Highlands 212, Wetland Mixedwood 214, Central Mixedwood 288, Lower foothills 492, DryMixedwood 1623 Total area cycle = 285
Tande	1979	Fire history and vegetation patterns of coniferous forests in Jasper National Park, Alberta.	Tree/Landscape	1665-1995	Jasper National Park	Field study Fire scars	MFRI <1913 = 5.5 yrs (8.4 yrs if fire > 500ha; 65.5 yrs if fires>43,200ha)
Tardif	2004	Fire history in the Duck Mountain Provincial Forest, western Manitoba	Tree/Landscape	1700-2000	Duck Mountain, Manitoba	Field study, Fire scars	Fire Cycle 1700-1880 = 55 years 1880-1960 = 200 years 1960-2004 = 15,000 years
Tymstra	2005	Alberta Wildfire Regime Analysis	Fire/Natural Subregion	1961-2005	Alberta	Fire records analysis	Fire Cycle = 273 years Whole of Alberta, Forest Protection Area Athabasca Plain fire cycle = 45years Boreal Highlands fire cycle = 124 years Central Mixedwood, mean fire cycle = 226 years Dry Mixedwood fire cycle= 1,053 years Kazan Uplands fire cycle = 82 years Lower Foothills fire cycle = 475 years Montane fire cycle = 4,736 years Peace River Lowland fire cycle = 1,013 years Sub-Arctic fire cycle = 132 years Subalpine fire cycle = 4,542 years Upper Foothills fire cycle = 627 years Wetland Mixedwood fire cycle = 367 years
Van Wagner	1978	Age-class distribution and the forest fire cycle.	Stand/Landscape	1600's-1960	Hinton Wood Products FMA	Stand age analysis	Fire cycle: <1915 = 50 years <1960 = 65 years
Wallenius	2011	Long-term decreasing trend in forest fires in northwestern Canada	Tree/Landscape	1750's-2000	Northwest AB/SW NWT/NE BC	Field study: fire scars	fire cycle = 50 years early 1800's 300 years late 1900's
Weir	2000	Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada	Tree/Landscape	1800's-1999	Prince Albert National Park, SK	Field study: fire scars	Fire Cycle <1890 = 15 years 1890-1945 = 75 1945-1999 = 1745

Many factors are responsible for variability in frequency. There is no disagreement in the literature that in complex terrain the interval between fires is longer on north and east aspects as compared to south or west aspects (Andison, 2000; Hawkes, 1980; Hawkes, 1979; Rogeau, 2005b; Rogeau, 2010).

Larsen (1997), and Barrett *et al* (2013) confirm that the proximity to waterbreaks and/or density of waterbodies in the region has a significant lengthening effect on fire cycles. In the boreal regions of Alaska, high water body density lengthens the fire cycle from 138 to 453 years over a 7,000 year observation period (Barrett *et al.* 2013). Larsen demonstrates that a water break can nearly double the fire cycle from 30 – 50 years, but this is observed over a much shorter time period (200 years). These conclusions are further supported by Senici *et al.* (2010).

The analysis of fire records to determine fire cycles in much of the province of Alberta (Tymstra *et al.,* 2005; Stelfox *et al.,* 2007; Rogeau, 2009) reveals that fire suppression has had a major effect on these parameters. In some Natural Subregions, the fire cycle from 1961-present is in excess of 10's of thousands of years. Some would argue that the time frame is too short to effectively measure fire frequency, but given that the provincial fire records are used in many studies to examine fire regimes, it calls into question the utility in fire records analysis in the suppression era to inform us of fire frequencies. Some researchers have attempted to account for suppression in their estimates (Cumming, 1997; Li, 2000), however these values don't appear to have been widely accepted or adopted. The rough factor by which Cumming reduces the fire cycle based on suppression (less than a 50% reduction) does not match what is observed in the studies showing multi-thousand year cycles, where the factor of suppression appears to be orders of magnitude difference.

More accurate values for fire frequency likely are given by age class analysis of the forest, however the size class distributions used (see discussion on size below) will affect these values too (Johnson *et al.* 1994; Van Wagner, 1978; Li, 2002). The detailed analysis of age class distributions has only been done on very small areas of the study region as a whole, which makes interpolation very challenging. The amount of work and cost involved to conduct field studies (stand origin mapping and fire scar analysis) across the region would make such an assessment essentially impossible. Stand record analysis might be cost effective, however there are well known issues with stand ages in the Alberta provincial inventory system (Andison, 1999b) make scaling this approach to the whole region of dubious value.

TIMING

The net trends in burn timing vary by location. These statistics are provided in abundance in numerous papers included in this review (see Table 7 below). This is not an area of active disagreement in the research community, as such the values for the number of lightning ignitions versus human caused ignitions in modern times are robust. There are some papers that attempt to reconstruct what the length of the burning season was in the past as compared to today (Albert-Green *et al.* 2013). As discussed in the section on “cause” previously, one of the more important elements of fire regime seasonality/timing is how it relates to the ignition source: if the historic regime had a large number of anthropogenic fires, then the season of burning might well have been different than it is today. This is a challenging question to answer. Although Boyd (2002, discussed previously) has described a new method for elucidating the portion of fires attributable to humans in the past, this has not been widely adopted, and no studies in the region using the silicophytolith analysis method exist.

Rogeau (2009, 2010a) determined that in the R11 FMU (west of Sundre, AB in the foothills and montane) the majority of the historical fires occurred in the spring, or dormant season for trees, with only 20-25% of fires occurring during the summer. This stands in stark contrast to the evaluation of the modern fire regime, where the vast majority (more than 80%) of fires occur between June and August. This is yet another line of evidence to suggest that First Nations burning may be the driving factor behind the fire regime of the region. Lewis (1978, 1982, 1988) describes that spring was the primary season for anthropogenic burning, but we have little quantitative evidence of this.

