Fire regimes of southern Alberta, Canada

by

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ABSTRACT

After decades of recent fire exclusion in southern Alberta, Canada, forests are progressively aging and landscape mosaics are departing from their historical conditions. A large-scale fire history study spanning three natural subregions: Subalpine, Montane and Upper Foothills, was undertaken to understand fire return intervals (FRI) prior to the period of effective fire suppression (pre-1948). This thesis presents an approach to conducting field-based fire history studies in remote landscapes. A paired-plot sampling approach was used to deal with landscapes regulated by large-scale, fully lethal, and mixed severity fires, where fire scar evidence is lost over time. For each natural subregion, point FRIs were used to conduct a fire frequency (i.e. survival) analysis that considers both FRI and time-since-fire data. A total of 3123 tree samples were collected at 814 sampling sites, from which 583 fire scars were identified. Results showed natural subregions had different fire interval distributions before 1948 and some level of FRI variance was also observed within a subregion. The median FRI for the Montane and Foothills sampling units ranged from 26 to 39 years, while the sampling unit located in the most rugged portion of the Subalpine had a median FRI of 85 years.

Other aspects of the fire regime were also documented for the three natural subregions including: severity, seasonality and cause. These results revealed an important anthropogenic influence on the amount and spatial distribution of burning prior to 1948. In contrast, the effective fire suppression measures taken since 1948 resulted in a substantial departure of 167% to 223% (median FRI = 84 to-104 years) for the Montane and Foothills, while the rugged Subalpine was found to be within its natural range of variation with a departure of 42% (median

FRI = 121 years). These findings may have important impacts for how wildland fire and forest management guidelines are set today, and in the future.

Another objective of this research was to evaluate the effects of topography on wildfire distribution. The aim of this study was to quantify the effects of elevation, aspect, slope and dominant species on probability of burning, and to re-evaluate the same effect when the forest is partitioned by seral stages. Fire return interval data were stratified by subregion and analyzed with the non-parametric Kaplan-Meier survival model and Cox Proportional Hazards regression model for survival data. The natural subregions were found to have distinct fire distributions with elevation and aspect being significant variables affecting the probability of burning. However, this effect was not constant across all seral stages. The outcome of this study contributes to understanding the ecological role of fire in mountain landscapes and where fire-adapted plant communities prevail. The impact of topography on fire frequency is variable with seral stage and is pertinent to forest and fire management activities such as ecological restoration needs, protection of old growth forests, and distribution of harvest blocks that are intended to spatially emulate natural disturbances.

PREFACE

This doctoral research stems from the collection of fire history data by Marie-Pierre Rogeau in 2004, 2005, 2010 and 2011 while doing fire regime consulting work for Spray Lake Sawmills FMA, Cochrane, AB and the Alberta Government. It is a paper-based doctoral thesis where Chapters 2, 3, and 4 are manuscripts that have been, or will be, submitted to scientific journals. Marie-Pierre Rogeau was responsible for the data collection, data analyses and redactions of all manuscripts. Co-authors assisted with reflections and debates on analytical methods to use, as well as edits to the manuscripts.

The first manuscript forming Chapter 2 is undergoing another round of revisions with the *Journal of Forest Science*. It is co-authored with Dr. Mike Flannigan, professor at the Department of Renewable Resources, and Dr. Marc-André Parisien Associate Professor and Research Scientist at the Northern Forestry Centre in Edmonton. The second manuscript (Chapter 3) is also undergoing a second round of revisions with the *International Journal of Wildland Fire.* It is co-authored with Dr. Mike Flannigan, Dr. Brad Hawkes (retired research scientist from the Pacific Forestry Centre in Victoria, BC), Dr. Marc-André Parisien and, Mr. Rick Arthur (retired wildfire specialist from the Alberta Government). I plan to submit the third manuscript with Dr. Glen Armstrong, professor at the Department of Renewable Resources at the University of Alberta, as co-author to *Forest Ecology and Management*.

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Each manuscript within this thesis contains an acknowledgement section that is particular to the support I received for the fire history data collection and subsequent analyses.

The decision of returning to school after 20 years was not an easy one, but a good one. This would not have happened without two colleagues: Marty Alexander and Rick Arthur for “keeping the fire” underneath me to do so and join the like-minded people of the Western Partnership for Wildland Fire Science.

I am also grateful toward Doug and Yo (the in-laws) for providing a home away from home for me while I needed to be on campus. And last but not least, my partner in crime, my love of twenty-five years Gord Irwin, who has been extremely supportive (enthusiastically and financially) of my return to school, and who had the tedious task of proof-reading version one of everything I wrote. Thank you, it meant a lot.

TABLE of CONTENTS

ABSTRACT II

PREFACE IV

ACKNOWLEDGEMENTS V

TABLE OF CONTENTS VI

LIST OF TABLES X

LIST OF FIGURES XII

GLOSSARY XIV

CHAPTER I - INTRODUCTION 1

SOUTHERN CANADIAN ROCKIES AND FOOTHILLS OF ALBERTA: A FIRE-DRIVEN LANDSCAPE 1

1.1 State of fire history knowledge 1

1.2 What we know of the fire regime 7
  1.2.1 Mean-fire-return interval 7
  1.2.2 Fire cause 9
    1.2.2.1 Lightning strike shadow 9
    1.2.2.2 Indigenous burning 10
  1.2.3 Fire size 10
  1.2.4 Fire seasonality 11
  1.2.5 Fire intensity, severity and patterning 12

1.3 Fire-adapted species 17

1.4 Managing fire-driven ecosystems 18

1.5 Questions to answer 21

1.6 Thesis research objectives 22

1.7 Thesis research methods 23

1.8 Thesis layout 25

1.9 References 26

CHAPTER II – MANUSCRIPT 1 33

FIRE HISTORY SAMPLING STRATEGY OF FIRE INTERVALS ASSOCIATED WITH LETHAL FIRES 33

2.1 Abstract 33

2.2 Introduction 34

2.3 Methods 35
  2.3.1 Study Area 36
  2.3.2 Sampling units selection 39
  2.3.3 Sample plot distribution 39
  2.3.4 Field sampling 41
  2.3.5 Fire dating 41
  2.3.6 Fire return interval calculation 43
  2.3.7 Survival analysis 44

2.4 Results 45

2.5 Discussion 51
  2.5.1 Data interpretation 51
  2.5.2 Review of fire history methods 53
  2.5.3 Dating accuracy 54
  2.5.4 Inclusion of censored observations 56

2.6 Conclusion 56

2.7 Acknowledgements 57

2.8 References 58

CHAPTER III – MANUSCRIPT 2 62

SPATIAL AND TEMPORAL VARIATIONS OF FIRE REGIMES IN THE CANADIAN ROCKY MOUNTAINS AND FOOTHILLS OF SOUTHERN ALBERTA 62

3.1 Abstract 62

3.2 Introduction 63

3.3 Methods 65
  3.3.1 Study area 65
  3.3.2 Fire frequency analysis 68
  3.3.3 Fire severity 70
  3.3.4 Fire seasonality 72
  3.3.5 Fire cause 72

3.4 Results 73
  3.4.1 Fire frequency analysis 73
  3.4.2 Other fire regime components 77

3.5 Discussion 82
  3.5.1 Spatial variation in fire frequencies 82
  3.5.2 Subalpine fire regime conditions 84
  3.5.3 Montane and Foothills fire regime 85
  3.5.4 Departure from historical conditions 88

3.6 Conclusions 89

3.7 Acknowledgements 90

3.8 References 91

CHAPTER IV – MANUSCRIPT 3 97

THE EFFECT OF TOPOGRAPHY ON FIRE RETURN INTERVALS IN THE CANADIAN ROCKIES 97

4.1 Abstract 97

4.2 Introduction 98

4.3 Study Area 101

4.4 Methods 105
  4.4.1 Fire history study 105
  4.4.2 Survival analysis 107
  4.4.3 Testing for predictive variables 108

4.5 Results 111

4.6 Interpretation 127
  4.6.1 Role of topography in fire-based ecosystems 127
  4.6.2 Topography and forest seral stages 130
  4.6.3 Choice of data and model in interpreting probability of survivorship to fire 133

4.7 Concluding remarks 137

4.8 Acknowledgements 138

4.9 References 139

4.10 Appendix: Formulas 146

CHAPTER V - CONCLUSION 147

5.1 Summary of Salient Findings 147
    5.1.1 Fire history approach 147
    5.1.2 Natural subregions and fire regimes 149
    5.1.3 Strong influence of human activity on the pre-industrial fire regime 150
    5.1.4 Fire regime departure post-1948 151
    5.1.5 Influence of topographic features on fire return intervals 153
    5.1.6 Variable effect of topography on FRI when seral stages are considered 154

5.2 Applied Management Strategies 155
    5.2.1 Forest management 156
    5.2.2 Wildland fire management 157

5.3 Concluding Remarks 158

5.4 References 159

BIBLIOGRAPHY 160

LIST of TABLES

Table 1-1 Fire rotation periods expressed as fire cycle (FC) or mean-fire-return-interval (MFRI) values from fire history studies of mountain landscapes in southern Alberta - south of the Brazeau River........ 3

Table 2-1 Characteristics of six sampling zones retained for fire history data collection in southern Alberta........ 38

Table 2-2 Estimated margin of error in fire scar dating from direct count when compared to documented fire events from central and southern Alberta........ 46

Table 2-3 Pseudo-replication (rep.) of fire return interval observations with proportion of replicates attributed to complete fire return intervals or time-since-fire (TSF) intervals (censored data)........ 47

Table 2-4 Density distribution of fire history sample plots by study unit, number of trees sampled, number of scars and releases, total number of fires by time period and, oldest tree sampled. SH: Subalpine-Highwood, SE: Subalpine-Elbow, MH: Montane-Highwood, M-G: Montane-Ghost, ME: Montane-East slopes, UF: Upper Foothills........ 48

Table 2-5 Range of fire return intervals (FRI) for censored interval data set (includes complete and time-since-fire (TSF) intervals) and uncensored intervals (complete intervals only), mean FRI including and excluding censored (TSF) data, number of total FRI records, number of uncensored events, and median FRI including censored data with its lower and upper 95% confidence intervals........ 49

Table 2-6 Kaplan-Meier survival probabilities calculated for pre-determined time periods highlighting differences among sampling units........ 51

Table 3-1 Kaplan-Meir probability median (MdFRI) and mean (MFRI) fire return intervals (years) for two temporal periods: pre- and post-1948. Intervals were calculated from a combination of complete fire return intervals and time-since-fire intervals (censored observations). The percent departure (change) from historical conditions was calculated using MdFRI and MFRI data........ 76

Table 3-2 Evaluation of historical fire intensity based on the number of fires identified at sampling sites, and based on forest patch complexity of the landscape........ 77

Table 4-1 Weibull fitting parameters and Anderson-Darling goodness-of-fit test (A^2) for fire return interval distributions of three natural subregions........ 112

Table 4-2 Permutation test probability values. Italics: strong collinearity ($p \geq 50\%$) between paired variable categories; bold: variables with significantly different categories ($p \leq 5\%$)........ 115

Table 4-3 Output results of Cox regression model and PH assumption test for three natural subregions. M1 model uses elevation classes and M2 model using continuous elevation data. Bold: significant covariate (p < 0.05). Underline: PH assumption is respected as rho values consistently near zero more than 50% of the time. 117

Table 4-4 Output results of Cox regression model and PH assumption test partitioned by forest seral stage, for the Montane (MT) natural subregion. M1 model uses elevation classes, while M2 uses continuous elevation data. Bold: significant covariate (p < 0.05). Underline: PH assumption is respected as rho values consistently near zero more than 50% of the time. 120

Table 4-5 Output results of Cox regression model and PH assumption test partitioned by forest seral stage, for the Subalpine (SUB) natural subregion. M1 model uses elevation classes, while M2 uses continuous elevation data. Bold: significant covariate (p < 0.05). Underline: PH assumption is respected as rho values consistently near zero more than 50% of the time. 121

Table 4-6 Output results of Cox regression model and PH assumption test partitioned by forest seral stage, for the Upper Foothills (UF) natural subregion. M1 model uses elevation classes, while M2 uses continuous elevation data. Bold: significant covariate (p < 0.05). Underline: PH assumption is respected as rho values consistently near zero more than 50% of the time. 122

Table 4-7 Response of elevation on fire return intervals when the landscape is stratified by cool and warm aspects, and response of aspect when the landscape is stratified by low and high elevations. Bold: highlight significantly different results (p <0.05), underlined: PH assumption is respected. Log rank test compares Kaplan-Meier fire return interval distributions. 123

Table 4-8 Mean fire return intervals (MFRI), probability Kaplan-Meier median (MdFRI) with lower and upper 95% confidence intervals. n = number of observations. 126

LIST of FIGURES

Figure 1-1 Example of a complex vegetation mosaic representing mixed severity burning. Five or six fires are estimated to have overlapped. The photo represents an area approximately 5 km x 5 km. 15

Figure 1-2 Example of a low complexity vegetation mosaic representing a typical burn pattern of a stand replacing fire in the Subalpine. The photo represents an area approximately 9 km x 9 km. 15

Figure 2-1. Location of study area. Upper left map inset displays the study area over the natural subregion map. Maps 1, 2 and 3 show the sample plot distribution across six sampling regions. 37

Figure 2-2 Lower and upper confidence intervals (CI) (0.05, 0.95) of Kaplan-Meier probability median statistic from bootstrap fire return intervals. Median values are marked as a circle. Montane-East (ME), Montane-Ghost (MG), Montane-Highwood (MH), Subalpine-Elbow (SE), Subalpine-Highwood (SH), Upper Foothills (UF).......... 49

Figure 2-3 Boxplots showing the spread of fire return intervals for six sampling units in southern Alberta. Montane-East (ME), Montane-Ghost (MG), Montane-Highwood (MH), Subalpine-Elbow (SE), Subalpine-Highwood (SH), Upper Foothills (UF). The vertical line represents the median and the dark circle the mean. The width of the box is the square-root of the number of observations. The box bounds the top of the first quartile and top of third quartile. The whiskers represent the lowest and highest datum within 1.5x the inter-quartile range. Empty circles are outliers.......... 50

Figure 3-1 Location of fire regime study area (dotted line) in Alberta, Canada, including the delineation of six fire history sampling regions. Distribution of sample plots is presented in other map insets.......... 66

Figure 3-2 A) Rugged subalpine landscape parted by rocky ridges. B) Rolling foothills landscape of extensive, dense forest cover. 67

Figure 3-3 Kaplan-Meier fire-frequency distributions of six sampling units: ME: Montane-East slopes, MG: Montane-Ghost, MH: Montane-Highwood, SE: Subalpine-Elbow, SH: Subalpine-Highwood and UF: Upper Foothills. The survival function represents the probability of survival from fire. 74

Figure 3-4 Fire spread dynamics at the interface between the rolling Foothills/Montane landscape and a rugged Subalpine landscape parted by rocky ridges. Example of the Elbow watershed (SE and ME fire history data). 75

Figure 3-5 Post-1948 fire return interval (FRI) medians (triangles) show the level of departure from historical conditions portrayed by pre-1948 FRI bootmedians (circles) and their 95% confidence limits (bars).......... 76

Figure 3-6 Above: example of historical Montane landscape from 1890. Photograph of the Bow Valley taken by surveyor James J. McArthur (Mount Yamnuska in the background). Below: example of Foothills landscape (Jumpingpound watershed) from 1897, photographed by surveyor Arthur O. Wheeler. (source: http://mountainlegacy.ca/) 80

Figure 3-7 Distribution of lightning-caused fires (1961 - 2003) on to a lightning strike density map plotted over 5 km x 5 km grid cells. 81

Figure 3-8 Examples of internal fire scars found on lodgepole pines. 87

Figure 4-1 Location of study area and outline of six fire history sampling units overlaid onto the natural subregion map of Alberta. The three map panes show the position of fire history sample plots distributed over six sampling regions. 102

Figure 4-2 Examples of landscapes within the study area: A) Subalpine natural subregion, B) Montane natural subregion shown as the lower slopes of a subalpine landscape, C) a variation of the Montane near the Foothills, and D) Upper Foothills natural subregion. 103

Figure 4-3 Interpretation of censored and uncensored fire return intervals in a stand replacing fire regime. p: pith origin = fire 1, X_1 = fire 2, X_2 = fire3, see text on how to interpret a, b, c, d. 106

Figure 4-4 Quantile-quantile plots showing the departure of observed fire return interval data from the Weibull fitted fire return interval distribution.. 112

Figure 4-5 Comparison of Kaplan-Meier survival distributions by natural subregion (upper left) and individual distributions with their 95% confidence bands. Note that the abscissa for the Montane is graduated differently due to the absence of fire-return-intervals longer than 260 years. 113

Figure 4-6 Verification of PH assumption using Schoenfeld residuals and elevation as a continuous variable. The consistent horizontal line shows that Proportional Hazards are mainly constant through time.. 118

Figure 4-7 Cox survival distributions adjusted for each combination of lead topographic groups and presented by natural subregion. Cool and warm aspect classes were combined with low and high elevation classes.. 125

GLOSSARY

The definitions are adapted in part, or in full, from the Glossary of Forest Fire Management Terms (Merrill and Alexander 1987). Some of the definitions have been adjusted to reflect my own interpretation of these terms in the context of fire history and fire regime studies.

Fire behaviour: the manner in which fuel ignites, flame develops, and fire spreads and exhibits other related phenomena as determined by the interaction of fuels, weather, and topography.