Of note with regard to timing, however, is a general consensus that the fire season is getting longer. This affects the total number of fires, the potential size they can grow to, the intensity under which they burn, and the severity of the burns over the long term. This factor alone substantially alters the fire regime going into the future, and leaves us with a biased record today.

Table 7: Research papers relevant to fire timing/seasonality for the study area and key findings

Lead Author	Year	Title	Grain/Extent	Time	Location	Method	Findings
Albert-Green	2013	A methodology for investigating trends in changes in the timing of the fire season with applications to lightning-caused forest fires in Alberta and Ontario, Canada	Fire/Biome	1961-2003	Alberta and Ontario	Fire records analysis	Start of fire season has shifted from 1st week of May (Julian Day 125) to mid April (JD 105) End of fire season has moved from JD 255 (mid Sept) to JD 285 (mid Oct). Overall, fire season has lengthened from May-Sept, and a period of 130 days to April -October and a period of 180 days. This will influence the number of fires that occur annually.
De Groot	2013	A comparison of Canadian and Russian boreal forest fire regimes	Fire/Ecozone	1970-2009	Boreal Canada	Fire records analysis	Provides statistics of CFFDRS Fire Weather Indices by time of year
Lewis	1988	Yards, corridors, and mosaics: How to burn a boreal forest	None/ethno study	1800's - 2000	No specific area	Ethnographic study	Season of burning: usually done in spring with snow on ground. Claim to have been actively doing this until 1950's
Magnussen	2012	Inter- and intra-annual profiles of fire regimes in the managed forests of Canada and implications for resource sharing	Fire/National	1980-2007	Canada	Fire records analysis	Describes variation in fire season length over the time period by province (beginning date and end date) Indicates week of maximum burning by province (Week 24 for AB, 24 for SK, 27 for NWT)
Parisien	2004	Saskatchewan fire regime analysis	Fire/Province	1945-2000	Forested Saskatchewan	Fire records analysis	Shows (figure 6) the number of fires per month by ecozone.
Parisien	2011	Contributions of ignitions, fuels, and weather to the spatial patterns of burn probability of a boreal landscape	Fire/Landscape	Theor-etical	Wood Buffalo National Park, AB	Modelling	Describes ignition timing assumptions used in modelling
Rogeau	1999	Fire history study of the Central Rockies Ecosystem Inter-Agency North-Saskatchewan Unit	Fire/Landscape	1961-1998	Upper North Saskatchewan River watershed	Fire records analysis	Describes months of highest fire activity from 1961-1998 from provincial forest fire records
Rogeau	2004	Fire Regime Study, Kananaskis District, Alberta. Part 1	Tree/Landscape	1500's to present	Spray Lakes Sawmills FMA	Field study Stand origin map, fire scars	Burning season by natural subregions: Alpine July-Aug, Subalpine July-Sept, Montane June-Sept, U Foothills May-Oct, L Foothills May-Oct, Parkland April-Oct Peak fire frequency: All (July-August), Lightning (July-August), Anthropogenic (April-August)
Rogeau	2005	Fire regime study C5 FMU, Alberta	Stand/Landscape	1800-2000	C5 FMU	Fire records analysis AVI analysis	Most fires (frequency) burn July-August. (51% of total fires) most area burned is in July
Rogeau	2008	Fire regime analysis of the Chinchaga River basin (FMUs P8-P15)	Fire/Landscape	Late 1800's to 2008	P8 and P15 FMU	Fire records analysis	Burning season: Central Mixedwood May-July; Dry Mixedwood April-Oct; Upper Boreal Highlands May-July; Lower Boreal Highlands April-Sept

Rogeau	2010	PartIII: R11 Fire regime departure. R11 FMU, Alberta	Tree/Landscape	1700's to present	R11 FMU	Modelling and Field study fire scar	Shows percentage of fires by sub-valleys and whether they occur in spring/Fall or summer
Stelfox		Chapter 5: The fire regime. Daishowa-Mirubeni Forest Management Plan	Fire/Landscape	1961-1995	Mirubeni Daishowa FMA	Fire records analysis	Mean monthly fire frequency and size (1983-1992) (#fires/size) Ja 6/9, F 7/0.2, Mr 11/0.6, Ap 108/36, My 350/15, Jn 432/15, Jl 568/98, Ag 532/4, S 107/17, O 77/2, N 10/0.1, D 7/0.7, Total 2215/34
Tymstra	2005	Alberta wildfire regime analysis	Fire/Natural Subregion	1961-2005	Alberta	Fire records analysis	Detailed statistics of # and size of fires by month for each Natural subregion

SIZE

Much of the research mentioned in the section on frequency above also includes size, as the fire cycle and other area-measures of fire regime frequency cannot be calculated without knowing the size of fires. Some of the research below (Table 8) describes observed ranges in fire size distribution, and there is general agreement that between 95-97% of the area burned throughout the study area is caused by 1-3% of the fires that occur. While there are many small fires, their landscape level impact is relatively small with regard to area burned. This does not discount the potential ecological importance of many small burns, as they maintain a degree of landscape heterogeneity and “island” habitat for many post-fire pioneer species.

Some of the “size” literature discusses theoretical concepts and mathematical equations governing fire size distributions. The previously commonly used negative exponential distribution of fire sizes has been shown to only apply in cases of 100% lethal fires (van Wagner, 1978). The section on severity (above) reveals that this assumption is largely violated along the foothills region, and much of the boreal too shows signs of mixed severity fires. Other distributions have been shown to fit fire size distributions better (ie. Weibull, pareto).