Fire boundary: represents the edge between a remnant stand and a stand that regenerated following a fire. It corresponds to the fire perimeter or to the outline of island remnants within the burn perimeter.

Fire cycle: the number of years required to burn an area equivalent to the size of the entire area of interest. Some areas may burn more than once, while others may not burn at all during a cycle.

Fire history: the study of recording past fires in a chronological order. It involves compiling fire evidence from a number of sources such as historical documents, fire reports, fire scars, pith origin, and charcoal.

Fire regime: a set of fire characteristics describing the conditions of a given area. These characteristics are:

cause: the source of the ignition classified as either lightning or anthropogenic. Human-caused fires can be divided in to subcategories including: recreation, resident, forest industry, other industry, railroad, incendiary, miscellaneous and unknown.

frequency: the average number of fires recorded for a specific point, or area, per unit of time.

intensity: the amount of energy released at the fire front that governs fire behaviour and the resulting fire effects on the land.

severity: represents the proportion of tree mortality following a fire. The severity level can also be gauged by the number of years it takes for post-fire recruitment trees to grow back.

season: the period of the year during which fires are more likely to start and spread. Based on the flammability of fuel types, the season is normally divided in to three periods: spring, summer and fall. The assessment of fire season is often divided between lightning and human-caused fires.

type: the way in which most fires tend to spread in the area of interest: surface, intermittent-canopy, or full canopy fires. This description is used to name the type of fire regime as: surface fire, mixed-severity, or stand-replacing, respectively.

Fire return interval: number of years between two fire events.

Fire scar: an external wound on a tree caused by heat injury from low to moderate intensity burning at the base of the tree. Scarred trees can have a single or multiple fire scars.

Fire tree-ring release: a sudden increase in the width of tree-rings sustained for several years as a result of a fire that killed neighbouring trees.

Fire weather: a set of weather parameters including dry-bulb temperature, relative humidity, wind speed and direction, precipitation, atmospheric stability, and winds aloft, that influence the chance of ignition, ease of fire spread, and subsequent fire behaviour.

Mean fire return interval: the average number of years between the occurrence of fire events at a given point, or for a pre-defined area such as a watershed or a region.

Mixed-severity fire: a fire that typically burns under a variety of intensities, which creates a complex forest mosaic as a result of variable proportions of stand mortality.

Rugged mountains: when the forest of each watershed is segregated by rocky ridges.

Stand-replacing fire: a fire that burns under prevailing high fire intensity conditions that result in a high proportion of tree mortality, usually greater than 75%.

Survival analysis: an assessment of fire return interval or time-since-fire data to predict the probability of burning of forest stands during a given period of time.

Time-since-fire: the number of years since the last fire event at a given point, or for a given area.

CHAPTER I - INTRODUCTION

Southern Canadian Rockies and Foothills of Alberta: a fire-driven landscape

1.1 STATE OF FIRE HISTORY KNOWLEDGE

The forest mosaic of the Foothills and Canadian Rockies of southern Alberta has been shaped by wildland fires for centuries according to paleoecological records. While most paleoecological studies from lake core sediments do not focus on dating historical fires, the rate of charcoal accumulation in sediments, vegetation pollen counts from pioneer tree species, plant indicators of salinity and amount of calcium carbonate, are all factors that contribute to understanding earlier climate and the expected level of forest or grassland fires on the landscape. Core sediments from multiple lakes have been collected in the Subalpine, Montane and Foothills natural regions of Kananaskis Country and Banff National Park (Beierle and Smith 1998), in the transitional forest zone between Boreal Forest and Aspen Parkland near Edmonton (Vance *et al.* 1983, Schweger and Hickman 1989), in the transitional zone between Aspen Parkland and Prairies near Red Deer (Campbell *et al.* 2000) and, near the transition zone between Foothills and Prairies near Bragg Creek (MacDonald 1989). All paleoecological studies have converging conclusions. The early Holocene climate was arid with much drier and warmer conditions. In the Subalpine, glaciers had receded completely by 9180 years BP and treeline was suspected to be higher than at present-day (Beierle and Smith 1998). Outside of the mountains, lake levels were much lower due to significantly depleted water tables until circa 6800 BP, at which time glaciers returned (Beierle and Smith 1998). Charcoal accumulation was at its maximum between 9400 and 8400 years BP (MacDonald 1989), but has been constantly present in significant amounts up until present, along with fire related vegetation species in all of the above paleo studies. A thick charcoal layer embedded in the sediments of Johnson Lake in the Montane region of Banff National Park was attributed to high fire frequency that denuded the landscape around 6800 BP (Beierle and Smith 1998). According to vegetation pollen counts, Schweger and Hickman (1989) concluded that the climate has been similar to recent times for the last 5000 years. This climate similarity considers a wide range of annual or decadal drought and precipitation levels (Sauchyn *et al.* 2002), which in turn affect the rate of fire incidence.

Assuming that the source and rate of ignitions had some level of variability in the last 5000 years, the natural range of variation of fire intervals obtained from local fire history studies could be perceived as representative of a temporal scale greater than the lifespan of tree ring data. In that regard, results from a paleo macro-charcoal fire history study in a subalpine environment of Kootenay National Park, British Columbia, supports a steady state of fire return intervals for the last 1000 years at 46 ± 5 years (Hallett *et al.* 2003). Macro-charcoal fragments (50 to 10,000 μm in diameter), collected from varved lake sediments do not disperse broadly in the atmosphere (Clark 1988a) and are used as a local signal (within several 100m from the lake) to document past forest fires in a specific water catchment (Clark and Royall 1995, Clark 1988b). Peak accumulation rates of macro-charcoal contribute to the local signal and to an annual event that can be linked to the local fire history (Clark 1988b).

Moving ahead to the contemporary era, a number of tree-ring based fire history studies from various areas of the central and southern Canadian Rockies, as well as the Foothills, have been completed since the late 1970s (Table 1-1). While the methods of data assessment varied, fire cycle (FC) and Mean Fire Return Interval (MFRI) values captured a wide range of variation based on different natural subregions (or ecoregions), watersheds and topographic locations covered. Many of these studies are unpublished technical reports (Table 1-1).

Table 1-1 Fire rotation periods expressed as fire cycle (FC) or mean-fire-return-interval (MFRI) values from fire history studies of mountain landscapes in southern Alberta - south of the Brazeau River.

Location / Reference	Ecoregion / natural subregion	Fire cycle or MFRI (years)	Method
Banff National Park (Van Wagner *et al.* 2006)	Montane & Subalpine	From 1285 to 1760: FC = 58 to 76 From 1761 to 1940: FC = 105 to 182	Calculated from a Time-Since-Fire map. Variation by temporal period is from using four different methods of fire cycle calculation on the age-class distribution.
Banff National Park (Rogeau *et al.* 2004)	Subalpine	FC = 65 - 220	Calculated from weighted mean ages using a Time-Since-Fire map. Variation is by topographic location.
	Montane	FC = 44 - 145	
Castle Watershed (Rogeau 2012*)	Subalpine	MFRI = 36 - 62	Calculated from a compilation of fire intervals obtained at fire history sampling sites. Variation is by watershed.
	Montane	MFRI = 19 - 31	
Elbow Watershed (Rogeau 2011a*)	Subalpine	MFRI: 58 - 133	Calculated from a compilation of fire intervals obtained at fire history sampling sites. Variation is by watershed.
	Montane	MFRI: 32 - 70	
Kananaskis Valley (Johnson and Larsen 1991)	Subalpine	FC: 90	Calculated from a Weibull model applied to an age-class distribution derived from a Time-Since-Fire map.
N. Saskatchewan, Whitegoat & Siffleur Wilderness Areas (Rogeau 1999*)	Subalpine	FC = 103 - 244	Calculated from weighted mean ages using a Time-Since-Fire map. Variation is by topographic location.
	Montane	FC = 71 - 82	
Peter Lougheed P.P. (Hawkes 1980)	Subalpine	MFRI = 101 - 304	Calculated from a compilation of fire intervals obtained at fire history sampling sites. Variation is by topographic location.
Porcupine Hills (Rogeau 2014*)	Montane	MFRI = 16 - 22	Calculated from a compilation of fire intervals obtained at fire history sampling sites. Variation is by watershed.
R11 Forest Management Unit (Rogeau 2010*)	Subalpine	Blackstone: MFRI = 54 - 84 Clearwater: MFRI = 57 - 59	Calculated from a compilation of fire intervals obtained at fire history sampling sites. Variation is by watershed.
	Montane	N. Saskatchewan: MFRI = 22 - 34 Red Deer: MFRI = 61	
	Upper Foothills	Lower Ram: MFRI = 39 - 71	

Location / Reference	Ecoregion / natural subregion	Fire cycle or MFRI (years)	Method
Spray Lake Sawmills FMA: Forest Management Units B9-B10 (Rogeau 2005*, 2006*, 2011b*)	Subalpine	Highwood: MFRI = 59 Elbow: MFRI = 87	Calculated from a compilation of fire intervals obtained at fire history sampling sites.
	Montane	FMU B10 Highwood: MFRI = 27 Ghost: MFRI = 30 East Slopes: MFRI = 44	
	Upper Foothills	FMU B9: MFRI = 50	
Waterton Lakes National Park (Barrett 1996*)	Lower Subalpine	dry aspect MFRI = 36 moist aspect MFRI = 55	Calculated from a compilation of fire intervals obtained at fire history sampling sites.
	Upper Subalpine	spruce-fir MFRI = 200 alpine larch MFRI = 64	
	Montane	low severity burns MFRI = 32 high intensity burns MFRI = 52	

** Unpublished data from technical reports*

Fire history research in Alberta was pioneered in the mountain parks situated in the main ranges of the Canadian Rockies, along and near the Continental Divide. With the common goal of natural resources protection and maintenance of ecosystem's ecological integrity, park managers encouraged fire history study initiatives that enhanced the understanding of historical burning and overall fire regime. Results were used to assist with the planning of fire protection measures of values at risk and fire suppression policies. In addition, due to the minimal area burned since the early 1940s, as a result of more effective fire suppression actions (Murphy 1985, White 1985b), fire history analysis results were also used to guide the spatial distribution of prescribed burns to re-introduce fire to the landscape in a controlled environment. Jasper National Park took the lead with Tande (1977, 1979) conducting fire history sampling in the Montane zone of the Athabasca valley around the Town of Jasper. It is the only fire history that outlined all fire perimeters as per the fire mapping approach developed by Heinselman (1973), and to this day it is still the most comprehensive fire history study in Alberta. Tande documented the mean-fire-return-interval (MFRI) by forest type, and fire frequency by elevation and aspect classes. Also in the late 1970s, the fire history of Peter Lougheed Provincial Park (formerly Kananaskis Provincial Park) was completed by Hawkes (1979, 1980). MFRIs by aspect, elevation and ecological subzones were calculated from point sampling data. Shortly thereafter, White (1985a) initiated the fire history of Banff National Park and concentrated sampling on the main watersheds. The sampling design targeted closed-forest type ecosites identified from the Ecological Land Classification map (Holland and Coen 1982). MFRIs from time-since-fire (TSF) data were reported by categories called "fire groups": warm/dry Montane, warm/dry Lower Subalpine, cool/moist Lower Subalpine and, Upper Subalpine. White (1985b) published an occasional paper for Parks Canada that detailed historical fires, burned area, various elements of the fire regime and a historical account of fire management in Banff National Park. In the early 1990s the fire history of Banff National Park was eventually completed by fully mapping TSF polygons using 1950 aerial photography to guide fire boundary mapping, and using fire scars, tree-ring releases and pith origin to date polygons (Rogeau and Gilbride 1994). The data set was in turn used to calculate fire cycles for main watersheds using the Weibull survivorship model (Rogeau 1996), an approach developed by Johnson and Van Wagner (1985). In the late 1980s a TSF map, produced using the same methodologies as described for Banff N.P. was developed for Kananaskis Valley (Johnson and Fryer 1989, Johnson and Larsen 1991). Combining fire history results from Kananaskis Valley and Peter Lougheed Provincial Park, a Weibull survivorship analysis was carried out to calculate a fire cycle for the combined areas (Johnson and Larsen 1991). At the south end of Alberta, the fire history of Waterton Lakes National Park was completed by Barrett (1996). MFRIs were calculated from point data for dominant forest types in the lower and upper subalpine zones.

While historical fire activity was well studied in the main mountain ranges of Alberta, little was known of historical burning and the overall fire regime for Alberta's Eastern Slopes, notably south of the North Saskatchewan River, until recently. This region covers a vast area of Subalpine and Montane natural subregions of the Rocky Mountains' front ranges, as well as the Foothills natural region (Natural Regions Committee 2006). The area comprises multiple land and forest uses such as protected wildland zones, recreational areas, campgrounds, timber harvesting, and oil and gas exploration. The Eastern Slopes back into the headwaters of many watersheds to the west, and to the east it extends to the forest zone limit as it transitions to open type deciduous forests and prairies where a number of villages and hamlets are located. To address timber resource and fire management concerns, a broad-scale fire regime study was initiated in 2003 (Rogeau 2004) and an extensive fire history sampling program was put in place to cover several watersheds of the Eastern Slopes: between the Little Red Deer River and the Bow Valley (Rogeau 2005); between the Bow Valley and the Sheep River (Rogeau 2006); from the Red Deer River to the North Saskatchewan River (Rogeau 2010); the Elbow valley and its tributaries (Rogeau 2011a); the Highwood watershed (Rogeau 2011b); Castle and West Castle watersheds (Rogeau 2012); and the Porcupine Hills (Rogeau 2014). These studies were funded by the Alberta Government and for sampling that took place on the Spray Lake Sawmills FMA, additional funding was provided by the Forest Resource Improvement Association of Alberta (FRIAA). MFRIs were calculated by natural subregion using point data samples and no TSF maps were produced.

Note on data interpretation from Table 1-1.

The mean-fire-return-interval (MFRI) and fire cycle (FC) values (Table 1-1) are not directly interchangeable unless burning rates are constant through time and fire interval or time-since-fire data can be expressed as a negative exponential distribution (Johnson and Van Wagner 1985, Johnson and Gutsell 1994). MFRIs represent the average fire interval calculated from a number of point data and correspond to the expected average rotation period at the forest stand level. In contrast, a FC obtained from a Weibull survival curve from cumulating areas of time-since-fire polygons represents the fire rotation period for the entire study area (Johnson and Gutsell 1994). Unless every parcel of forest has an equal probability of burning through time, the MFRI will vary spatially on the landscape, whereas the FC provides a single, average value for the entire study area. Despite these differences, the margin of error between the two values is expected to be within 5 to 20% (personal observations).

1.2 WHAT WE KNOW OF THE FIRE REGIME

There are many characteristics that make up a "fire regime" (see Glossary). The following sub-sections cover each of these characteristics and describe how they differ between the three natural subregions of interest found in southern Alberta: Subalpine, Montane and Upper Foothills.

1.2.1 Mean-fire-return interval

It is recognized that mean-fire-return-interval (MFRI) and fire cycle (FC) values are not exactly the same, but both provide information on the historical burning rate (Equation 1).

Average annual burn rate (ha/yr) = (1 / MFRI or FC) * (forested area) **[Eq. 1]**

The MFRI when calculated from point sample data can provide some insight on the variability of past fire frequencies. The FC, which is based on area burned, is not a reliable measure for frequency because the resulting fire cycle can be the outcome of multiple small fires, or of a few large size ones.

Nonetheless, the common thread between the two types of calculations is that the burning rate before effective fire suppression was greater in the Montane and the Foothills than in the Subalpine. Data from Table 1-1 also points to an increase in burning rate from west to east, with what would appear to be a greater number of fires in the front ranges at the interface with the rolling foothills. In terms of MFRI values, the Montane regions nearing the Foothills typically experienced a MFRI that was less than 50 years, while Montane regions that spread deeper into the mountain ranges had a MFRI as long as 145 years.

In the Subalpine natural subregion, interesting patterns have emerged from MFRI and FC values observed over a broad landscape ranging from the Blackstone watershed (north of Hwy 11 and south of Jasper N.P.) to Waterton Lakes National Park. The shortest MFRI values (36 to 62 yr) are found at the southern end of the province (Highwood watershed to Waterton Lakes N.P.). For most other watersheds to the north, the low range of MFRI values vary from 54 to 65, with an upper range variation that is considerably wider (84 - 244 yr). The longest intervals or FC documented are found in the most rugged portion of the Subalpine. In the Upper Foothills, the MFRI ranges from 39 to 71 years based on the watershed or region sampled.

1.2.2 Fire cause

There are two lead sources of fire: lightning strikes and anthropogenic. While it is not possible to determine the specific cause of most historical fires, it is possible to gain some insight by using the distribution of fire in the contemporary era. The Government of Alberta has kept track of lightning strike locations since the l980s with location accuracy having greatly improved since 1990. However, the positioning error of strikes can still be as large as 16 km in the mountains (Nimchuk 1989). Province wide fire occurrence reports are available back to 1961, from which a precise fire cause (if known) is recorded (Tymstra *et al.* 2005).