Using the right size class distribution is an important element of fire regimes, especially with regard to calculating fire cycles and mean fire return intervals. More recent fires erase the evidence of older fires underneath them, and without the proper size class distribution, reconstructing these partially (or fully) erased older fires is impossible.

A detailed analysis or discussion of these papers related to size class distributions is beyond the scope of this review, however they are mentioned in the table, and experts in this field may wish to expand upon this discussion.

Table 8: Research papers relevant to fire size for the study area and key findings

Lead Author	Year	Title	Grain/Extent	Time	Location	Method	Findings
Andison	1998	Temporal patterns of age-class distributions on foothills landscapes in Alberta.	Stand/NSR	N/A	Foothills Model Forest	Modelling, derived from Stand Origin Map	Lower Foothills NSR Area Burned 25% per 20 years Subalpine NSR Area Burned 16% per 20 years Upper Foothills NSR Area Burned 20% per 20 years
Andison	2003	Disturbance events on foothills and mountain landscapes of Alberta	Stand/NSR	1800-1990	Foothills Model Forest	Stand record analaysis	Single large remnant patches are rare within events. Undisturbed remnant patches are more evenly distributed by size ~35% of events have only 1 disturbance patch, 26% have 2-5 disturbance patches, 15% have 6-10 disturbance patches As event size increases, number of patches increase Events are dominated by a single disturbance patch that accounts for (on average) 73% of the total disturbed area .
Andison	2003	Patch and event sizes on foothills and mountain landscapes of Alberta	Stand/NSR	1800-1990	Foothills Model Forest	Stand records analysis	A small number of disturbance patches larger than 2,000, and in some cases over 10,000 hectares, historically dominated all five NSRs in the study region.
Andison	2004	Island remnants on foothills and mountain landscapes of Alberta: Part II on residuals	Stand/NSR	1800-1990	Foothills Model Forest	Stand records analysis	Islands < 2ha account for 27% of island area, and 91% of the number of islands
Burton	2008	Large fires as agents of ecological diversity in the North American boreal forest.	Fire/Ecozone	1959-2008	Boreal Forest	Fire records analysis (>200ha)	Boreal Plains mean large (>200ha) fire size = 6,183 ha Taiga Plains mean large (>200ha) fire size = 12,748 ha Boreal Shield mean large (>200ha) fire size = 8,780 ha Boreal Cordillera mean large (>200ha) fire size = 6,297 ha
Cumming	2001	A parametric model of the fire-size distribution	Fire/NSR	1961-1998	~AlPac FMA	Fire records analysis	Logarithm of fire size is exponential distribution for fires above 3ha
de Groot	2013	A comparison of Canadian and Russian boreal forest fire regimes	Fire/Ecozone	1970-2009	Western Boreal Canada	Fire records analysis	Presents annual area burned, number of fires per year, and fire size distribution for all of Canada between 2001-2007
Johnson	1998	Wildfires in the western Canadian boreal forest: Landscape patterns and ecosystem management.	Fire/Biome	n/a theory	Boreal Western Canada	Literature review	Confirms statistics that majority of area burned is from large fires and that small fires do not contribute much to total area burned
Li	2000	Reconstruction of natural fire regimes through ecological modelling.	Fire/Management unit	1700-2000	Hinton Wood Products FMA	Modelling	Modeling approaches to calculating "natural" fire size distributions that are free from suppression influences are described
Macias Fauria	2008	Climate and wildfires in the North American boreal forest.	Fire/Biome	1900-2010	Boreal north America	Fire records analysis	Discussion relating fire size to climate cycles

Parisien	2004	Spatial patterns of forest fires in Canada, 1980–1999	Fire/Ecozone	1980-1999	Forested Canada	Fire records analysis	Max fire size by ecozone: Boreal Cordillera 180,173 Boreal Plains 599,596 Boreal Shield W 571,248 Taiga Plains 887,804 Montane Cordillera 21,577
Parisien	2009	Saskatchewan fire regime analysis	Fire/Province	1945-2000	Forested Saskatchewan	Fire records analysis	Exponential decrease in number of fires as a function of fire size
Rogeau	1999	Fire history study of the central Rockies. Ecosystem InterAgency North Saskatchewan Unit.	Fire/Province	1945-2000	Upper Saskatchewan River watershed	Fire records analysis	Fire Size Occasionally fires as large as 20,000 ha occur in the region Drivers: Valley orientation is a key driver of fire frequency and size.
Rogeau	2005	Fire regime study of C5 FMU	Stand/Landscape	1800-2000	C5 FMU	Fire records analysis AVI analysis	Largest fire size on record 21,163 ha. Only 0.8% of all fires are larger than 200ha detailed fire size distribution tables are presented Mean fire sizes: Subalpine 1670 ha, Montane 985 ha
Rogeau	2008	Fire regime analysis of the Chinchaga River Basin (FMUs P8-P15)	Fire/Landscape	Late 1800's – 2008	P8 and P15 FMU	Fire records analysis	Mean fire size (>10ha): Central Mixedwood 518ha; Dry Mixedwood 56ha; Lower Boreal Highlands 1773ha; Upper Boreal Highlands 7,486 Also shows detailed fire size distribution
Rogeau	2009	Fire regime study FMU R11: Part 1.	Fire/Landscape	1961-2008	R11 FMU	Fire records analysis	Largest fire in the region = 9,214 ha in Subalpine and Upper Foothills Less than 2% of fires become larger than 200ha Upper Foothills: 3.29 (1,577); Lower Foothills: 15.76 (7,646); Subalpine: 54.51 (9,214); Montane: 1.2 (81) Numbers are: mean fire size in hectares (max fire size in brackets)
Stelfox	2007	Chapter 5: The fire regime. Daishowa-Mirubeni Detailed Forest Management Plan	Fire/Landscape	1961-1995	Mirubeni Daishowa FMA	Fire records analysis	Mean monthly fire frequency and size (#fires/mean ha) : J 6/9, F 7/0.2, M 11/0.6, A 108/36, M 350/15, J 432/15, J 568/98, A 532/4, S 107/17, O 77/2, N 10/0.1, D 7/0.7, Total 2215/34
Tymstra	2005	Alberta Wildfire Regime Analysis	Fire/Natural Subregion	1961-2005	Alberta	Fire records analysis	Detailed fire size distributions for all of Alberta summarized by NSR, cause, month etc.

One of the largest challenges with reconciling research on fire size is that the measurement depends on the way in which it is defined. As Andison (2012) describes, how the boundaries of the fire event are defined has a significant effect on our downstream understanding of the phenomenon. Furthermore, the spatial scale at which this is measured has a large effect too (Morgan *et al.* 2001; Falk *et al.* 2007).

SEVERITY

Severity is discussed in greater detail following Table 9 (below). In this section papers have been included that discuss fire intensity, island remnants, fire shape, and levels of mortality observed in fires. As Keeley (2009) describes, fire severity is the description of the *effects* of fire intensity, which includes the level of mortality, the depth of burn, and other metrics that determine what will or will not grow on a site following a fire. To take this one step further, fire severity is the OUTCOME of the fire cause, frequency, size, and intensity, and is the vegetation pattern on the landscape. While not everyone will agree with this statement, this is the rationale behind why all these components of fire regimes are bundled together under the heading “severity”.

Severity is often discussed as a scale ranging from “low” to “high”. Following table 9, there is a substantive discussion of low, mixed, and high severity fire regimes in both forested and grassland ecosystems. Within severity, it becomes impossible to ignore the previous elements of cause, frequency, timing and size.

Table 9: Research papers relevant to fire severity for the study area and key findings

Lead Author	Year	Title	Grain/Extent	Time	Location	Method	Findings
Adams	2013	Mega-fires, tipping points and ecosystem services: Managing forests and woodlands in an uncertain future	N/a	N/a	Global	Literature review	Trends in postfire revegetation suggest that conifers may be in decline and deciduous on the rise. This is due to increased fire activity, but will result in lowered fire activity due to lower flammability
Amoroso	2011	Evidence of mixed-severity fires in the foothills of the Rocky Mountains of west-central Alberta, Canada	Tree/Landscape	1889-2009	Hinton Wood Products FMA	Field study, fire scar analysis	Evidence of mixed severity fires burning over past 1.5 centuries in an area formerly considered a high severity regime
Andison	2003	Patch and event sizes on foothills and mountain landscapes of Alberta	Stand/NSR	1800-1990	Foothills Model Forest	Stand records analysis	Highly detailed descriptions of event sizes, numbers of patches, distributions of patches, all broken down by Natural Subregion. A small number of disturbance patches larger than 2,000, and in some cases over 10,000 hectares, historically dominated all five landscapes.
Andison	2002	Disturbance in riparian zones on foothills and mountain landscapes of Alberta	Stand/NSR	1800-1990	Foothills Model Forest	Stand records analysis	As the amount of riparian area in a fire increases, the proportion of island remnant area in riparian zones increases Higher order streams have more disturbance islands than lower order stream Island remnants occur in riparian zones in higher proportions than expected (compared to rest of landscape), this tendency decreases as the width of the riparian zone increases The proportion of high-survival islands in riparian zones is greater than the proportion of low survival islands (compared to the whole fire)
Andison	2003	Disturbance events on foothills and mountain landscapes of Alberta	Stand/NSR	1800-1990	Foothills Model Forest	Stand record analaysis	69% of a fire "event" is burned to varying degrees, with 31% unburned in "matrix remnants" Disturbance patches are more convoluted in shape than disturbance events. Complexity increases in relation to size Shape complexity increases as events become larger
Andison	2004	Island remnants on foothills and mountain landscapes of Alberta: Part II on residuals	Stand/NSR	1800-1990	Foothills Model Forest	Stand records analysis	Islands < 2ha account for 27% of island area, and 91% of the number of islands
Arno	2000	Mixed-severity fire regimes in the northern Rocky Mountains: consequences of fire exclusion and options for the future.	Landscape/Eco-zone	1500-1900	Wyoming and Montana	Literature review	Discussion and definitions of mixed severity fire regimes
Boulanger	2012	An alternative fire regime zonation for Canada	Fire/Nation	1980-1999	Forested Canada	Fire records analysis	Divides the Boreal study region (this project area) into 12-13 distinct Homogenous Fire Regimes.