1.2.2.1 Lightning strike shadow

It has been demonstrated through the spatial mapping of lightning strikes that a buffer zone of roughly 20 km along the east side of the Continental Divide gets few lightning strikes over the course of a fire season (Weirzchowski *et al.* 2002). The number of strikes increases along a west to east gradient, with the Upper Foothills recording the most strikes (Rogeau 2004). However, no strong association was established between the number of total strikes and lightning fire ignitions. Results from the Kananaskis and Spray Lake Sawmills FMA regions (Rogeau 2004) had a measure of association of 0.48 (Cramer's V) and showed that past a certain threshold of 26 to 50 strikes per 25 km^2, the chance of lightning fire ignitions did not increase (Rogeau 2004). In a separate study (R11 - Rogeau 2009), the correlation was evaluated between the number of lightning-caused fires and positively charged strikes because the measure of association was found to be slightly better, but still weak (Cramer's V of 0.36), than using the number of total strikes. In this case, the study area lies entirely in the lightning strike shadow. It was found that a threshold of 4 to 6 positive strikes per 25 km^2 was needed for lightning fire ignitions to occur in that specific region (R11). Positive strikes accounted for only 6.5% of the total number of lightning strikes.

1.2.2.2 Indigenous burning

Based on provincial fire occurrence data between 1961 and 2003, anthropogenic fire ignitions outweigh lightning ignitions except for the Upper Foothills where 58 % of fires are caused by lightning. In the Montane, 90% of fires are caused by people, whereas 75% of fires are caused by people in the Subalpine (Rogeau 2004). Due to the small influence of lightning strikes on the fire regime, coupled with short MFRIs calculated for many watersheds, one must assume that First Nations played a large role in shaping the forest mosaic prior to the arrival of settlers. Indigenous fire use in North-America is well documented (Barrett and Arno 1982) and has been reported by Lewis (1977) and Lewis and Ferguson (1988) in northern Alberta. Such an argument can be further supported through the position of fire scars along the dormant or within the early-early wood portion of the tree cambium tissues. This is an indication that burning occurred outside of the period of tree growth (early spring and fall), or before leaf flush, both of which coincide with periods when lightning activity is low.

1.2.3 Fire size

There is not a good data set on historical fire size for this region, and sizes recorded on contemporary fire occurrence reports reflect fire suppression actions. Between 1961 and 2002, 87% of fires were less than 4 ha; the average fire size in the Rocky Mountain natural region was 9.5 ha, whereas it was 71 ha in the Foothills (Tymstra *et al.* 2005).

Using only pre-1950 fires that had not been masked by other fires in the Subalpine region of Banff National Park (Rogeau 1996), the average fire size was estimated to be approximately 1900 ha. Some of these fires had received some form of fire suppression actions. Using this data set, 60% of fires are expected to be less than 2000 ha, while the maximum fire size recorded was 18,000 ha (Rogeau 1996). The range of potential fire size is correlated in part with the extent of the fuel cover and how many fuel breaks (i.e. rocky ridges, lakes) are present on the landscape. In the rugged subalpine environment of the Rocky Mountains, fires are typically small, as about 50% of the landscape is non-vegetated - notably in the main mountain ranges. In contrast, the front ranges encompass larger tracts of connected forest cover and over 90% of the foothills are vegetated, which can allow for fast spreading fires that have the potential to reach large dimensions.

1.2.4 Fire seasonality

An analysis of monthly fire occurrence and area burned by natural subregion was compiled for the entire province of Alberta using 1961-2002 data (Tymstra *et al.* 2005). It shows that the bulk of fires in the Foothills occur between May and August and these fires are normally caused by lightning during June, July and August. In terms of area burned, June is the month with the most area burned in the Upper Foothills, followed by May. Considering that 29% of the annual rain precipitation typically falls during the month of June (Kananaskis and High River weather stations, Environment Canada 2016), the area burned is likely to have occurred before the onset of June precipitation, that is in the early part of June. In the Lower Foothills, it is the month of May that experiences the most area burned from both lightning and human-caused fires. The reason is that the Lower Foothills, which include a greater component of aspen forests that have a thick forb and grass understory layer, have cured surface fuels that are readily available for burning in May before the leaf flush and grass turning green.

Not surprisingly, due to six months of snow coverage in many of the Subalpine watersheds, the peak period for the number of fires is July and August, but the peak months for area burned are August, followed by June. Human-caused fire ignitions from May to November are considerable, but do not amount to any sizeable area burned. All of the significant areas burned are caused by lightning fires. In the Montane, human-caused fires can occur year-round, with the bulk of ignitions being distributed in the period between April and September. In contrast, lightning fires occur mainly in July and August, with a few occurring in June or September. The area burned from man-caused fires is concentrated in April and May, and from lightning-caused fires in August.

1.2.5 Fire intensity, severity and patterning

An important trait of the fire regime in many regions of southern Alberta is the complex patterning in which fires have burned. Because fire history studies inherently deal with historical fires, it is important to remember that little to no fire suppression actions were executed on many of the fires examined and that fires burned in a natural manner. Mixed severity burning encompasses a wide range of fire behaviour as a result of various factors that affect fire intensity and severity. Such factors include transitions in the surface or aerial fuel load, fuel type, terrain, as well as changes in the fire weather at the time of burning (Barrows 1951, Countryman 1972). At the upper range of mixed severity burning, high intensity fires have a broad lethal effect on the forest and large tracts of forests are killed. This type of burning is referred to as a stand-replacing. Under lesser fire intensities, passive crown fire activity (Van Wagner 1977), described as individual tree candling or torching of a cluster of trees (Merrill and Alexander 1987), leads to a partial stand replacement and can form complex burn patterns. The fire front of an active crown fire can also drop to the ground with a change in weather such as precipitation, calmer winds or higher relative humidity (Van Wagner 1977). The fire can be dormant for a while, or move as a surface fire for some distance, before re-surfacing as a crown fire with partial to full stand replacement effect. Such burning behaviour over a number of weeks can lead to complex burn patterns at the landscape scale. Decades later, the evidence of burning complexities from historical fires is found in the intricacy of the current vegetation mosaic (assuming that the mosaic has not been disturbed by harvesting or other anthropogenic activities in recent times).

It was not until the early 2000s that the term "mixed-severity burning" was formally acknowledged in the literature in western Canada (Amoroso *et al.* 2011, Heyerdahl *et al.* 2012, Marcoux *et al.* 2015). Sampling designs have also been adjusted to better detect mixed severity burns. Following decades of fire suppression, much of the forest that was historically subjected to low or moderate intensity fires has grown, and the forest understory has been filled with sub-canopy trees (Keane *et al.* 2002). To the untrained eye and without stand age verification and fire history studies, today's dense and homogeneous pine forests that blanket much of the Foothills appear to be evenly-aged and the result of large stand-replacing fires from the early 1900s. Recent fire history studies in southern British-Columbia, central and southern Alberta, actually paint a different portrait of historical fire behaviour and burning patterns for some of the broad, low elevation valleys and foothills landscapes (Rogeau 2005, 2006, 2010, 2011a, 2011b, 2012, 2014, Amoroso *et al.* 2011, Heyerdahl *et al.* 2012, Marcoux *et al.* 2015).

The lower elevations of the Montane and Foothills used to experience mixed severity burns as per the vegetation complexity patterns observed on 1950 aerial photography (Fig. 1-1). Fire history studies along the Foothills reported numerous fires at fairly short intervals, which explain the intricacy of stand age patches and overall vegetation mosaic complexity that is far more complex than those observed in stand replacing fire regimes common to the Subalpine (Fig. 1-2). At the stand level, the frequent burning kept the duff low, the sub-canopy trees sparse, and deadfall low. Under such conditions, grass and forbs were likely dominating these more open-type forests. Fire history studies documented repeat-fire activity, often less than 20 years apart in many stands, where it would have been more difficult for fires to build energy momentum to burn as high intensity fires. For this reason, many of these historical fires burned at low to moderate intensity and fires could only kill small diameter trees. In turn, the small diameter fire-killed snags and deadfall could easily be consumed during subsequent burns. To this day, many lodgepole pine stands of the Foothills are still “park-like” with a clean understory (personal observations). In support of such statements, healed-over fire scars containing trapped charcoal, have been uncovered numerous times in the Foothills and Montane (Rogeau fire history studies). Immature lodgepole pine trees, aged from 4 to 30 years, have been documented to survive these low intensity fires. The fact that tree saplings could survive some forest fires is indicative that fire intensity had to be low.

Figure 1-1 *Example of a complex vegetation mosaic representing mixed severity burning. Five or six fires are estimated to have overlapped. The photo represents an area approximately 5 km x 5 km.*

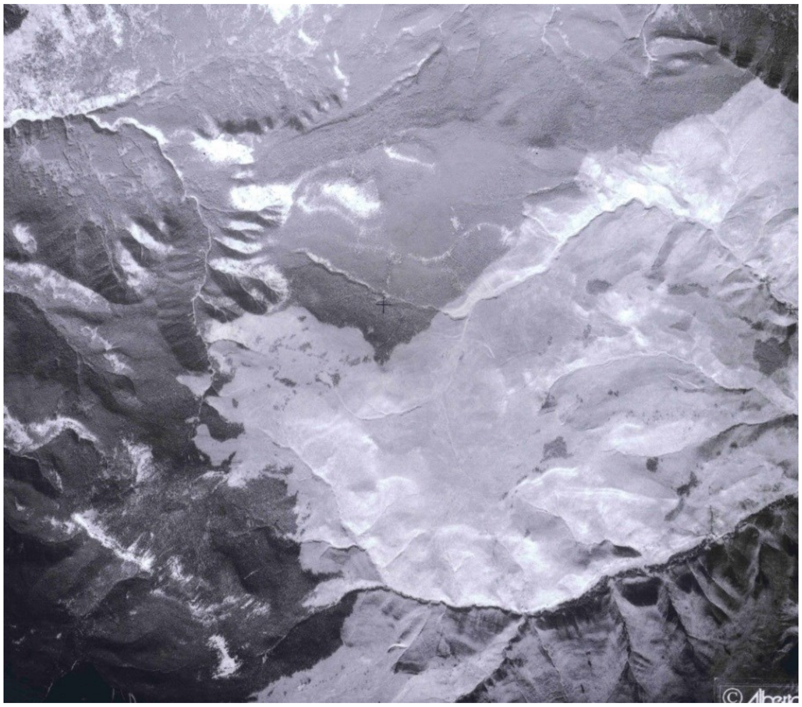

Figure 1-2 *Example of a low complexity vegetation mosaic representing a typical burn pattern of a stand replacing fire in the Subalpine. The photo represents an area approximately 9 km x 9 km.*

In the Subalpine, the longer fire return intervals provide a greater opportunity for fuel load to develop (Hély *et al.* 2000), as well as horizontal and vertical fuel arrangements to evolve. These ladder fuels, such as saplings, understory trees and resting snags provide a way for surface fires to climb into the canopy and become an active crown fire (Van Wagner 1977). Assisted by wind, a moving crown fire generates high intensity outputs associated with the rate of fire spread (Alexander *et al.* 1984, Stocks *et al.* 2004). The steeper terrain found in the mountains also increases the rate of fire spread due to increased radiant heat transfer (Barrows 1951) and flame tilting effect (Werth *et al.* 2011), which will result in greater stand mortality on steep slopes. While crown fires are predominantly lethal, there often are forest remnant patches left standing within the fire perimeter. The number, size and distribution of remnant patches are highly variable however (Andison and McCleary 2014). Controlling factors, such as micro-topographic elements (gully, rocky edges), fuel interruption (rocky ridges, water bodies), changes in fuel load and, changing fuel type, can modify fire spread patterns. In addition, top-down controls such as local changes in the wind pattern (i.e. drop in wind speed or sudden shift), increased humidity level, and precipitation can also modify fire behaviour in a way that decreases fire intensity and allow for patches of a forest to survive. A potential factor that explains the survival of stands, notably if they are narrow elongated patches that come as a single or series of burnt and unburnt strips of forests, referred to as “tree crown streets” (Werth *et al.* 2011), is the formation of horizontal roll vortices at the time of burning. More specifically, it is believed that tree crown streets are the result of counter-rotating (i.e. rotating in opposite directions), longitudinal vortex pairs that occur more often on the fire flanks, but also ahead of the fire when the main plume has a bifurcating smoke column (Werth *et al.* 2011, Haines and Smith 1987). The surviving strips have been documented to be narrow and to range between 30 to 60m in width. This phenomenon is well explained by Werth *et al.* (2011), but how tree crown streets are exactly formed is still not perfectly understood. Haines and Smith (1987) reported that they developed under conditions of low relative humidity and a slow moving fire.

1.3 FIRE-ADAPTED SPECIES

The recurring presence of fire on this landscape explains the fire resistance traits and genetic adaptability to fire of many of the dominant pioneer tree species (Habeck and Mutch 1973). For instance, lodgepole pine (*Pinus contorta* Loudon) can maintain its population following low to high intensity forest fires at intervals greater than 20 to 50 years through cone serotiny and other adaptations (Brown 1975, Lotan 1976, Muir and Lotan 1985). With maturity, pine trees develop a thicker bark, shed their lower branches, and also acquire greater levels of cone serotiny (Clements 1910, Lotan 1967, Lotan *et al.* 1985, Turner *et al.* 2003). Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is resistant to lower intensity fires with its cork-like bark that insulates the cambium from heat damage and which gets thicker with age (Ryan *et al.* 1988). The fast growth of Douglas-fir results in large diameter trees and a crown base that can tower well above the flames of a surface or moderately intense fire (Peterson and Arbaugh 1989, Keeton and Franklin 2004). Aspen (*Populus tremuloides* Michx.) and other poplar (*Populus spp*) trees that populate the lower elevations of the Montane and Foothills landscapes are shade intolerant species that colonize natural disturbances rapidly via their suckering root system (Mitton and Grand 1996, Gom and Rood 1999), as long as soil scorching is not too severe. Poplars also produce millions of seeds each spring that disperse effectively in the wind over long distances. While the germination of these seeds require moist sites and do not typically do well in arid landscapes of the interior American northwest, thousands of aspen seedlings colonized successfully from seeds following the 1988 Yellowstone fire (Mitton and Grant 1996, Turner *et al.* 2003). With a warmer climate, aspen seeds are successfully colonizing harvested stands at higher elevations in the Rocky Mountains (Landhausser *et al.* 2010) where aspen did not typically grow. A similar recruitment pattern could be expected following burning.

1.4 MANAGING FIRE-DRIVEN ECOSYSTEMS

The front ranges of the Canadian Rockies and the Foothills of southern Alberta encompass different land classifications including wildland parks, provincial parks, recreational areas and, forest management units in which timber harvesting takes place. While each land classification type has different resource management objectives, all land managers must take into consideration knowledge acquired from fire regime and fire history studies to develop appropriate forest and fire management plans that will meet their management goals. Such goals include the protection of lives and infrastructure from fire as a priority, as well as other values-at-risk attached specifically to each land classification type. For timber harvesting areas, the main value-at-risk from fire are the forests. Protected areas have various ecosystems that are valued including forests, but in contrast, fire is often seen as an inherent aspect of ecosystem processes and is considered a rejuvenating agent that ensures the ecological integrity and resilience of forest ecosystems, as well as ensuring a diversification of wildlife habitats. In a not so distant past, parks' ecosystems were being protected from fire and all fires were suppressed.

Increasingly, protected area managers are developing plans that include a prescribed burn program to first create fire breaks and to eventually re-introduce fire for ecological restoration needs. For larger protected areas, let-burn policies are also considered in safe zones. As the various land use zones share common boundaries, the exclusion or acceptance of fire as well as the use of fire as a tool can prove challenging.

Timber harvest planning on landscapes historically regulated by fire must take into consideration the spatial variability of fire occurrence probability and adapt to the unexpected occurrence of large scale wildfire. Timber harvest practices are also encouraged to emulate natural disturbances when possible to narrow the gap between fire and harvest effects on forest ecosystems. The understanding of historical fire regimes is an essential principle of sustainable forest management (FSC 2004) in order to maintain long-term forest ecosystem health, which in turn will provide socio-economic benefits for future generations. In my opinion, it is doubtful that fire-adapted ecosystems can remain ecologically sound by strictly relying on harvesting and excluding fire. Both forms of forest management treatments: prescribed burning and harvesting, will require coordination based on knowledge and our understanding of the historical range of variation of past fire regime conditions.

An important consideration to forest and fire management, beyond land classification type, is the important role that forests play in this region. The front ranges of the Canadian Rockies hold the headwaters of many important rivers and their tributaries. Many of these water basins are the water source for communities large and small, including the Calgary metropolis. Thus, the protection of headwaters and riparian zones from disturbance is of prime importance (Richardson and Danehy 2007). Severe burning of considerable scale in a mountainous watershed causes slope erosion accompanied by stream washouts, as well as direct stream bank erosion when there is no riparian vegetation left (Spigel and Robichaud 2007). The consumption of the duff layer by intense fire sets free heavy metal pollutants that have been accumulating for decades or centuries as a result of atmospheric pollutants deposited by rain and snow. Following a severe fire, intense rainfall events and spring snow melt wash these pollutants into streams - an issue that can recur for years (Kelly *et al.* 2006, Emelko *et al.* 2011). Nutrients are also released (Schindler *et al.* 1980, Bladon *et al.* 2008) and the influx of sediments cause significant turbidity (Silins *et al.* 2009). Furthermore, denuded slopes and stream banks no longer provide shade and can increase water temperature (Minshall *et al.* 1989). All of these impacts can be detrimental to aquatic macroinvertebrates and fish life (Kelly *et al.* 2006, Mellon *et al.* 2008), and taken altogether are also problematic for maintaining water quality standards for potable water (Emelko *et al.* 2011).

Another essential role of the forests is its carbon capture capacity (Harmon *et al.* 1990, Harmon 2001), which is increasingly important in a warming climate that could see more forest fires, an increase in area burned and an extended fire season (Flannigan *et al.* 2001, Gillet *et al.* 2004, Flannigan *et al.* 2005). Managing forests, fire risk and ecological integrity where fire was historically an integral part of the ecosystem is a balancing act and a challenging task for the future when fire is still being perceived as more harmful than beneficial by the general public and forest industry.