Burton	2008	Large fires as agents of ecological diversity in the North American boreal forest.	Fire/Ecozone	1959-2008	Boreal Forest	Fire records analysis (>200ha)	Examination of fire size: island size and island numbers
Eberhart	1987	Distribution of residual vegetation associated with large fires in Alberta	Fire/Ecozone	1970-1983	Boreal Plains and Boreal Shield Alberta	Fire records analysis	Detailed analysis of number of islands per fire by fire size class, shape indices
de Groot	2013	A comparison of Canadian and Russian boreal forest fire regimes	Fire/Ecozone	1970-2009	Western Boreal Canada	Fire records analysis	fire intensity values and mean fuel consumption (duff, dead, live) for whole study area
Keeley	2009	Fire intensity, fire severity and burn severity: a brief review and suggested usage	N/a	n/a	n/a	Literature review	Excellent discussion of concepts and terminology for severity
Hawkes	1979	Fire history and fuel appraisal of Kananaskis Provincial Park	Tree/Landscape	1586-1978	Kananaskis Provincial Park	Field study Fire history	High severity fire appears to be the norm for the area most fires are of medium to high intensity, with lower and moderate intensities on edges and backing sections
Johnson	1998	Wildfires in the western Canadian boreal forest: Landscape patterns and ecosystem management	Fire/Biome	n/a theory	Boreal Western Canada	Literature review	All fires have variable severity
Lewis	1988	Yards, corridors, and mosaics: how to burn a boreal forest	None/ethno study	1800's - 2000	No specific area	Ethnographic study	Season of burning: usually done in spring with snow on ground to reduce severity. Claim to have been actively doing this until 1950's.
Narayanaraj	2013	Influences of forest roads and their edge effects on the spatial pattern of burn severity	Fire/Landscape	2000-2007	Okanogan - Wenatchee National Forest	Fire records analysis/ remote sensing	Burn severity lower close to roads Burn severity lower close to streams
Parisien	2006	Spatial patterns of forest fires in Canada, 1980-1999	Fire/Ecozone	1980-1999	Forested Canada	Fire records analysis	Describes shape index of fires by ecozone
Rogeau	1999	Fire history study of the central Rockies. Ecosystem InterAgency North Saskatchewan Unit.	Tree/Landscape	1700-1999	Upper Saskatchewan River watershed	Field study, fire scars	Valley orientation key driver of fire severity (and size)
Rogeau	2004	Fire Regime Study, Kananaskis District, Alberta. Part 1	Tree/Landscape	1500's to present	Spray Lakes Sawmills FMA	Field study Stand origin map, fire scars	1950's air photo screening reveals substantially higher vegetation complexity (lower severity fire regime) than current landscape. Details by valley and watershed
Rogeau	2005	Fire history study Kananaskis District, Alberta 2004 field results	Tree/Landscape	1500's to present	Spray Lakes Sawmills FMA	Field study Stand origin map, fire scars	Significant evidence of mixed severity fire regime in the field
Rogeau	2005	Fire regime study of C5 FMU	Tree/Landscape	1500's to present	C5 FMU	Fire records analysis,	1950's air photo screening reveals substantially higher vegetation complexity (lower severity fire regime) than current landscape. Details by valley and watershed

Rogeau	2008	Fire regime analysis of the Chinchaga River basin (FMUs P8-P15)	Fire/Landscape	Late 1800's – 2008	P8 and P15 FMU	Fire records analysis Historical document analysis	Higher vegetation complexity pre-1950, historical records support this too
Rogeau	2009	Fire regime study FMU R11: Part 1	Fire/Landscape	1949 - 2009	R11 FMU	Fire records analysis	1950's air photo screening reveals substantially higher vegetation complexity (lower severity fire regime) than current landscape. Details by valley and watershed
Rogeau	2010	Fire regime departure R11 FMU: Part 3	Fire/Landscape	1800's to present	R11 FMU	Modelling, based on field study and fire records analysis	Fire regime severity departure level "critical" for most areas of the landscape
Tande	1979	Fire history and vegetation patterns of coniferous forests in Jasper National Park, Alberta	Tree/Landscape	1665-1995	Jasper National Park	Field study Fire scars	Most fires between 1665-1913 were of low to medium intensity (although high intensity fires did occur)

LOW SEVERITY FIRE REGIMES

Low severity fire regimes are uncommon in the area, and likely restricted to portions of the montane, grasslands, and aspen parkland.

In low severity fire regimes in forested ecosystems, stand structure tends to be open, with widely spaced trees, little ladder fuel, and relatively light surface fuel loading. Topography is usually gentle, as steeper slopes increases upslope radiative drying of fuels, which would result in increased candling and/or crown fire dynamics. Low severity fire regimes are considered "stand maintaining" as they cause little overstory mortality, but reduce understory competition significantly, allowing the overstory to dominate for long periods of time. Finding evidence of low-severity fire regimes generally involves examination of fire scars. In these fire regimes, overstory trees that have survived multiple low-severity fires will show multiple fire scars which can be dated.

The fire cycles and fire return intervals in low severity regimes tend to be relatively short: fuel loads are quickly eliminated, and cannot build up to sufficient volume to cause higher severity fires that result in overstory mortality. Fuel burnt in low severity fire regimes is often grass, herbaceous vegetation or shrubs. This requires a frequent and somewhat regular ignition source that coincides with flammability of the fuel. These ecosystems often occur in locations with associated weather patterns that have regular lightning storms, but can occur in lightning shadows if the ignition source is anthropogenic, where they coincide with corridors of frequent human use (Wierzchowski et al, 2002; Tande, 1979).

MIXED SEVERITY FIRE REGIMES

Mixed severity fire regimes are complex. There are two essential types of mixed severity regimes which intergrade significantly: *temporal* mixed severity, and *spatial* mixed severity (Schoennagel et al, 2004; Agee, 1993; Veblen, 2003).

Temporal mixed severity fire regimes are those that when measured over time show alternating fire behavior between low and high severity. They may have long periods of one type of fire severity, and then "switch" to a different fire severity. The reasons for this can be complex: different ignition sources may cause different severities, climate patterns can shift, or other disturbances may interact with fire. An area may be burned on a frequent basis by First Nations in the spring, with resulting low severity burns, but occasional lightning strikes at a different time of year under extreme conditions can ignite massive crown fires. Differential weather patterns can cause varying burn intensities. Climate anomalies may create unusual conditions every so often that create massive blazes (Girardin and Sauchyn, 2007). Other disturbance agents such as the mountain pine beetle, spruce budworm, or forest tent caterpillar can alter the fuel complex over tens of thousands of hectares within a few years.

In general, a *temporal mixed severity* fire regime is caused by variability in climate, and/or interactions with other disturbances that significantly change vegetation composition and fuel loading over time (Carcaillet *et al*., 2001). Detecting the presence of a temporal mixed severity fire regime is challenging. If the most recent fires have been high intensity, finding evidence of previous low-intensity fires is difficult. When this happens, searching for multiple-fire scarred trees, snags and logs can be like searching for fossils, which are very difficult to locate using standard sampling schemes.

A further complication in detecting temporal mixed severity fire regimes is that a time period must be studied that is long enough to adequately capture the variation in fire history. But, this needs to be done with caution. As longer periods of time are studied, variation rises significantly in all regions as climate variation, and other disturbance agents' variability is captured (Power *et al,* 2007).

Spatial mixed severity fire regimes show differential burning severities across the landscape. These are driven far more by variations in topography and fuels. The influence of topography on fire behavior is well studied, topography derived gradients explain significant differences in vegetation (and therefore fuel structure). In the Subalpine regions of the East Slopes there is considerable evidence for the presence of spatial mixed severity fire regimes which will be discussed below.

While mountainous and foothills terrain variability might be obvious with regard to their influence on burning severity, even on flatter ground topography can have a big influence. In boreal landscapes, differences in elevation of only a few inches can make big differences with regard to soil moisture, which in turn can create conditions for differential fuel type expression. While patterns of fire severity impacts have been studied extensively (Andison, 1998; Andison, 2000; Andison, 2003a; Andison, 2003b; Andison, 2003c; Andison 2004; Cumming, 1997; McLean *et al*., 2003; Rogeau, 2005b), rarely has pattern been correlated to subsurficial variables such as soils, and parent material. Granted, in severe fire weather situations, the influence of these factors may be overwhelmed.

A challenge with classifying spatial mixed severity fire regimes is where to draw the line between mixed severity and high severity fire. In Table 3, the distinction is drawn at 75% crown mortality, but the difference between the two is purely arbitrary. As landscapes become more complex in topography and fuel variability, the level of survival within a given fire event rises. As the topography and fuels become more uniform, the level of potential mortality rises. This is, of course, ignoring weather variability *during* a fire event, which in itself is a significant driver of fire severity.

To further complicate our understanding of *spatial* mixed severity fire regimes*,* some researchers differentiate between ***mosaic*** fire regimes*,* which are spatially mixed severity fire regimes as described above, but with patches of fully burned, and patches of unburned trees within the fire perimeter, and "pure" ***spatial mixed severity*** fire regimes, where there is 25%-75% crown mortality evenly distributed within the fire perimeter. The mosaic fire is one with intermittent crown fire activity, whereas the spatial mixed severity fire is one with intermittent candling (Barrett *et al*., 2010). With all these various classifications, one could conclude that all fires are "mixed severity", and this may be the real insight to be obtained: very few fires burn 100% of the vegetation within them, and to treat fire regimes in this extreme manner (see high severity fire regimes below) may well be misleading.

Tande (1979) found the majority of fires in the montane in Jasper were of low intensity, but larger, more intense fires did occur periodically. Stand structure varied from even-aged to multi-aged over short distances, which indicates that there is both a mosaic mixed severity, and a temporal mixed severity fire regime operating in the area over the time period in question. Since 1913, fire frequency and extent have been markedly reduced, and landscape heterogeneity has also been reduced, which has been confirmed by Rhemtulla (1999).

HIGH SEVERITY FIRE REGIMES

High severity fire regimes are dominated by crown fire activity. They tend to kill the majority of overstory vegetation within a fire perimeter (75% or more according to Table 3). Within a region characterized by high severity fire regimes, there tends to be lower variability in topography and fuel structure. Fire activity is more binary in nature: when fires ignite they either become active crown fires, or extinguish quickly due to lack of available fuel. Over time and space, they exhibit relatively little variation in severity.

High intensity crown fires tend to maintain a landscape in a mosaic of even-age, single-species stands. Depending on the time since fire, stands may succeed towards mixed composition, but if fire cycles are not too long, stands that result from this type of disturbance tend to be fairly uniform coniferous forests which are reset by high intensity fire. These fire regimes are often referred to as stand-replacing fire regimes. The size of fires within high severity fire regimes tends to be very large, occasionally in excess of 100,000 ha, and with one fire in known Canadian history exceeding 1M ha in size (Chinchaga).

To illustrate the point of arbitrary distinctions between mosaic spatial mixed severity fire regimes (mortality ranging from 25% to 75% mortality), consider a region with a spatially mixed severity fire regime with a mean of 70% mortality. This is much more similar to a region with a high severity fire regime with a mean of 80% mortality than it is to another mixed severity fire location with a mean of 30% mortality.

Numerous fire regime studies have been conducted on the Boreal Plains at a national scale (Rowe and Scotter, 1973; Johnson *et al*., 1998; Parisien *et al*., 2006), in Saskatchewan (Parisien *et al*., 2004) and in Alberta (Armstrong, 1999; Tymstra *et al*., 2005). There is a wide consensus that the fire regime is dominated by frequent, large, high severity wildfire. Given the definitions provided earlier on the delineation between *high severity* and *mosaic spatial mixed* severity there is room for debate as to which is the case, but the only real difference between the two is what total proportion of affected area is burned, and what proportion survives in remnants. Significant work has been done by Andison to quantify and describe these patterns using the NEPTUNE model (Foothills Research Institute, 2009). Using 75% mortality as the cutoff between high and mixed severity, we might find that much of the Mixedwood's fire regime is indeed a mosaic spatial mixed severity fire regime. In the Central and Dry Mixedwood Natural Subregions, this likely is true due to the high proportion of aspen in the region, which burns infrequently.