1.5 QUESTIONS TO ANSWER

Little was known of historical fire frequency for this region until 2003-2004 when a fire regime study was conducted on the Spray Lake Sawmills FMA (Rogeau 2004). Situated outside of the main mountain ranges, the history of recurrent fire activity uncovered during the field seasons of 2004 and 2005 (Rogeau 2005, 2006) was in contrast to what had been documented in the national parks and provincial parks located to the west in the main ranges of the Rocky Mountains, as well as with a more recent fire history study conducted in the rugged subalpine environment of the Elbow watershed (Rogeau 2011a), which is the water source for Calgarians. The questions raised by land managers were the following:

1) How different were the mean and distribution of fire return intervals (MFRI) between the local natural subregions: Subalpine, Montane and Upper Foothills in the pre-industrial era?

2) Did MFRIs vary spatially within a subregion?

3) How departed are these fire-landscapes since the on-set of the industrial period when efficient fire detection, prevention and suppression started taking place?

More specifically, in terms of forest and fire management decisions, should harvest rotation be modified spatially and adapted to historical burning rates associated with natural regions or to other topographic variants? Should the gap between the historical burning rate and the current fire cycle (i.e. under strict fire exclusion policies) be reduced, and by how much? And where should fire be re-introduced and excluded?

1.6 THESIS RESEARCH OBJECTIVES

The above three main questions translated into specific research objectives and hypothesis testing that are being addressed in this doctoral thesis.

Objective 1) To determine if fire return interval distributions are significantly different between and within natural subregions.

H_{01}: Fire return interval distributions are not different among subregions;

H_{02}: Fire return interval distributions are not different within a natural subregion;

Objective 2) To determine the effect of topographic elements such as aspect, elevation and slope, on fire return interval distributions. And are such effects similar between natural subregions.

H_{03}: Aspect does not affect fire return intervals.

H_{04}: Elevation does not affect fire return intervals.

H_{05}: Slope does not affect fire return intervals.

3) To quantify fire return interval departure from pre-industrial conditions.

H_{06}: Median fire return intervals pre- and post-1948 are not different.

The year 1948 corresponds to the establishment of the Eastern Rockies Forest Conservation Board. The following is a summary from Murphy (1985). The mandate of the Board was to protect the headwaters and forest cover from fire and was a pivotal point in the level of resources and capital expenditure this area received until 1960 when the Province took back fire protection control for this region. The Board continued its function as a policy and planning group until 1973 when it was terminated. Prior to 1948, the Great Depression (1930-38) prevented the Government of Alberta to adequately fund firefighting and subsequently, World War II created a shortage of man power to fight fires. In the earlier 1900s, fire awareness campaigns towards fire prevention were helpful, but fire detection and response time to remote fires were often days most notably in mountain areas. In 1950 the construction of the Forestry Trunk Road from Coleman to Nordegg was initiated, and the networks of fire roads, trails, ranger stations, look-out and communication towers were expanded; all of which increased the rapidity in fire detection and response. During the 24 fire seasons of the Board's existence (1949 – 1972) the average annual burn rate dropped to 0.007%. Other statistics published in 1953 showed that the Rocky Mountains Forest Reserve[1] benefited greatly from the additional firefighting resources as an average annual area burned of 300 acres per 1000 square mile (1.2 km^2 per 2590 km^2, or 0.05% rate) could be maintained in comparison to the less funded Northern Alberta Forest District that averaged 7000 acres per 1000 square miles (28.3 km^2 per 2590 km^2, or 1.1% rate).

1.7 THESIS RESEARCH METHODS

Fire history data collected for the Spray Lake Sawmills FMA and the Alberta Government (Rogeau 2004, 2005, 2006, 2011a) are being used as the foundation to address the research objectives. One of the biggest challenges of this research is to demonstrate that direct tree-ring counting, without cross-dating, is an acceptable approach to determine fire return

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[1] it included the Clearwater, Bow and Crowsnest Forests, of which this thesis' study area is a part.

distributions to guide science-based forest and fire management programs. Faced with important limiting factors such as budget restriction, an extensive study area, a high intensity fire environment that produces large size fires with a high rate of tree mortality, and hence few fire scarred trees, the sampling design and data collection protocol are geared towards finding evidence of as many historical fires as possible while mitigating fire dating errors. The forest fire survival analysis (also known as a fire frequency analysis) is based on point fire return intervals obtained from visiting 814 sampling sites and collecting 3123 trees including a total of 583 fire scars. The popular Weibull survival model did not fit the data set, as a result the non-parametric Kaplan-Meier product limit estimator is used as the survival function to determine the probabilities of survival as forest stands increase in age. The Cox Proportional Hazards survival function is also used to evaluate the effect of covariates on survival probabilities. Due to the positive skew of fire interval distributions, median fire interval values are discussed rather than the mean.

The contribution of this research is many fold. First, it fulfills a knowledge gap in our understanding of fire return interval in southern Alberta. Second, the sampling design and methods of data analysis are different than what has been used in many of the neighboring fire history studies to the west. Because the study area covers a broad landscape and straddles three natural subregions with two different fire regimes, methods of data collection and analyses consider time-since-fire data collected in high severity stand replacing fires as well as complete fire return interval data gathered in mixed-severity fires where multiple fires could be detected at sampling sites. Third, this research attempts to show that the popular Weibull model of survival analysis in biological studies is not an appropriate model for determining fire return intervals for the three natural subregions in our study area. Survival models such as the non-parametric

Kaplan-Meier and semi-parametric Cox Proportional Hazard are better suited to test the research hypotheses proposed for this dissertation. Both models are seldom used in fire survival analysis, but have gained in popularity in recent years.

1.8 THESIS LAYOUT

The thesis format consists of three stand-alone chapters - Chapters II, III and IV -that have been written in a format ready for publication in scientific journals. Each chapter states background information, some literature review, a full description of the study area and methods used to conduct fire history sampling and survival analysis. Chapter II focuses on fire history sampling methodologies and fire return interval distribution results between natural subregions and sampling units. Chapter III puts the focus on the various aspects of the fire regime and departure from historical conditions in a fire management context. Chapter IV addresses the effect of topography on fire return interval distributions. Chapter V is the conclusion. It includes a summary of findings and outlines some ideas on how the outcome of these results can be used in a forest and fire management context.

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CHAPTER II – MANUSCRIPT 1

Fire history sampling strategy of fire intervals associated with lethal fires

2.1 ABSTRACT

This paper proposes a series of methods to conduct a field-based fire history study designed to learn about landscape fire regimes regulated by partially to fully lethal fires. In the context of applied forest and fire management, a case study based on six sampling units across the Montane, Subalpine and Upper Foothills natural subregions of the southern Canadian Rockies of Alberta is presented. The methods make use of historical aerial photography and a targeted paired-plot sampling strategy along fire boundaries and edges of island remnants. This process allows for the calculation of point fire return intervals (FRI) even when fire scars are absent. The Kaplan-Meir non-parametric likelihood estimator is used for the fire frequency analysis. A total of 814 sampling sites were visited from which 3123 tree cross-sections containing 522 fire scars were collected. The average fire scar dating accuracy was 0.98 ±0.73 years for 1900 fires. The period of data analysis ranged from the oldest stands sampled in the unit (1535 to 1770) to 1948, before effective fire suppression. The probability median FRI for the Montane units ranged from 26 to 35 years, while it was 39 years for the single Upper Foothills unit sampled. The two Subalpine units presented probability median FRI values of 65 and 85 years. Data interpretation and efficiency of the proposed methods are discussed. We concluded the approach to be practical for landscapes regulated by large fires with significant tree mortality and with an average fire interval greater than 20 years.

2.2 INTRODUCTION

Fire history studies have long been employed to interpret historical or natural fire regime conditions and stand structure of various ecosystems. Outputs from these studies, either in the form of fire maps (Heinselman 1973), fire intervals (Grissino-Mayer 1999), or age-class distributions obtained from time-since-fire data (Johnson and Larsen 1991, Cyr et al. 2007), provide an understanding of past fire occurrences in terms of their frequency, size, severity, spatial distribution on the land and long-term temporal distribution (Lynch et al. 2002, Stambaugh and Guyette 2008).

Different methods of conducting fire history studies have been presented over the decades (Stokes and Smiley 1968, Heinselman 1973, Arno and Sneck 1977, Arno et al. 1993, Johnson and Gutsell 1994, Grissino-Mayer 1999). Some rely on an abundance of trees bearing multiple fire scars to analyse mean fire intervals (average number of years between two fire events - Romme 1980) such that only trees with more than one scar are considered in the analysis process (Kilgore and Taylor 1979, Romme 1980, Grissino-Mayer 1999). For landscapes with relatively infrequent high severity fires, other studies have used stand origin based survival analysis from random plot distributions to document the historical fire cycle (i.e. fire rotation - the time required to burn an area equivalent in size to the entire study area) (Johnson and Gutsell 1994, Bélisle et al. 2011).

In many boreal ecosystems, fire regimes can be regulated by a wide range of fire frequencies causing various degrees of forest mortality. These mixed- to high-severity fires overlap each other overtime and can result in a complex forest age mosaic of various patch sizes (Marcoux et al. 2015, Andison and McCleary 2014). The intricacy of the age mosaic complexity coupled with the scarcity of trees bearing more than a single scar due to repeated lethal fires both create a challenge for dating and mapping past fires.

The primary objective of this paper is to present a fire history and fire frequency analysis approach tailored to broad landscapes regulated by large fires of mixed- to full-severity with limited fire scar data. While the proposed methods deal with limiting factors such as size of landscape, remoteness, accessibility and, sampling cost, they are suitable for finer scale studies of small study areas also regulated by lethal fires.

2.3 METHODS

The proposed methods were initially designed in the context of landscape fire and forest management planning where decisions are based on seral or age-classes, and prepared by natural subregion. The case study presented applied fire frequency information for ecosystem restoration needs, FireSmarting (Alberta 2016) landscapes at the wildland urban interface using prescribed burning and fuel modification procedures (Swetnam et al. 1999, Vose 2000, Brown et al. 2004, Moritz et al. 2014), and to natural disturbance emulation programs via adaptive forest harvesting practices (Bergeron et al. 2002). In this section, we introduce the study area and present the sequence of methods used from the identification of sampling units, distribution of sample plots, choice of trees, processing of cross-section samples, tree-ring count, estimation of dating error margin, calculation of fire return intervals and time-since-fire intervals, to the final step of fire frequency analysis. The proposed methods have been inspired and adapted from a combination of various fire history studies, notably those by Arno and Sneck (1977), Knowles and Grant (1983), McBride (1983), Veblen (1986) and Johnson and Gutsell (1994).

2.3.1 Study Area

The study area covers three natural subregions of south-western Alberta: Subalpine, Montane and, Upper Foothills. The fire history study targeted six sampling units within the forests of the Spray Lake Sawmills Ltd. Forest Management Agreement Area (SLS FMA) and the Elbow Fire Management Compartment of Alberta, which overlaps the lower portion of the SLS FMA (Fig. 1). The bounding coordinates are 50° 08 15"N - 115° 23' 37"W and 51° 52' 20"N - 114° 27' 20"W, and the study area covers 667 673 ha west of the City of Calgary, between the Little Red Deer River to the north and the Sheep River to the south. The area is approximately 190 km in length with a varying width of 5 km to 60 km.

The study area includes variable landforms and tree species with meso-climate conditions driven by a strong elevation gradient. These gradients exert different precipitation and snow accumulation regimes, as well as a gradual cooling from low to high elevation. The snow and frost-free period tends to range between the last week of May and the end of August. On average, the study area receives 385 mm of rain annually and 257 cm of snow in the mountainous portion of the study area. The snow amount decreases in an easterly fashion to 175 cm near the interface between foothills and prairies (Environment Canada 2016 - Kananaskis and High River weather stations). The relative humidity in southern Alberta is low year round and can frequently be lower than 30% during the fire season.

The entire landscape is largely dominated by lodgepole pine (*Pinus contorta* Loudon) which is a fire-adapted tree species via cone serotiny (Lotan 1967). The Montane and Foothills pine forests

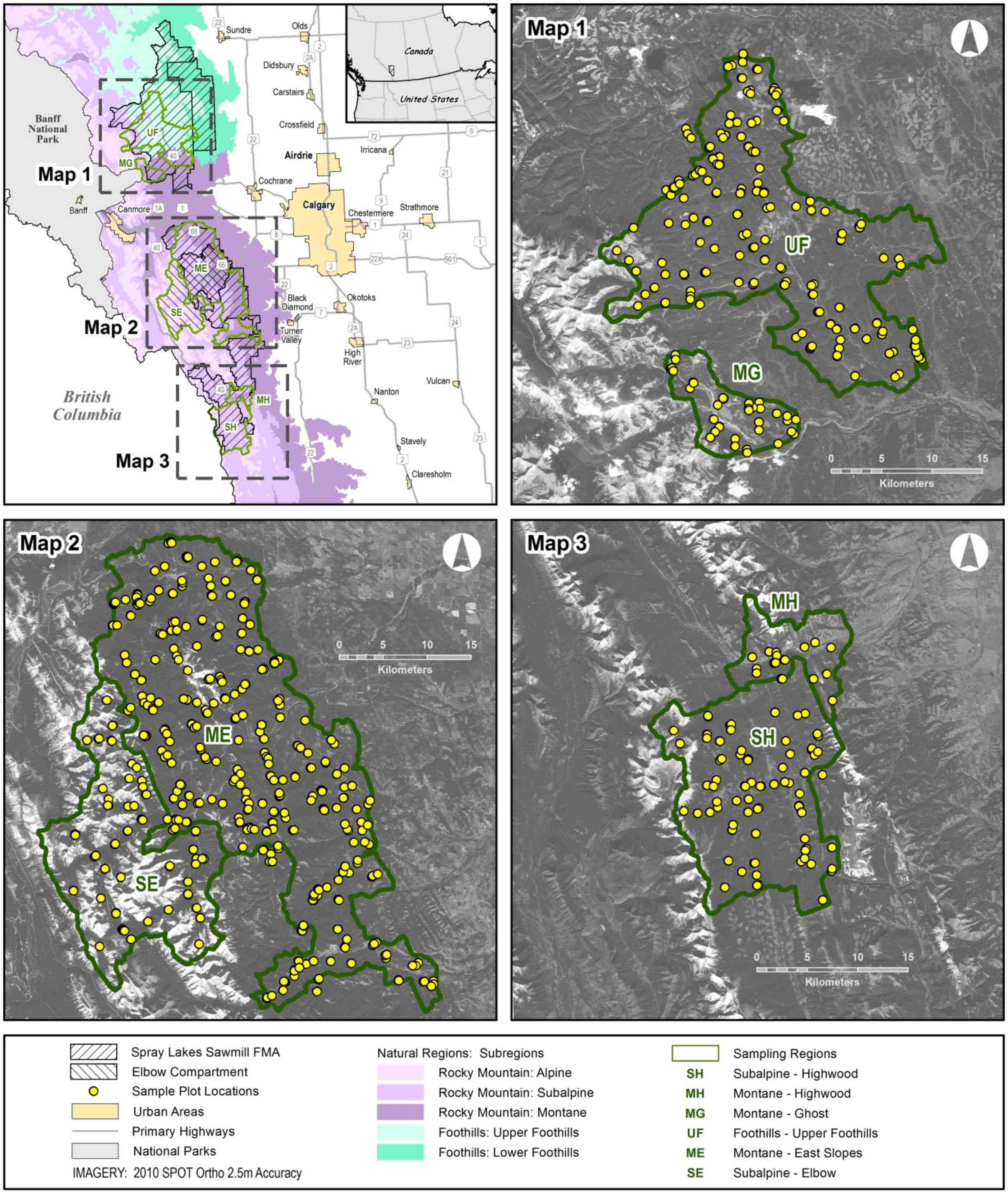

Figure 2-1. *Location of study area. Upper left map inset displays the study area over the natural subregion map. Maps 1, 2 and 3 show the sample plot distribution across six sampling regions.*

are interspersed with patches of aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss), whereas in the Subalpine, pine forests co-exist with extensive stands of Engelmann spruce (*Picea engelmannii* Parry *ex* Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) that are notably found at higher elevation and on the cooler mountain faces. The six sampled units contain various proportions of pioneer species, such as pine and aspen (Table 1), a sign that the role of fire was not equal across the whole landscape.

Table 2-1 Characteristics of six sampling zones retained for fire history data collection in southern Alberta.

	Subalpine - Highwood	Subalpine - Elbow	Montane - Highwood	Montane - Ghost	Montane – East Slopes	Upper Foothills
Area (ha)	29 792	35 946	7158	11 646	41 163	43 848
Non-vegetated (%)	9	62	9	1	8	7
Elevation range (m)	1480 - 2968	1606 - 3200	1424 - 2761	1293 - 1751	1369 - 2933	1262 - 2869
Weighted mean elevation (m)	1968	2210	1748	1497	1745	1637
Natural subregion (%)	Subalpine: 88 Alpine: 10	Alpine: 51 Subalpine: 48	Subalpine: 55 Montane: 40[a]	Montane: 100	Subalpine: 59 Montane: 38	U. Foothills: 83 Subalpine: 14
Age mosaic complexity (%)	Moderate: 61 Low: 22	Moderate: 36 Low: 64	Very high: 100	High: 100	High: 46 Moderate:41 Very high: 12	High: 61 Moderate:21 Very high: 18
Pine cover (%)	45	25	51	66	77	83
Other lead species (%)	spruce: 55	spruce: 75	spruce: 32	aspen: 19	spruce: 20	spruce: 16

2.3.2 Sampling units selection

A visual screening of historical aerial photography is a crucial step in the process of identifying the potential range of variability in fire frequency and fire severity when dealing with landscapes that cover thousands of hectares. As it could be cost prohibitive to obtain a field-based fire history profile for each watershed within the study area, this coarse-scale screening approach (Hardy et al. 2001, Schmidt et al. 2002) allows for the identification of sampling units that capture the range of variation encountered on the landscape. We used 1:40 000 black and white aerial photography, flown between 1949 and 1952 (oldest continuous quality coverage available) to assess 121 watersheds for their total number of visible fires and forest age mosaic complexity score, which were entered in a Geographic Information System (Idrisi version 17.02 Selva Edition). To limit bias, the screening was performed by a single photo interpreter and the forest age mosaic complexity level was ranked on a scale of 1 to 5, 5 being highly complex. A watershed of low complexity score would be the outcome of few, high severity fires leading to a forest cover of homogeneous appearance. In contrast, a watershed including a larger number of mixed- to high-severity overlapping fires, which create an intricate patch mosaic of forest ages, would be ranked the highest. Using land accessibility as an additional criterion of selection, this process led to the selection of six sampling units across the Subalpine, Montane and Upper Foothills natural subregions (Table 1).

2.3.3 Sample plot distribution

There are debates in the literature over the merits of a random, systematic grid, stratified, or targeted distribution of fire history sample plots or tree selection (Johnson and Gutsell 1994, Baker and Ehle 2001, Parsons et al. 2007). For stand-replacing fire regimes producing few fire-scarred trees, it is strongly advocated to choose a targeted sampling approach because fire scars are not randomly distributed and their formation is closely associated with fire behaviour at the time of burning (Stokes and Smiley 1968). Scars form when the moving flame has a long enough residence time to penetrate the bark and kill part of the cambium tissues (Gutsell and Johnson 1996), while it is low enough that it is not completely lethal to trees. This process is influenced in part by the fire environment such as topographic features and fuel type conditions (Barrows 1951, Countryman 1972).

As part of a targeted sampling approach, historical aerial photography guided the positioning of paired sample plots along fire boundaries (ecotones) and edges of island remnants no longer visible today. A fire boundary is the interface between a past fire and an adjacent unburned or partially unburned stand that suffered a lower fire intensity encroachment when the fire was dying off for a number of reasons (e.g. changes in weather, fuel type or fuel load, fire suppression). This process often produces a number of fire scars especially along the fire boundary itself. The paired-plot approach served two purposes: 1) to ensure fire evidence found (growth releases, healed-over or questionable scars) in the remnant stand was effectively dating the younger age cohort sampled and, 2) to determine a fire interval by calculating the time difference between the pith origin of the older and younger age cohorts in case of a lack of scar or growth release. In additional to the paired-plots, verification plots were distributed in large homogeneous-looking forest patches to ensure potential historical burns were not overlooked.

A significant portion of the sampling was carried out by helicopter due to the extensive size of the land base, coupled with a poor road access network. Opportunistic sampling was done by accessing helicopters during man-up for high fire hazard periods. As such, the majority of plots were positioned within 500 m of access points to reduce sampling time and limit costs. The targeted sampling approach can ultimately be limited by the absence of landing sites.

2.3.4 Field sampling

Four representative trees of the stand were sampled, giving preference to scarred trees and lodgepole pines in mixed coniferous stands. Along a fire boundary, the double plot strategy amounted to eight tree samples. In forest stands of apparent uneven structure, cross-sections were collected from six to eight trees. The field plot size varied from 30 m^2 to 100 m^2, and up to 300 m^2 after combing the area for scarred trees.

When fire scarred trees are absent, not visible, or too rotten for sampling, an alternative is to use growth releases to date fires (Lorimer 1985). To optimize uncovering a fire-related release, cross-sections were taken from surviving trees positioned exactly on the fire boundary and facing the younger aged stand (i.e. the fire).

All samples came from felling live trees, with the exception of a few sampling sites that made use of cut stumps from recent harvest blocks with known dates of harvesting. Partial cross-sections were removed from the base of the tree, normally less than 20 cm from the ground. For scarred trees, cross-sections were wide partial or complete cross-sections. If trunk rot was severe, occasionally cross-sections were taken up to 1.5 m and missing years were adjusted by judging tree growth rate at the early years of origin from neighbouring sampled trees.

2.3.5 Fire dating

Tree cross-section samples were air dried and surfaced with progressively finer sandpaper (Speer 2010) (up to 220 grit) using a commercial belt sander. If necessary, light grade oil or a diluted blue food color dye was used to enhance the contrast of pale wood fibre, particularly for aspen tree rings. An important cost-saving factor to the project was doing direct tree ring counting with a variable power dissecting microscope, which is six times faster (Madany et al. 1982). The process of cross-dating was by-passed because many fire dates came from tree establishment, which inherently introduces a dating error of 2 to 15 years depending on past burn severity and environmental growing conditions. The accuracy of dating fire scars from direct ring counts was verified by comparing 193 fire scars collected from 15 separate known fire events that occurred in the 1900s in central and southern Alberta.

Fire scars or growth releases were used to date a stand-replacing fire event if it could be supported by a nearby age cohort that established within 10 to 20 years of the fire event. In the absence of fire evidence at the sampling site, fire scars and releases collected within a distance of 5 km were used to assist with stand dating. If unsuccessful, fire evidence from further away within the valley was considered, but only if fuel continuity made it possible for a fire to spread over a longer distance.

Tree growth releases associated with fire scarring normally indicated that past fire intensity was high enough for neighbouring tree mortality to occur. A growth release pattern needed to be greater than 100% wider than previous ring widths and sustained for at least 10 years to be used in lieu of scars. At times, this rule was softened if the cross-section was taken along a fire boundary or within a small island remnant where the growth release was very likely to be the result of fire disturbance. Alternatively, when no fire scars or releases could be found on site, stand structure was used and fire origin dating relied solely on tree establishment dates (Romme and Knight 1981, Senici et al. 2010). The oldest tree of an even-aged pine cohort was rounded down to the nearest fire year increment to establish a fire origin date. An even-aged pine cohort consisted preferably of a 10-year age span, but a spread of up to 20 years was considered.

The stand dating of uneven-aged pine stands relied on a combination of fire scars, growth releases and stand ages for dating multiple fires at the sampling site. In contrast, dating of uneven-aged mature spruce-fir forests was done by using the oldest tree and rounding it down to the nearest 10 year interval. Additional clues of charred stumps, snags, woody debris, and charcoal were noted, as well as relative duff depth, relative amount and size of historical fire killed deadfall on the ground. Such observations were useful for gauging the time lapse since the last fire and determining if short-interval burning occurred.

2.3.6 Fire return interval calculation

The number of years between fire events (i.e. fire interval) recorded at each sampling site was calculated, and then aggregated by sampling region to establish a list of fire intervals for analysis. The period of data interpretation to document the historical fire regime was set prior to 1948. It corresponds to the year the Eastern Rockies Forest Conservation Board was established; a federal-provincial agreement resulting in increased fire protection and management of the Rocky Mountains Forest Reserve, which drastically reduced the area burned (Murphy 1985). Of added relevance, prior to 1948, the ca. 1950 aerial photography showed no signs of harvest blocks, roads, mining, or settlements and confirmed that forests were in a pristine state.

Many stands sampled in landscapes of mixed-severity fire regime contained multiple fires and produced complete fire return intervals (FRI). However, due to the nature of stand replacing fires, many stands were also the outcome of a single fire, notably the younger stand of the paired-plot sampling scheme, or old growth forest patches. Under these circumstances, we have an incomplete fire interval (right-censored observation) that corresponds to the time since fire, which was calculated as the time difference between the stand origin date and 1948 (the end of the data analysis period).

The pseudo-replication of fire history data (Polakow and Dunne 1999), which comes from sampling the same fire interval calculated from the same fire events numerous times, is a potential issue for landscapes with large-size fires. To avoid interpreter bias in choosing which observations should remain in the data set, a bootstrap resampling approach of FRI (50% of observations with replacement) was applied to mitigate the issue of spatial connectivity of plots sampling the same fire events.

2.3.7 Survival analysis

It is common practice to describe mean fire return intervals or fire cycles using a survival model. The Weibull model has been popular with fire frequency analysis studies dealing with point fire interval data (Grissino-Mayer 1999) or time-since-fire maps (Johnson and Van Wagner 1985). Our data failed to fit the Weibull model. Instead we opted to use the non-parametric Kaplan-Meier (K-M) product-limit estimator (Kaplan and Meier 1958, Meier et al. 2004) to fit FRI observations (Drobyshev et al. 2008). The K-M estimate of the survival function is an unbiased curve fitting approach that is frequently applied in survival analysis (epidemiology studies), mechanical failure (engineering) studies, or other ecological studies that deal with censored data. The data process and analyses followed methods of Kleinbaum and Klein (2012) and David Diez (www.openintro.org/stat/surv.php) using the R (R Development Core Team 2016) open source Survival package version 2.38-3 (Therneau 2016). The K-M curve was fit with 95% confidence bands (Brookmeyer and Crowley 1982, Emerson 1982). Probabilities of survival after 20, 40, 60, 80, 100, 125, 150, 175, 200, 225, 250, 275, 300 and 350 years were queried for all sampling units to assess regional differences. In addition to fitting the original data, the K-M was fit to 1000 iterations of bootstrap FRI samples (Moritz 2003). Due to the heavy right skewing of the distributions, probability median statistics from the K-M survival distribution were calculated rather than the mean (Fulé et al. 2003). To test for significance among sampling units, a permutation test was applied to all paired units (15 pairs) using bootstrap median FRI data.

2.4 RESULTS

A total of 814 plots were distributed among the six sampling units for a variable sample plot density of 1 plot per 96 to 364 ha (Fig. 1). A total of 3123 tree cross-sections were collected, 66.5% of which from *Pinus contorta* (2078). Other species sampled included *Picea Engelmannii* and *glauca* (890), *Populus tremuloides* (106), *Populus balsamifera* (7), *Pseudotsuga menziesii* (7), *Abies lasiocarpa* (31), *Larix Lyallii* (6) and *Pinus albicaulis* (1). A total of 623 fire scars were identified on 522 trees largely from pines. Most trees held single scars (450), 54 had double scars and only 23 individuals had either three or four scars. The number of scars for the pre-1948 period of data analysis amounted to 582. The average dating accuracy of fire scars from direct tree-ring counts was calculated to be 0.98 ± 0.73 years (Table 2).

Table 2-2 Estimated margin of error in fire scar dating from direct count when compared to documented fire events from central and southern Alberta.

Known Fire year	Location	N scars	Precise count	± 1 yr	± 2 yrs	>2 yrs	% accuracy ± 1 yr	% accuracy ± 2 yrs	% error from missing ring	% error from false ring
Jun. 1961	1	8	8	0	0	0	100	100	n/a	
1939	2	5	3	0	0	2	60	60	100	
May 1936	3	5	5	0	0	0	100	100	n/a	
Aug. 1936	4	20	0	13	5	2	65	90	100	
1936	5	15	0	13	1	1	87	93	100	
Aug. 1934	4	3	1	1	0	1	67	67	100	
Jun. 1919	6	32	12	17	2	0	91	97	74	26
Apr. 1915	7	2	2	0	0	0	100	100	n/a	
1914	6	13	3	6	4	0	69	100	80	20
July 1910	4	1	0	1	0	0	100	100	n/a	
May 1910	8	8	0	6	2	0	75	100	100	
July 1910	9	61	2	50	9	0	85	100	100	
July 1910	2	13	7	3	3	0	77	100	100	
July 1910	10	6	2	2	2	0	67	100	100	
Apr. 1906	11	1	0	0	0	1	0	0	100	
15 separate fire events		193	45	112	28	7	81	96	95	5
Average dating error: [(45x0)+(112x1)+(28x2)+(7x3)]/193 = 0.98 ± 0.73										

Location: 1- Sheep valley, Willmore Wilderness Park, 2- Waiparous valley, Kananaskis District, 3- Smoky valley, Willmore Wilderness Park, 4- Castle valley, Castle Special Management Area, 5- Highwood valley, Kananaskis District, 6- Ghost & Waiparous valleys, Kananaskis District, 7- N. Saskatchewan Valley near Nordegg, 8- Porcupine Hills Region, 9- Elbow valley, 10- Red Deer valley, Kananaskis District, 11- Red Deer & James valleys, Kananaskis District

A verification of data pseudo-replication (Table 3) showed fire intervals from similar fire events were most pronounced in the Montane (30%) and Upper Foothills (24%) natural subregions due to continuous forest cover leading to large size fires. In contrast, the rugged portion of the Subalpine (SE sampling unit) had 9.8% of replicates due to fuel discontinuity and smaller size fires. Replication was often the outcome of time-since-fire interval data from the paired sampling approach.

Table 2-3 Pseudo-replication (rep.) of fire return interval observations with proportion of replicates attributed to complete fire return intervals or time-since-fire (TSF) intervals (censored data).

Sampling Unit	Total FRI	% TSF	N rep. from total	% rep. from total	% rep. from complete FRI	% rep. from TSF
MG	73	17.81	23	31.51	21.67	76.92
MH	37	6.67	1	2.70	3.57	0.00
SH	131	22.31	18	13.74	6.93	37.93
SE	102	32.67	10	9.80	4.41	21.21
ME	585	26.00	186	31.79	23.65	57.33
UF	289	23.18	70	24.22	17.57	46.27
			Natural subregions			
Montane	695	24.26	210	30.22	22.33	58.18
Subalpine	233	26.84	28	12.02	5.92	29.03
Upper Foothills	289	23.18	70	24.22	17.57	46.27

Multiple fire intervals (2 to 7) were commonly found in the Montane and Upper Foothills natural regions as a result of mixed-severity burning. The Subalpine, which is regulated by more severe stand replacing fires had more sites with a single fire event, but it was not uncommon to find stands with evidence of two or three fires.

The number of individual fires detected between 1840 and 1948 ranged from 13 to 32, depending on the sampling region (Table 4). For the era between 1700 and 1840, the reduced number of fires detected was the result of fewer island remnants left as evidence of past fires. In the case of the Subalpine units, the lower fire frequency in the recent period allowed for the detection of a similar number of fires in the older period of data assessment, which confirmed a consistent fire frequency over the 250-yr period. The age data spanned as far back as 1375 in the Subalpine (Elbow unit), but few stands from these periods were uncovered and their fire origin establishment dates were uncertain. All sampling units contained some pockets of old growth forests (250+ yr).

Table 2-4 Density distribution of fire history sample plots by study unit, number of trees sampled, number of scars and releases, total number of fires by time period and, oldest tree sampled. SH: Subalpine-Highwood, SE: Subalpine-Elbow, MH: Montane-Highwood, M-G: Montane-Ghost, ME: Montane-East slopes, UF: Upper Foothills.

Area	N. plots	Sampling density (ha)	N. trees	N. scars	N. releases	N. fires 1840-1950[a]	N. fires 1700-1839[b]	Oldest tree
MH	18	364	83	29	16	17	6	1770
MG	43	252	171	33	46	13	9	1665
SH	90	301	386	54	83	20	24	1595
SE	73	188	276	16	57	21	20	1375
ME	392	96	1465	307	327	32	8	1650
UF	198	207	742	144	239	22	21	1535

a: fire years only one year apart were considered as one fire event.
b: fire years three years apart were considered as one fire event.

Confidence intervals obtained from Kaplan-Meier bootmedian sampling (Fig. 2) show the expected range of variation in probability median FRIs between sampling units. The boxplots (Fig. 3) show all FRI distributions were positively skewed with a variable degree of spread and number of outliers in the longer intervals. FRI statistics (Table 5) highlight differences between mean and median FRIs, as well as between the inclusion or exclusion of time-since-fire data (censored observations) in the evaluation of mean-fire return intervals (MFRI).

The permutation test ran on observed FRI detected no difference between the three Montane sampling units (MH-MG: $P \geq 0.71$; MH-ME: $P \geq 0.23$; MG-ME: $P \geq 0.23$). Despite these similarities, the permutation test using bootmedian FRI data found each sampling unit to be significantly different from all others ($df = 999$, $P \leq 0.01$). Additional differences among sampling units are highlighted by the variable probability of survival rates obtained from K-M curves (Table 6).