FIRE REGIMES IN GRASSLAND ECOSYSTEMS

While there is not a large amount of grassland within the LANDWEB Project area, by either the natural subregion or terrestrial ecoregion classification systems, it is an important component of the region due to its significant presence within the Montane Natural Subregion, some large prairie complexes around Grande Prairie and High Level, Alberta, and in the Aspen Parkland which defines the southern limit of this study. The grasslands that occur within the Project Area are forecast to increase in area in the face of climate change.

Numerous authors have investigated the role of fire in prairie and Great Plains ecosystems (Rowe, 1969; Axelrod, 1985; Collins and Wallace, 1990; Archer, 1999). To claim that fire is solely responsible for the maintenance of this ecosystem is an oversimplification. Nonetheless, fire is one of several critical processes that have shaped this ecosystem and regulated vegetation patterns and succession on the landscape over tens of millennia. Other processes include climate, grazing by large mammals, herbivory by smaller animals, human use (First Nations burning, hunting, and settlement), soils, and topography.

Variations in the frequency of fire can produce large effects on the ecosystem. If the lag time is considerable between fire events, in grasslands, just as in forests, significant vegetation succession occurs. Depending when fire strikes during the successional pathway, it can have a variety of effects on the long term vegetation dynamics of a grassland system. The northern Great Plains have short fire return intervals, between less than one, and up to 35 years

(Henderson, 2006), with mean intervals of 4 to 10 years (Wright and Bailey 1980). It is possible for fires to burn more than once in the same year, as spring fires followed by summer regrowth and senescence can burn again between fall and the following spring (Bragg 1982). Thirty five years is a theoretical maximum, which is based on known successional dynamics within grasslands: over this time frame, grasslands without fire and/or grazing pressure will succeed to shrub and/or forest land given a local seed source.

For those used to studying fire dynamics in forested ecosystems, some elements of fire regimes in grasslands are counter-intuitive. Brown *et al*. (2005) demonstrated that moist periods correlate to high fire activity due to high productivity. Grasslands tend to be fuel limited systems, so in periods of drought, there often is not enough fuel to carry fire. This is similar to desert systems in the American Southwest, and has been shown to be relevant to the Canadian Great Plains. This is the opposite dynamic one sees in forested ecosystems, where high fire activity correlates to periods of drought, and lower activity during wet periods (Clark, 1989).

The concept of a *temporal mixed severity fire regime* also loosely applies to grasslands. Fire is not a constant steady process in grasslands, but varies with climate. Cycles tend towards 160 years between peak fire years (Brown *et al*., 2005; Umbanhowar, 1996). This rate is observed continent wide and in Greenland, which suggests that there is a hemispheric climate cycle at play. This 160 year number is not a “fire cycle” or a mean fire return interval, but instead correlates to “peak fire activity”. This peak might be represented by area burned, depth of burn (severity), or the number of fires per year. It might be that the periods of peak fire behaviour in grasslands occurs during low periods of fire activity in the forested ecosystems which are not fuel limited, but driven largely by moisture which drives ignition potential. On this cycle, there have been massive peaks in fire activity synchronized across the Great Plains occurring between 1700-1740, and between 1850-1900.

With regard to the sizes of grassland fires, Rowe (1969) found that most lightning fires in southwestern Saskatchewan grasslands were smaller than two hectares because subsequent rain fall quickly extinguished the flames, but a few fires burned more than 1000 ha, with the largest at 4600 ha. Henderson (2006) reports that in the semiarid grasslands of Montana and North Dakota, a population of 293 fires from the mid 1900’s showed a negative exponential distribution with a fires ranging from small patches of only a few square meters, to more than 1100 hectares, with a mean of 10.8 ha. In another study in Montana fire sizes ranged from < 1 ha to nearly 4500 ha (Wakimoto and Willard 2005). Pre-settlement mean and maximum fire sizes would likely be greater than these numbers as numerous landscape level fuel breaks currently exist that limit the spread of grass fires.

While some research has been done on fire *behavior* and fire *effects* in grasslands in the Canadian prairies and northern USA (Engle and Bultsma, 1984; Redmann *et al*., 1993; Archibold *et al*., 1998; Shay *et al*., 2001; Pylypec and Romo, 2003; Archibold *et al*., 2003; among others), there have been virtually no studies of historic "fire regimes" as we consider them to be measured in forest ecosystems. Unlike forest fires, grassland fires do not leave readily dateable fire scars to help us determine what fire activity was like before modern fire records were kept. Nor can we determine fire boundaries using scars like we do in forests. Given what we know of First Nations fire use in grasslands, detailed studies of lightning fire do not give us an accurate picture of what historic fire regimes in grasslands would have looked like, as lightning likely only accounted for a fraction of total fire on the landscape.

SECTION 3: DISCUSSION AND CONCLUSION

FOREST FIRE REGIMES - GENERAL

Current evidence published in the peer reviewed literature has suggested that much of the foothills and boreal regions of Alberta have a typical "stand-replacing" fire regime, with long fire cycles, and infrequent, high intensity fires. Whether these are "high severity fire regimes" or "mosaic fire regimes" is a matter of where one chooses to draw the distinction between high and mixed severity. Regardless of the name, in the mountain regions, the fire regime tends to be dominated by high intensity stand-replacing fires (White 1985; Johnson and Fryer, 1987; Johnson and Larsen 1991; Rogeau 2004a; Rogeau 2005a; Rogeau 2005b; Rogeau 2005c; Rogeau 2010c; Rogeau 2011; Rogeau 2012). These fire regimes are also the most dominant in the foothills regions adjacent to Jasper National Park, and throughout much of the boreal region of Alberta (Rowe and Scotter, 1973; Cumming, 1997; Andison, 1998; Andison, 2000; Andison, 2003a; Andison, 2003b; Andison, 2003c; McLean et al, 2003; Andison 2004).