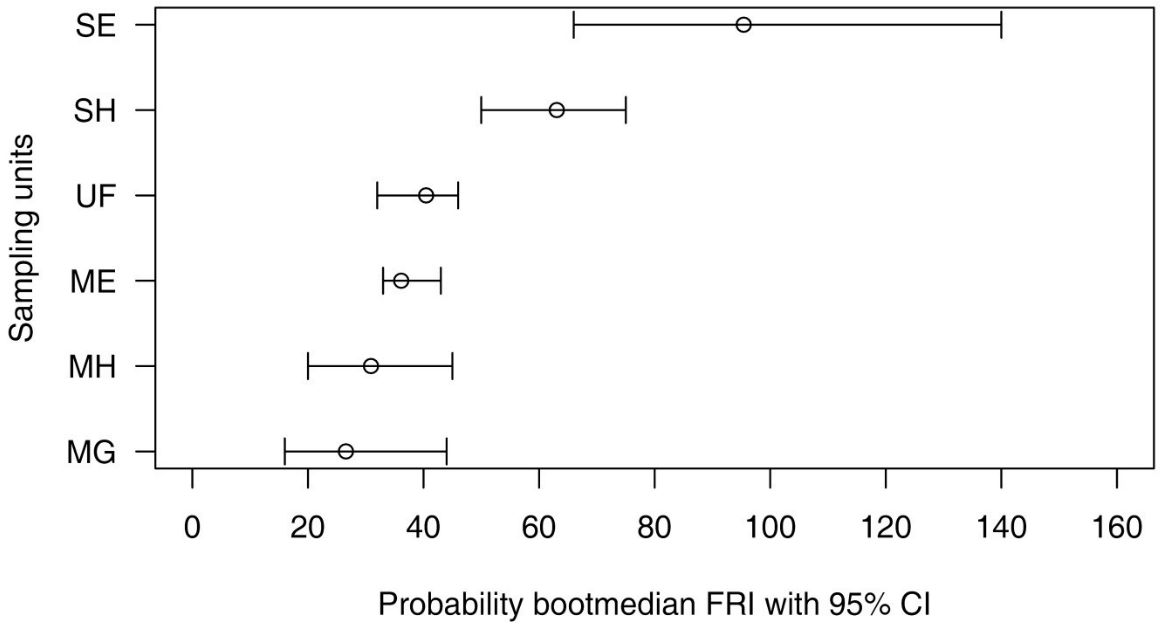

Figure 2-2 *Lower and upper confidence intervals (CI) (0.05, 0.95) of Kaplan-Meier probability median statistic from bootstrap fire return intervals. Median values are marked as a circle. Montane-East (ME), Montane-Ghost (MG), Montane-Highwood (MH), Subalpine-Elbow (SE), Subalpine-Highwood (SH), Upper Foothills (UF).*

Table 2-5 Range of fire return intervals (FRI) for censored interval data set (includes complete and time-since-fire (TSF) intervals) and uncensored intervals (complete intervals only), mean FRI including and excluding censored (TSF) data, number of total FRI records, number of uncensored events, and median FRI including censored data with its lower and upper 95% confidence intervals.

Samplin unit	FRI range censored	FRI range uncensored	Mean with censoring	Mean no censoring	N total intervals	N uncensored events	Median with censoring	0.95LCI with censoring	0.95UCI with censoring
MH	34-98	3-115	35.08	31.55	37	33	26	21	51
MG	1-71	6-237	35.57	39.68	73	59	32	21	45
SH	12-238	4-169	77.86	60.96	131	101	65	55	75
SE	23-423	4-360	111.30	89.96	102	69	85	70	135
ME	12-258	4-226	42.98	38.06	585	433	35	33	40
UF	6-413	4-219	49.77	44.39	289	222	39	35	46

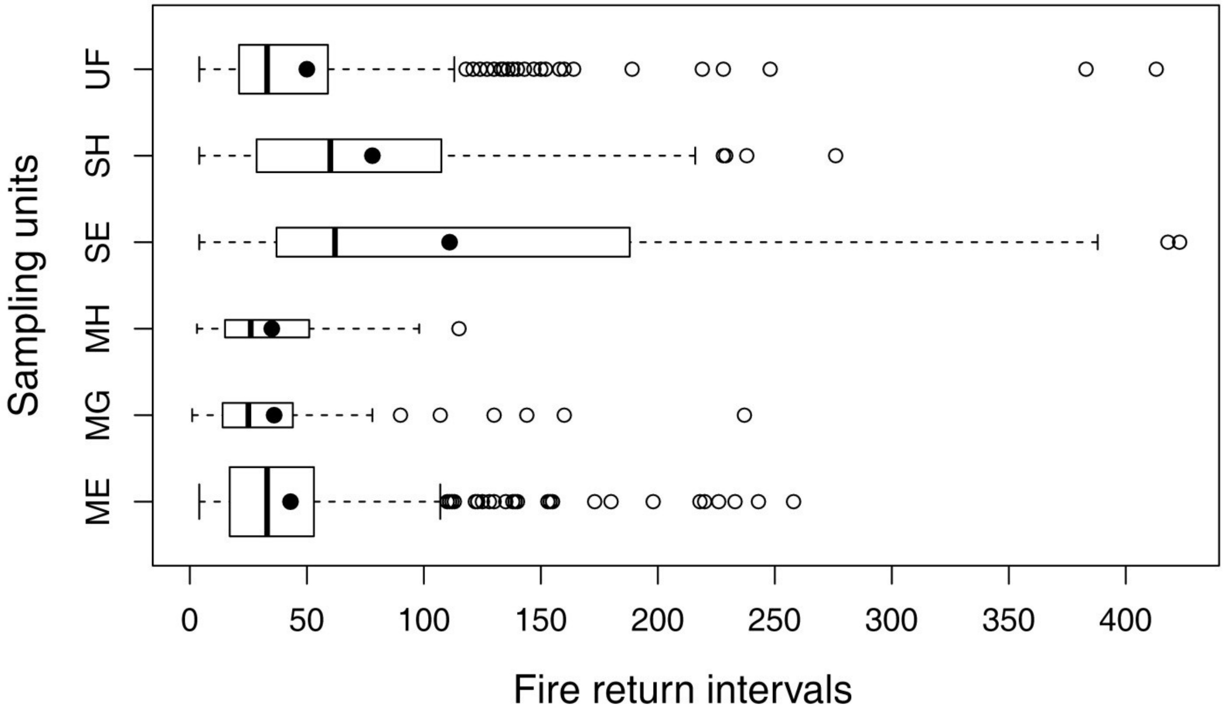

Figure 2-3 *Boxplots showing the spread of fire return intervals for six sampling units in southern Alberta. Montane-East (ME), Montane-Ghost (MG), Montane-Highwood (MH), Subalpine-Elbow (SE), Subalpine-Highwood (SH), Upper Foothills (UF). The vertical line represents the median and the dark circle the mean. The width of the box is the square-root of the number of observations. The box bounds the top of the first quartile and top of third quartile. The whiskers represent the lowest and highest datum within 1.5x the inter-quartile range. Empty circles are outliers.*

Table 2-6 Kaplan-Meier survival probabilities calculated for pre-determined time periods highlighting differences among sampling units.

Years	Sampling Units					
	MH	MG	SH	SE	ME	UF
20	0.649	0.625	0.843	0.873	0.719	0.767
40	0.322	0.403	0.665	0.716	0.450	0.491
60	0.226	0.262	0.519	0.645	0.329	0.371
80	0.129	0.138	0.364	0.531	0.237	0.283
100	0.086	0.115	0.319	0.468	0.193	0.210
125	0.000	0.092	0.244	0.403	0.116	0.145
150	0.000	0.046	0.234	0.364	0.085	0.071
175	0.000	0.023	0.192	0.351	0.074	0.054
200	0.000	0.023	0.171	0.338	0.043	0.045
225	0.000	0.023	0.152	0.310	0.035	0.036
250	0.000	0.000	0.152	0.263	0.026	0.036
275	0.000	0.000	0.152	0.206	0.000	0.036
300	0.000	0.000	0.000	0.160	0.000	0.036
350	0.000	0.000	0.000	0.160	0.000	0.036

2.5 DISCUSSION

2.5.1 Data interpretation

FRI distributions were found to vary within, as well as between, natural subregions and reflected the range of variation in fire occurrence and severity observed on the ca.1950 aerial photography. Permutation test results using bootstrap samples demonstrated that each sampling unit had a statistically different population of FRI. However, statistical tests using the complete data set determined significant similarities between units of the Montane. Confidence intervals of Kaplan-Mayer probability median values (Fig. 2) showed the range of variation can be wide, notably for the Subalpine, due to the high number of right censored observations from which bootmedian statistics were produced.

Differences between sampling units were better highlighted in the boxplots (Fig. 3). Within the Montane natural subregion (ME, MG, MH) the Kaplan-Meier probability median FRI were similar (35, 32, 26 years), but the data spread of the right tails and outliers were distinct. The outliers represent observations sampled in fire refugia, which are patches of forest that have been able to escape several forest fires usually as a result of their topographic location (Camp et al. 1997). In the Montane and Upper Foothills, such patches were not necessarily associated with what is typically known as old-growth forests (250+ years). The data showed landscapes of frequent fire activity, such as Montane-Highwood (MH), that “old growth” may be difficult to achieve as no stands are expected to survive past 125 years. For the three Montane units the survivorship analysis showed the probability of survival to fire past 40 years is only 32 to 45% and drops to 2.6% past 250 years for the Montane-East (ME) landscape. The higher number of outliers (refugia) detected in the ME were in part due to the fact that the area sampled was four times larger than in the Ghost (MG) or Highwood (MH) watersheds, and that targeted sampling favored the identification of a larger number of remnant stands from which fire scars and growth releases were sought.

Similar observations were made for the Subalpine natural region where regional differences in FRI distributions were apparent between the Elbow (SE) and Highwood (SH) watersheds. With 62% of its region being non-vegetated, the rugged Elbow is partitioned by multiple rocky ridges that make fire spread difficult. As a result, its probability median FRI of 85 years is the longest within the entire study area. The prevailing smaller size fires also foster conditions encouraging the formation of old growth forests based on a 20% chance of forest survival to fire past 275 years. This survival pattern was also observed in the length of right-tail spread with the presence of outliers beyond a 400 year FRI. In contrast, SH can be affected by larger size fires due to the extensive continuity of its forest cover (fuel breaks < 9%). As a result, its 65-year probability median FRI was 20 years shorter than for SE, and forest survivorship to 275 years was reduced to 3.6% with extremely little chance of a stand surviving past 300 years.

2.5.2 Review of fire history methods

The initial step of screening historical aerial photography for differences in burn pattern complexities and fire frequency proved to be useful for identifying the range of spatial variability in the fire regime at the landscape scale when a large number of watersheds are considered.

In ecosystems where fire scars are not abundant and difficult to find, dating past fire events is challenging and is subject to the interpreter's knowledge of fire behaviour, fire ecology and the region's fire environment. In mountainous terrain, field observations showed the greatest likelihood of finding fire scars is on flat benches where the rate of fire spread would have been reduced, on edges of gullies, stream banks, rock outcrops or any areas where the canopy becomes sparse. The lush forb layer of deciduous stands can also reduce fire intensity and increase the chance of scar formation on the edges or within such stands. Fire scars were also found along fire boundaries and edges of island remnants. Considering the low density of fire scars in Alberta (as a general rule 17% of trees sampled have fire scars, personal observations), targeted sampling ensured that the most complete fire history information was collected in the most resource-efficient manner.

Destructive sampling of trees revealed many trees with healed-over fire scars (Niklasson and Granström 2000), which were frequently not noticeable from the outer bark. Healed over scars would not have been detected if an increment borer had been used to collect tree cores. Investigating recent harvest blocks also provided good opportunities for discovering healed-over scars. This information becomes relevant in understanding past fire regimes where fire intensity was low enough for small diameter trees to survive.

The paired-plot sampling strategy worked well to calculate a fire interval when no fire scars or growth fire-related releases were present. However, this method can cause some issue of pseudo-replication by re-sampling the younger age cohort of the paired-plot multiple times when dealing with recent large size burns. This issue can easily be mitigated by removing some observations from plots that are spatially close, or by using an unbiased bootstrap resampling approach as we did.

FRI data distributions by sampling unit (Fig. 2) were positively skewed and as such, the probability median obtained from the survival analysis is a better descriptive statistic when FRI data are not normally distributed (Sherriff *et al.* 2001). The difference of 26 yr between mean and median FRI is wide enough in the rugged Subalpine (SE) to influence forest or wildland fire management guidelines, whereas for regions of shorter fire intervals such as in the Montane, a difference of less than 10 yr would unlikely make a notable difference in long-term planning (Moritz *et al*. 2009).

2.5.3 Dating accuracy

The dating verification process showed 81% of fire scars were precisely dated, or be within one year of documented fire events from the 1900s. This corroborates the assessment of dating accuracy from Madany et al. (1982) using ponderosa pine. Only five percent of errors were due to false rings and most dating errors were possibly attributed to “missing rings”. In this case, it is likely the rings were present and could have been detected with 600 to 800 grit sanding paper. Based on studies by Houston (1973) and Agee et al. (1990), that took place in similar forests, it is estimated the dating accuracy from fire scars could gradually drop to about ± 2-5 years for fires having occurred before the 1900s. Fire scars older than 1800 are extremely rare on this landscape and the level of rot usually makes it difficult to use these specimens to date fires with confidence. Overall, we found the small reduction in accuracy does not affect the interpretation of fire frequencies for fire regimes regulated by median FRIs that are much longer than the dating imprecision factor.

For fire history studies making use of snags and stumps, or have for research objectives to establish relationships with annual weather, the use of cross-dating is required. However, in the context of applied forest and fire management of landscapes covering a wide range of elevation and climate gradients, cross-dating can be a costly endeavour (Madany et al. 1982) and become a deterrent to conduct field base fire history studies. For our study area, a separate dendrochronology study conducted in parallel would have been necessary to cross-date our samples. Personal observations from several field sampling seasons showed the forest growing season in the Foothills starts in late May – early June, whereas Subalpine trees do not start growing until late June – early July. In the upper reaches of the Subalpine on north facing slopes, where snow cover lingers, tree growth may not initiate until well into July and can easily miss spring and early summer drought markers that maybe present at lower elevation. The creation of a number of master chronologies would have been needed to cover the range of climatic conditions and growing seasons. Of additional concern was the choice of trees along fire boundaries associated with our fire history sampling design. Such trees are lesser candidates for creating master chronologies due to atypical ring patterns resulting from nearby tree mortality caused by stand-replacing burning (Speer 2010). These are all caveat factors that must be weighed in the scale of affordability and needs given the initial research objective and size of the study area.

2.5.4 Inclusion of censored observations

Results of fire history studies are often reported in the literature as mean fire return intervals (MFRI). It was found that such values can be inaccurate, notably when censored observations (time-since-fire data) are excluded from the data set. The discrepancy in MFRI between the inclusion and exclusion of stands that have not burned yet widens for regions regulated by infrequent stand replacing fires. For the rugged Subalpine (SE), the difference in MFRI amounted to 21 years, which could impact forest and fire management planning. These results corroborate those by Moritz et al. (2009) and echo concerns raised by Polakow and Dunne (1999) with regards to excluding censored observations in survival analysis.

2.6 CONCLUSION

The targeted paired-plot fire history sampling method was found to be an effective way to identify past fires and calculate fire intervals when fire evidence is not abundant. We determined the level of precision in fire dating is well below the shortest median FRI of 26 yr that was detected, or age-class grouping used for forest and fire management planning. Thus the proposed methods appear to be a practical strategy to interpret past fire frequencies for landscapes regulated by large fires with significant tree mortality. While the case study objective was to learn about spatial variation of FRI at the landscape scale confronted with poor land accessibility, the proposed fire history sampling strategy and fire frequency analysis can be applied to study areas of any magnitude. Most of our methods are also transferrable to many ecosystems of the American and Euro-Asian continents regulated by mixed- and full-severity fires occurring at intervals greater than 20 years on average, notably those associated with high elevation mountainous environments.

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CHAPTER III – MANUSCRIPT 2

Spatial and temporal variations of fire regimes in the Canadian Rocky Mountains and Foothills of southern Alberta

3.1 ABSTRACT

The spatial variability of historical fire return intervals is evaluated using a fire frequency analysis based on fire history data from the Subalpine (SUB), Montane (MT) and Upper Foothills (UF) natural subregions. The level of departure from historical conditions following decades of fire exclusion policy since 1948 is measured using median fire return intervals (MdFRI). Fire severity, seasonality and cause are also documented by natural subregion. Pre-1948 MdFRI ranged between 65 and 85 years in SUB, between 26 and 35 years in MT, and was 39 years in UF. The fire exclusion era resulted in a critical departure of 197% to 223% in MT (MdFRI: 84 to 104 yr). The departure in UF was 170% (MdFRI = 104), while regions of continuous fuels in SUB were departed by 129% (MdFRI = 149). The rugged Elbow region of SUB is within its historical range of variation with a departure of 42% (MdFRI = 121). More mixed-severity burning took place in MT and UF. SUB and MT are in a lightning shadow pointing to a predominance of anthropogenic burning. A summer fire season prevails in SUB, but occurs from spring to fall elsewhere. These findings will assist in developing fire and forest management policy and activities in the future.

3.2 INTRODUCTION

Like many fire-adapted ecosystems of western North America, decades of fire exclusion policy in the Rocky Mountains and Foothills of southern Alberta, Canada is raising concern with fire ecologists and managers over the loss of ecological integrity (Noss 2000; Allen *et al.* 2002; Keane *et al.* 2002; Brown *et al.* 2004) and forest health (Covington *et al.* 1997). The region examined in this study contains an extensive timber extraction license agreement, is popular for outdoor recreational activities and, includes the headwaters of many watersheds. As such, forest and fire management plans and activities can raise concerns with local land users and residents that require them to have a good understanding of the fire regime. By definition, a fire regime includes characteristics such as cause (ratio of lightning vs anthropogenic fires), frequency (e.g. fire return interval), size, seasonality (timing of burning during the fire season sometimes classified as spring, summer or fall), prevailing type of fires (ground, surface, intermittent or complete stand replacement) and, severity (low, moderate or high as reflected by the amount of tree mortality) (Romme 1980; Merrill and Alexander 1987).

Murphy (1985) reported that during the early 1900s fire prevention campaigns were effective but fire detection and fire suppression response times for remote fires often took days to occur in mountain areas. The Great Depression (1930-38) prevented the Government of Alberta to adequately fund firefighting and subsequently, World War II created a shortage of man power to fight fires. In 1948 the Eastern Rockies Forest Conservation Board, a federal-provincial agreement, was established to protect the forested headwaters of the southern Canadian Rockies Front Ranges from fire. This was a pivotal point in the level of resources and capital expenditure forested watersheds of southern Alberta received. In 1950, the construction of a forestry trunk road covering over 300 km between Coleman and Nordegg was initiated, and the networks of fire roads, trails, ranger stations, look-out and communication towers were expanded; all of which increased the rapidity in fire detection and suppression. During the 24 fire seasons of the Board's existence (1949 – 1972) the average annual burn rate dropped to 0.007%. Other statistics published in 1953 showed this region benefited greatly from the additional firefighting resources resulting in an average annual area burned of 1.2 km^2 per 2590 km^2 (0.05% rate). This figure contrasts sharply with the lower funded Northern Forest District suppression program that averaged 28.3 km^2 per 2590 km^2 (1.1% rate).

Up to the present time, fire management policy in Alberta has called for full suppression of all unplanned fires. The re-introduction of fire through prescribed burning is being conducted on a limited basis in localized areas to enhance ungulate habitat and to create landscape level fuel treatments to limit fire spread into high resource use and values areas (e.g Alberta FireSmart program - Alberta 2016a).

For fire-adapted forest ecosystems to be managed sustainably in the future there is a necessity to document and quantify past fire regime conditions (Moore *et al.* 1999; Swetnam *et al.* 1999; Bergeron *et al.* 2002; Harvey *et al.* 2002; Keely *et al.* 2009*;* Long 2009). Both fire return intervals (FRIs) and severity have been commonly used to assess departure (i.e. divergence) from historical conditions (Fulé *et al.* 1997; Morgan *et al.* 2001) following decades of fire exclusion.

The main goal of this study was to assess the spatial variation of pre-1948 FRIs between three natural subregions of southern Alberta and to determine if FRIs from the contemporary era of successful fire exclusion (1948 - 2014) are still within the historic range of variation. The two null hypotheses tested are historical FRI distributions were homogenous across the entire landscape and fire exclusion policies have not modified the median fire return intervals. To assist with our understanding of past and present fire regime conditions, fire cause, severity and seasonality were also characterized.

3.3 METHODS

3.3.1 Study area

The study area is located west of Calgary, Alberta in the front ranges and foothills of the Rocky Mountains. The bounding coordinates are 50° 08' 15" N - 115° 23' 37" W and 51° 52' 20" N - 114° 27' 20" W and cover an area of 667 673 ha (Fig. 1). The region is composed of three natural subregions (Natural Regions Committee 2006): Subalpine, Montane and Upper Foothills. The Subalpine is a rugged landscape with valley headwaters that are secluded by rocky ridges (Fig. 2*a*). It contains the highest elevations (up to 3359 m including the non-vegetated Alpine subregion) with a tree line ranging between 1970 m and 2100 m. Warm aspects and valley bottoms are covered with lodgepole pine (*Pinus contorta* Loudon), whereas Engelmann spruce (*Picea engelmannii* Parry *ex* Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) prevail on cooler aspects and higher elevation. The Montane lies directly below the Subalpine, has elevation ranging between 1288 m and 1994 m and its dominant forest cover is lodgepole pine with scattered pockets of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and trembling aspen (*Populus tremuloides* Michx.). The Foothills subregion (Fig. 2*b*) extends furthest east and is composed of rolling hills ranging from 1262 m to 2869 m in elevation, which are covered with a continuous canopy of lodgepole pine with small patches of mixedwoods consisting of aspen

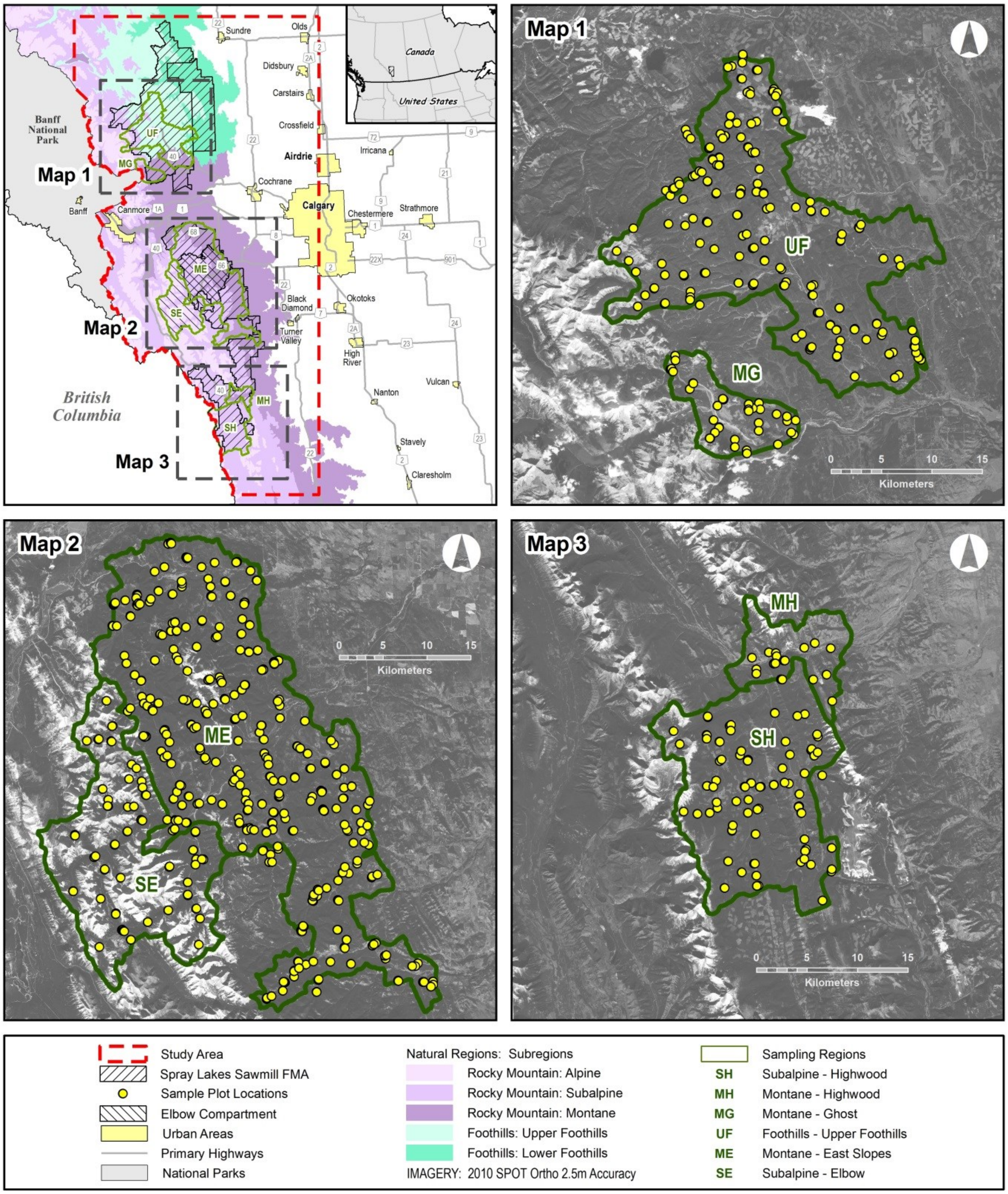

Figure 3-1 *Location of fire regime study area (dotted line) in Alberta, Canada, including the delineation of six fire history sampling regions. Distribution of sample plots is presented in other map insets.*

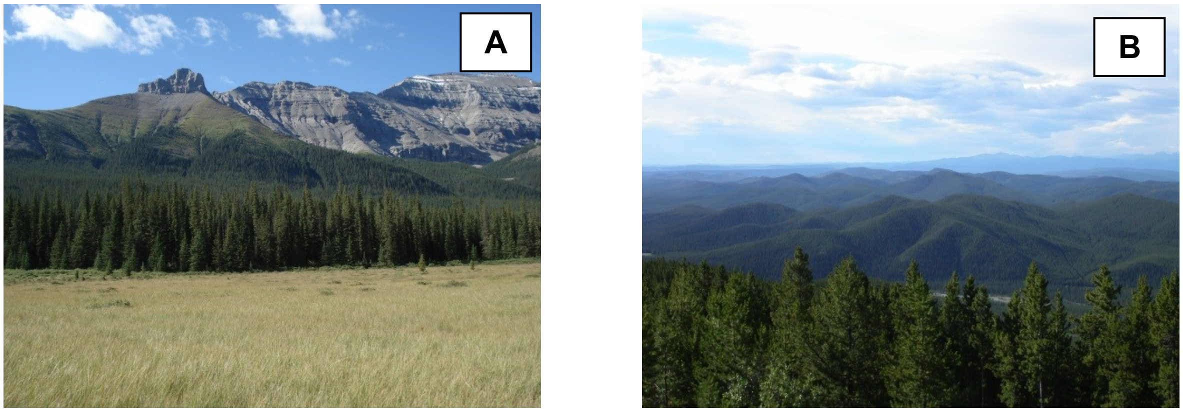

Figure 3-2 *A) Rugged subalpine landscape parted by rocky ridges. B) Rolling foothills landscape of extensive, dense forest cover.*

and white spruce (*Picea glauca* (Moench) Voss). The two most distinctive features among the three natural subregions are their difference in elevation range and landscape scale fuel continuity. The most rugged region of the Subalpine has narrow valleys bound by rocky ridges contributing to a large portion of the landscape being non-vegetated (45 to 63%). In contrast, valleys of the Montane and Foothills are broader and currently have a nearly continuous mature forest cover, which can facilitate crown fire spread producing large forest fires.

The fire environment within this extensive study area is highly variable due to a range of landforms and forest species coupled with meso-climate conditions driven by a strong elevation gradient, which exerts different precipitation and snow accumulation regimes, as well as a temperature gradient with warmer temperatures found at lower elevations. Canadian climate normals between 1981 and 2010 (Environment Canada 2016) for the Subalpine Kananaskis weather station (1391 m, 15 km west of study area) indicate a short snow free period (i.e. short fire season) focused around the months of June, July and August with daily temperature maximums averaging 20.7°C and an annual daily average temperature of 3.6°C. The total average precipitation is 405 mm with 29% of precipitation falling in June, and a total snowfall averaging 257 cm. At the interface of Prairie and Montane natural subregions (High River weather station,1219 m, 45 km east of study area), the annual daily average temperature increases to 4.2°C with average yearly precipitation of 364 mm, 110 mm of which falling in June alone. The average yearly snowfall is 175 cm and rarely occurs during the three summer months. The relative humidity in southern Alberta is low year round and can frequently be lower than 30% on sunny days.

3.3.2 Fire frequency analysis

To provide statistics involving time prediction to the next fire event, a fire frequency analysis is often carried out by fitting either FRI or time-since-fire (TSF) data to a survival model such as the Weibull (Johnson and Gutsell 1994, Grissino-Mayer 1999). Because our landscape is regulated by high- to mixed-severity stand replacing fires, fire scar evidence is not abundant and fire dating must resort to a combination of elements such as fire scars, growth release and pith origin of even-aged cohorts within a stand (Sibold *et al.* 2006). For the fire frequency (i.e. survival) analysis, we used a combination of point data FRIs and TSF observations obtained from sampling sites of a broad scale fire history study (see Chapter II). A total of 814 sampling sites and 3123 tree cross-sections containing 583 fire scars were collected across six sampling units: three in the Montane (MG, MH, ME), two in the Subalpine (SH, SE) and one in the Upper Foothills (UF) (Fig. 1). Fire dates identified at each sampling site produced a total of 905 complete FRIs and 296 TSF intervals for the pre-1948 period of data analysis, and a total of 20 FRIs and 899 TSF intervals for the period ranging between 1948 and 2014. The length of the pre-1948 period is variable between sampling units and is based on the oldest stand sampled, which varied from 1375 to 1770 (see Chapter II). While a complete FRI is the time between two documented fire events, TSF represents the time between the origin of a stand and 1948 or 2014. For this study, TSF records include even-aged fire initiated stands as well as uneven-aged old growth stands. A TSF observation is thus an open-end interval where the time of occurrence of the next fire event is unknown and is treated as a right-censored observation in the survival analysis.

FRI and TSF data were aggregated by sampling unit and fitted to the two-parameter Weibull model (Grissino-Mayer 1999), but failed the goodness-of-fit test. Using the weighted three-parameter Weibull (Cousineau 2009*a, b*) to improve fit also proved unsuccessful. We opted to use the Kaplan-Meier (K-M) product-limit estimator (Kaplan and Meier 1958; Meier *et al.* 2004) to model FRI distributions. The K-M is a non-parametric, unbiased curve fitting approach that does not make any assumption about the rate of survival through time. It is frequently used in survival or failure rate analysis in the field of epidemiology, engineering, and ecological studies that deal with censored data, including fire frequency analysis (Drobyshev *et al.* 2008).

Methods of analysis were done in R (R Development Core Team 2016) using the open-source survival package (version 2.36-10) (Therneau 2016) and followed the approach outlined by Kleinbaum and Klein (2012) and D. Diez (www.openintro.org/stat/surv.php). The median probability fire return interval (MdFRI) and 95% confidence limits were obtained from the K-M survival function, which represent the central tendency of the fire return interval distribution.

Spatial differences in FRI distributions between the sampling units were tested for significance ($\alpha < 0.05$) by running a permutation test and the *survdiff* non-parametric log-rank test from the R survival package on 15 possible pairs of regions. To avoid potential bias from pseudo-replication (Polakow and Dunne 1999), as a result of re-sampling the same large size fires, a bootstrap resampling approach (Moritz 2003) was implemented (50% of FRI data with replacement) to create 1000 bootmedian records from which another permutation test was applied to the 15 paired regions.

A similar assessment of change in FRI distribution between the two temporal periods was not possible because over 85% of intervals were right-censored in the post-1948 period, which makes the Kaplan-Meir survival analysis inaccurate. Instead, post-1948 MdFRI were directly compared to the K-M probability median 95% confidence limits of the pre-1948 period.

3.3.3 Fire severity

A coarse-scale approach of appraising historical fire severity at the watershed level (Hardy *et al.* 2001; Hann 2004; Schmidt *et al.* 2002) was used for 121 watersheds. This process was initially used to identify sampling units (see Chapter II). High severity fires represented stand level tree mortality greater than 75%, whereas fires spreading as intermittent crown fires and resulting in a greater abundance of surviving patches of trees and individuals were characterized as mixed-severity burning. Overlapping fires of mixed- and high-severities can in turn create complex landscapes of intricate forest patch mosaic (Marcoux *et al.* 2015).

Black and white aerial photography at a scale of 1:40,000, flown across all of Canada between 1948 and 1952, was used to detect the type of fire occurrence and severity that prevailed in the early 1900s (Johnson and Gutsell 1994). A benefit of this coverage is the proximity in years during which these photos were taken as the amount of burning, fire severity and complexities of the fire mosaic can be compared across a similar timeline between regions. For each watershed, the forest-patch complexity score, resulting from fire, was ranked on a scale from 1 to 5 (from least to most complexed) and was stored spatially in a Geographic Information

System (Idrisi Selva Edition). Examples of low vegetation complexity are watersheds covered with lodgepole pine forests of homogenous appearance resulting from a large, high-severity stand replacing fire with few island remnants, or a watershed largely covered with old-growth forest from which past fire evidence is no longer discernible. In contrast, a highly complex forest-age mosaic could result from mixed-severity fires or a greater number of fires overlapping each other.

The forest-age mosaic complexity was used as a proxy for fire severity and as a supportive line of evidence to the fire frequency analysis (Morgan *et al.* 1994; Morgan *et al.* 2001). Our understanding of past fire regimes was also supplemented with photographs taken by land irrigation surveyors (www.mountainlegacy.ca) from the turn of the 19th century, which provided a deeper insight of the vegetation composition, forest structure and fire mosaic complexity of the mid- to late-1800s (Rhemtulla *et al.* 2002; Watt-Gremm 2007). The intent of this process is to provide a holistic view of landscape scale burning patterns and the coarseness of this approach is not designed for fine scale ecological fire restoration.

Past fire severity conditions was also verified by quantifying the number of fires detected at each sampling site. Sites with evidence of multiple fires are an outcome of mixed-severity burning (Marcoux *et al.* 2015), while sites with only one fire-initiated age cohort is the result of a high severity fire resulting in complete tree mortality. This information was compared with the watershed forest-age mosaic complexity assessment to determine the reliability of aerial photo screening in capturing landscape scale fire regime variations.

3.3.4 Fire seasonality

The exact period of burning of historical fires could not be determined, but two proxies were used to assist with our understanding of periodical fire distribution. The first indicator was the positioning of fire scarring tissues within the annual growth ring as described by Speer (2010). This was a relative measure of seasonal timing as there is no published data on rate of tree growth over the topographic gradient this region covers. As elevation and climate conditions vary widely between natural subregions, coupled with typical annual weather variations, the positioning of scarred tissues could mean a difference of several weeks in the timing of burning. Based on personal field observations the early earlywood (EEW) period for trees growing in the Montane and Upper Foothills would likely correspond to the middle of June, whereas for the higher elevations of the Subalpine, the EEW tends to coincide with the early to middle part of July. Due to the uncertainty in timing, we restricted our evaluation to differentiating between fires occurring during the dormant period or not. Which means early spring or fall burning when the grass is cured and outside of the peak lightning activity.