There is, however, growing evidence from throughout the North American Rocky Mountain east slopes, and especially in the Montane and Lower Foothills Natural Subregions of both forms of mixed severity fire regimes, with spatially and temporally variable mixtures of stand-maintaining and stand-replacing fires (Gruell, 1983; Arno *et al*., 2000; Rogeau, 2009; Rogeau, 2010a; Rogeau 2010b; Amoroso *et al*., 2011). The biggest challenge to identifying, locating, and quantifying the extent of non-mosaic spatial and temporal mixed severity fire regimes is that they require a unique sampling methodology (Rogeau, 1999).

There is ample anecdotal, little field-based, and virtually no published evidence for the existence of low intensity surface fires occurring throughout the region. The identification of their extent requires sampling strategies that are very time consuming due to the high number of sample plots required. The historical extent and/or frequency of a mixed severity fire regime is unknown. Determining the extent of the various forms of mixed severity fire regimes along the east slopes is a question well worth answering. The impacts of a mixed fire regime on landscape structure and species mix have serious implications for wildfire and mountain pine beetle risk, timber harvesting and silviculture, and wildlife habitat (woodland caribou for example).

Misinterpretation of the fire regime of an area, and thus the resulting natural range of variability, can lead to significant management errors: if the historical disturbance severity and extent is overestimated, resulting land management actions based upon natural disturbance dynamics may be too large and severe. This can lead to larger-than-natural disturbance events that retain too few islands and too little coarse woody debris (CWD). Conversely, underestimating disturbance severity and extent can lead to disturbance events that are too small and retain large amounts of CWD and islands, which can lead to significant forest health issues due to higher than "normal" levels of landscape forest continuity.

De Groot *et al.* (2013a) summarized fuel loads, height to live crown, fire weather indices and various parameters useful for modelling wildfire in the Canadian boreal forest. While most studies of fire regimes state that they need to study many fires over time and space to understand the fire regime, De Groot notes that studies of individual fires can still provide useful information regarding the fire regime: studies of fuel consumption can be useful surrogates for fire regime severity; rate of spread can inform fire size; variations in dates of fires inform the timing of the fire regime.

A question that often arises is whether the past should be used as a model for the future? This is a challenge that faces all management activities: we can learn about the current system by studying its past, determine the driving mechanisms, and project them forward in time, but what if the conditions of the future are fundamentally different? Adams (2013), describes research showing that the rising trend in severity of fires in the boreal forest may be shifting the dominant vegetation from black spruce to aspen. So, while the short term trend is towards more severe fires, the long term trend might be less fire as the fuel complex changes to one that is considerably less flammable, which is also supported by McIntire *et al.*(2005).

Given that most of the large-area studies of fire regimes that have been cited throughout this review largely depend upon analysis of fire records, and that there is a trend towards larger and more severe fires, how representative of the longer term past are modern records? Especially when one considers how many fires have been successfully extinguished in the past 50 years: what would the "natural" order be if those fires had been left to burn? As the discus. Chapsion on frequency revealed, many of the studies that have used fire records analysis likely are providing values too large for the "natural" fire cycle.

As discussed previously with regard to the Modifiable Areal Unit Problem, and knowing that most of the area in question has not had rigorous field studies to determine fire frequency or to detect mixed severity fire regimes, we have to make a difficult decision: is the variability observed over space for all fire regime parameters representative of the variability we would see over time? The few studies that examine fire history over longer periods of time would suggest that this is not the case: temporal variations in climate, and their subsequent effects on vegetation succession, ignitions, and fire intensity would suggest that the Natural Range of Variability is huge. However, we are not completely without guidance: we do know many of the local scale drivers of this variation.

THE TOWER OF BABEL – CONFUSING TERMINOLOGY

One of the leading problems in fire regime analysis, not unlike other fields of science, is the varying, and often confusing use of terminology. This document is not designed to create a common set of definitions for fire regime analysis in Alberta, and in many ways, if Alberta were to invent its own terminology that was different from other regions, we would likely find that confusion would increase still further. What we can do, however, is be more aware of what different terms mean, and recognize that numerous questions need to be asked of any research study we look at to be sure we know what it is really saying.

While terms like "fire cycle" appear to be universally understood, there are different *methods* of calculating it, using different equations that make different assumptions. The methods for calculating a fire cycle that have been largely used as created by Johnson and Van Wagner (1985) assume that fires start in random locations, but Cumming (2000) has shown this assumption is not true. Numerous other mathematical models have been developed, but the point is that there are several ways of doing this. This makes direct comparison of fire regime studies difficult if the methods were different, even if the terminology is the same.

Fire return intervals and mean fire return intervals are used interchangeably by some, which confuses the issues of fire regimes even further. There are so many different definitions of "severity" that literature reviews have been written on that subject alone.

Given A) the variety of parameters used to *measure* fire regimes (see Table 1), B) that each parameter has numerous attributes that can be measured, and C) that each of those attributes has different methods associated with how to calculate them, the potential for confusion is immense. What is important is to ensure that fire regime studies are conducted with clear objectives in mind, and that when land managers wish to use fire regime information to aid in decision making, they need to be sure the objectives and assumptions attributes of each piece of information they are using are understood, and that the attributes measured are useful to the management activities that are planned.

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