The second indicator consisted of using the modern-day fire occurrence data set (1961 – 2003) to establish the monthly distribution of fire ignitions. Unfortunately the seasonality of area burned by wildfire could not be estimated in a reliable manner as 83% of fires were suppressed at less than 1 ha and only six fires grew larger than 200 ha between 1961 and 2003 (Rogeau 2004).

3.3.5 Fire cause

This aspect of the fire regime was documented quantitatively using a previous analysis (Rogeau 2004) that utilized the provincial fire occurrence dataset (1961 – 2003, Alberta 2016b).

Lightning strikes recorded between 1990 and 2003 were used to estimate the yearly average probability density of strikes on a 5 km x 5 km grid. As there is a documented lightning strike shadow over most of the study area (Wierzchowski *et al.* 2002), lightning-fires were also recorded on the same probability density grid to verify the effect of the shadow on number of lightning fire starts.

Additional insights on historical fire cause came from a survey of turn of the 19th century forestry reports, accounts from early explorers, fur traders and surveyors' journals, historical timber surveys, as well as archeological reports.

3.4 RESULTS

3.4.1 Fire frequency analysis

FRI distributions were all positively skewed (see Chapter II) with pre-1948 K-M probability MdFRI ranging from 26 to 35 yr in the Montane, a MdFRI of 39 yr in the single Upper Foothills unit sampled, and ranging between 65 and 85 yr in the Subalpine (Table 1). K-M curves (Fig. 3) show variations in probability of survivorship overtime among the sampled units. The pairwise comparison of K-M survival curves using the *survdiff* logrank test with rho = 0 and rho = 1 ($\alpha \leq 0.05$), found MG and MH ($P = 0.5$) and, ME and UF ($P = 0.35$) to be similar to each other, while the permutation test done on bootmedian data found all regions to be statistically different from each other ($df = 999$, $P \leq 0.01$). However, the same permutation test executed on observed data found all Montane units to be comparable to each other (MH-ME: $P \geq 0.23$; MG-ME: $P \geq 0.23$; MH-MG: $P \geq 0.71$), but not with the Upper Foothills (UF).

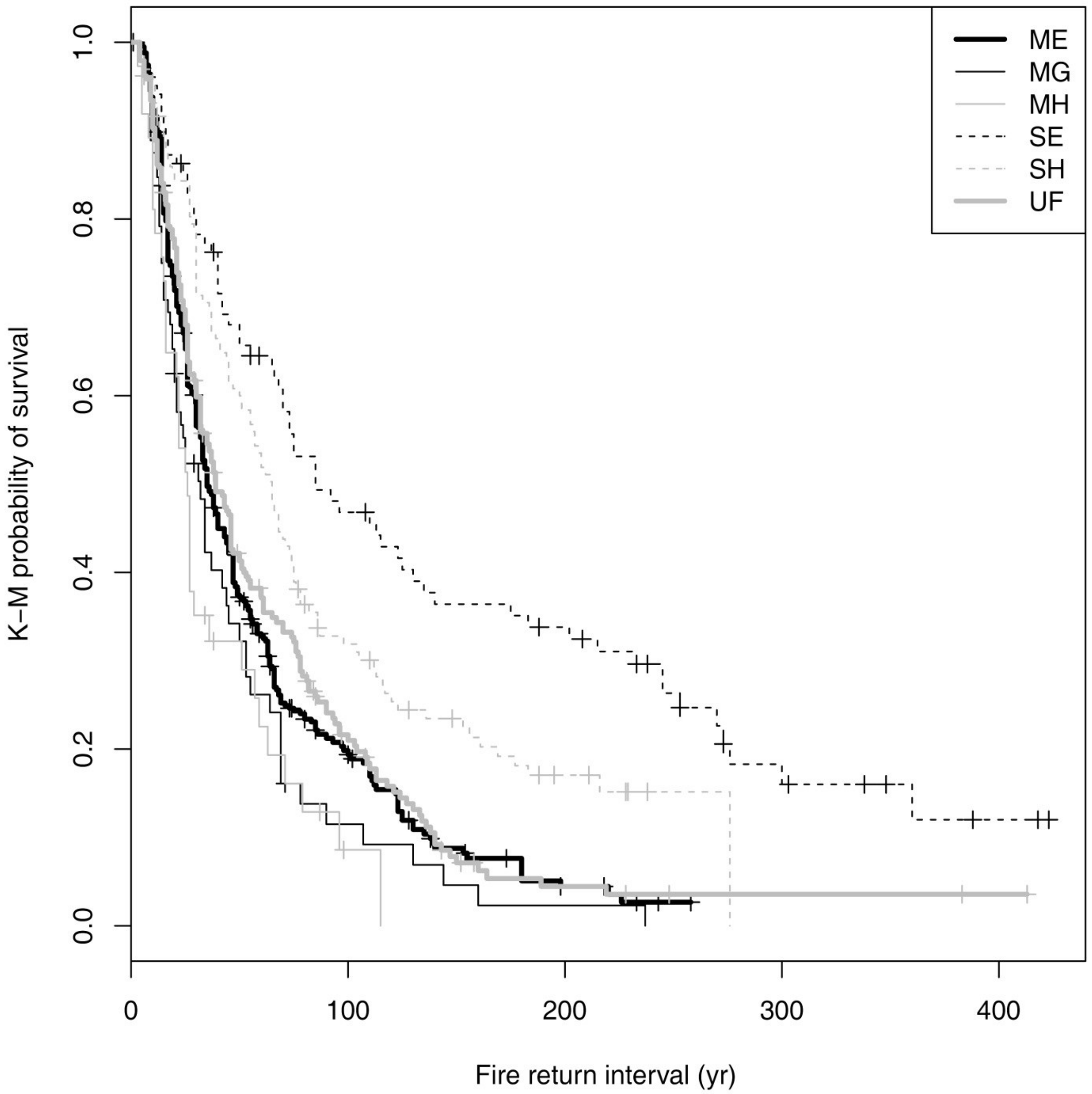

Figure 3-3 *Kaplan-Meier fire-frequency distributions of six sampling units: ME: Montane-East slopes, MG: Montane-Ghost, MH: Montane-Highwood, SE: Subalpine-Elbow, SH: Subalpine-Highwood and UF: Upper Foothills. The survival function represents the probability of survival from fire.*

Contrasting fire frequencies between the Montane and Subalpine are highlighted by outlining estimated fire perimeters using fire evidence found at sampling sites from the adjacent SE and ME sampling units (Fig. 4).

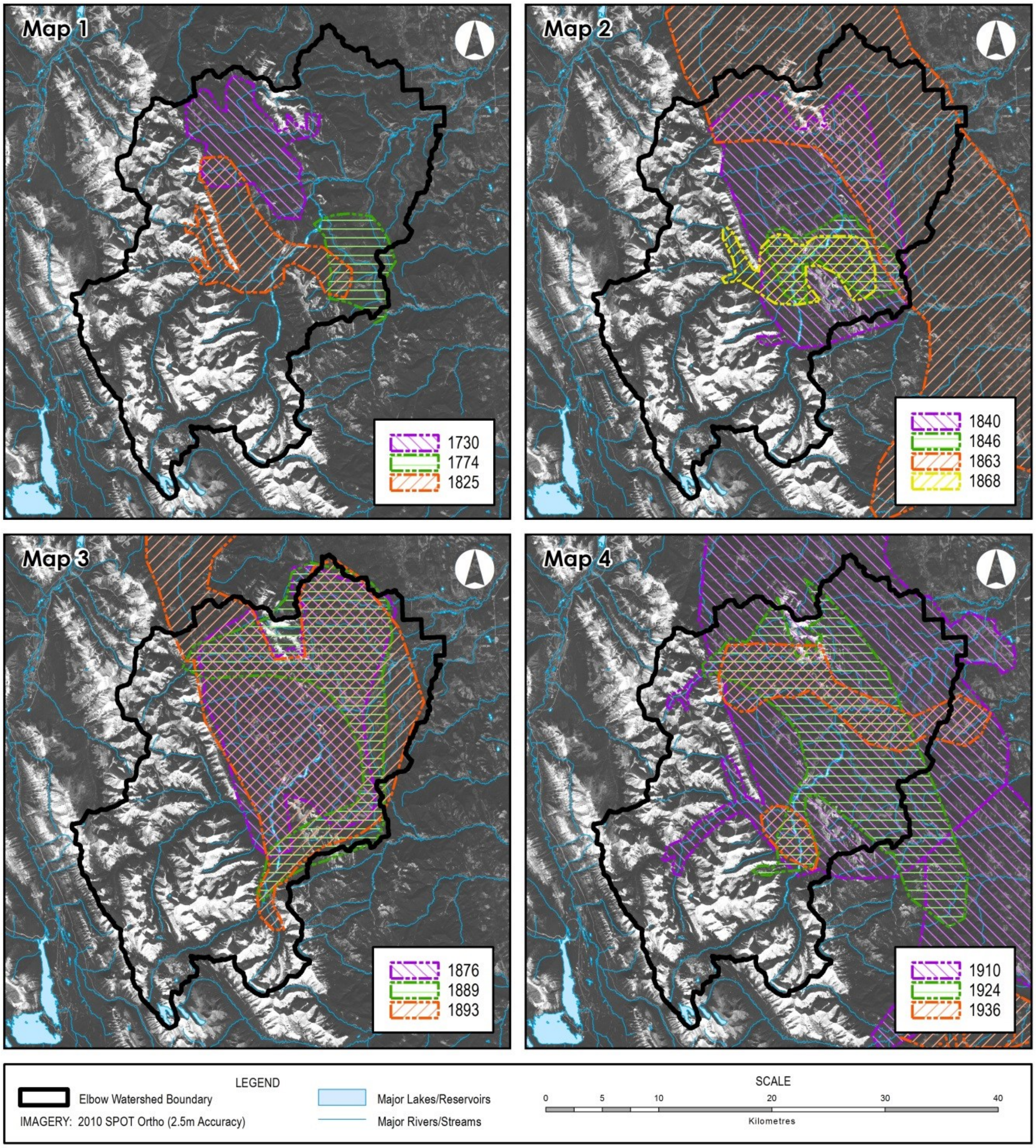

Figure 3-4 *Fire spread dynamics at the interface between the rolling Foothills/Montane landscape and a rugged Subalpine landscape parted by rocky ridges. Example of the Elbow watershed (SE and ME fire history data).*

The temporal change in MdFRI and mean fire return interval (MFRI) revealed an important level of departure between the pre- and post-1948 period (Table 1). With the exception of the most rugged region of the Subalpine (SE), contemporary median FRIs fall markedly outside of the historical range of variation obtained from bootmedian 95% confidence limits (Fig. 5).

Table 3-1 Kaplan-Meir probability median (MdFRI) and mean (MFRI) fire return intervals (years) for two temporal periods: pre- and post-1948. Intervals were calculated from a combination of complete fire return intervals and time-since-fire intervals (censored observations). The percent departure (change) from historical conditions was calculated using MdFRI and MFRI data.

	MdFRI		**MFRI**		**MdFRI**	**MFRI**
Region	**pre-1948**	**post-1948**	**pre-1948**	**post-1948**	**% dep.**	**% dep.**
MG[1]	32	95	37.58	93.52	197	149
MH[1]	26	84	31.43	85.13	223	171
ME[1]	35	104	42.85	130.10	197	204
UF[2]	39	104	50.03	118.15	167	136
SH[3]	65	148.5	76.73	165.00	129	115
SE[3]	85	121	111.30	175.87	42	58

[1] Montane, [2] Upper Foothills, [3] Subalpine

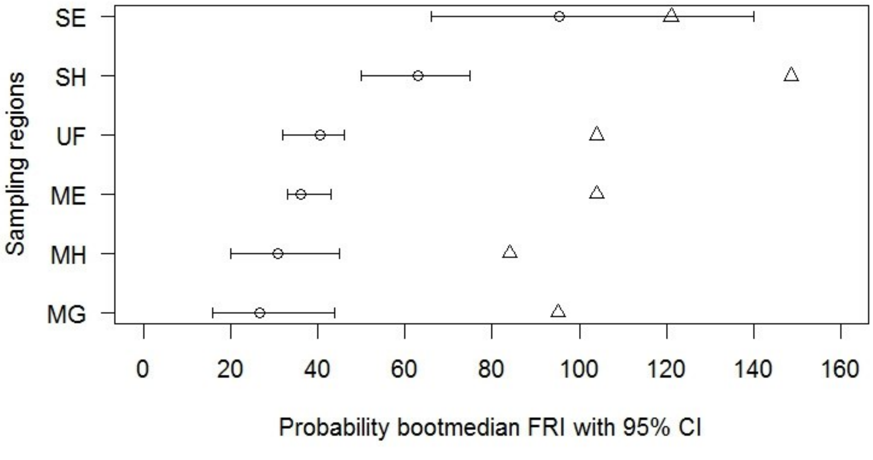

Figure 3-5 *Post-1948 fire return interval (FRI) medians (triangles) show the level of departure from historical conditions portrayed by pre-1948 FRI bootmedians (circles) and their 95% confidence limits (bars).*

3.4.2 Other fire regime components

The proportion of sampling sites with single, two to three, or four fires and more, appear to correlate well with the intricacy level of forest age mosaic detected using aerial photography (Table 2). Sampling units with a greater proportion of moderate, high to very high patch complexity can be characterized as having been regulated by a preponderance of mixed-severity fire regime conditions before c.1950. Heritage photographs taken in the Montane during the late 1800s and early 1900s support the assumption of a mosaic of younger aged forests (Fig. 6).

Positions of fire scarring tissue within an annual growth ring point to differences in the season of burning notably between the Subalpine and Montane. No observations were recorded for the Upper Foothills (Table 3).

The monthly distribution of fire ignitions by cause and area burned during the contemporary fire regime (data period: 1961 – 2003) (Table 4) showed 81% of lightning fires occur between July and August, as expected. In contrast, anthropogenic fires can occur year round with the bulk (68%) of ignitions starting between April and August. Not enough records existed within the study area for partitioning the data by natural subregion and month. Fire

Table 3-2 Evaluation of historical fire intensity based on the number of fires identified at sampling sites, and based on forest patch complexity of the landscape.

Subregion	**Subalpine**			**Montane**		**Upper Foothills**
Sampled region	**SH**	**SE**	**MH**	**MG**	**ME**	**UF**
1 fire/site	32%	49%	15%	37%	38%	32%
2 - 3 fires/site	58%	37%	54%	47%	45%	52%
4+ fires/site	10%	14%	31%	16%	17%	16%
Max. number of fires/site	8	6	6	9	8	7
forest patch complexity	62% mod., 22% low	64% low, 36% mod.	100% very high	100% high	51% mod., 45% high	57% high, 23% mod., 20% v. high

occurrence records determined an annual average of 42 fire ignitions and an average area burned of 385 ha. By excluding one large fall burn (2001 Dog Rib Fire), which occurred outside of the regular fire-fighting season, the average area burned drops to a low 168 ha/yr. Most of the active burning took place between August and September, as well as in February due to Chinook wind conditions in the Foothills.

Table 3-3 Fire scar position in the annual growth ring and relative correlation with period of the year associated with the two most dominant positions. EEW: early earlywood, MEW: middle earlywood, LEW: late earlywood, LW: latewood, D: dormant period.

Subregion	**Subalpine**		**Montane**			**Upper Foothills**
Sampled region	**SH**	**SE**	**MH**	**MG**	**ME**	**UF**
fire scar position	35% EEW, 35% EW, 19% LEW, 11% D	29% D, 29% EEW, 14% EW, 14% MEW, 14% LW	33% EEW, 33% LW, 23% MEW, 11% D	not recorded	39% D, 33% EEW, 16% LEW, 7 % LW, 5% MEW	not recorded
timing of fire occurrence	Jul.	Jul. - Aug. & Sep.	Jun. & Aug.		May-Jun. & Sep.	

Lightning- and human-caused fires are not randomly distributed on this landscape. The effect of the lightning strike shadow is greatest over the Subalpine and Montane, and subsides further east into the rolling Foothills where the lightning-strike density triples, and number of lightning-caused fires quadruples (Table 5). The overlapping pattern of lightning fires and lightning strikes appears to indicate there is not a direct positive relationship of strikes to fires (Fig. 7).

Table 3-4 Monthly distribution of fire ignition by cause, and area burned, for the entire study area Source: Alberta Government fire occurrence data 1961-2003 (Rogeau 2004).

Month	**Lightning %**	**Human %**	**Area burned ha**
January	0.00	2.16	101.95
February	0.00	1.87	2,175.14
March	0.22	6.27	442.26
April	0.22	12.01	515.98
May	4.53	17.39	542.29
June	10.78	12.54	127.09
July	42.89	13.43	352.04
August	38.15	12.91	2,467.54
September	3.23	9.25	9,241.86
October	0.00	6.94	266.44
November	0.00	3.58	147.01
December	0.00	1.64	194.74
Total area burned in 43 years:			16,574.34

Table 3-5 Percent ratio of lightning (ltg) and anthropogenic (ant) fires normalized for 1000 km^2, average number of lightning (ltg) and anthropogenic (ant) fire starts for the entire study area and normalized for 100 km^2 area. Average number of total and positive lightning strikes per year per 100 km^2. Source: Alberta Government fire occurrence data 1961-2003, lightning strike data 1990-2003 (Rogeau 2004).

	Subalpine	**Montane**	**Foothills**
ratio lightning/ human fires	25 / 75	10 / 90	58 / 42
N avg ltg fires/yr	3	2	5
N avg ltg fires/yr/100km^2	0.05	0.06	0.2
N avg ant fires/yr	5	19	4
N avg ant fires/yr/100km^2	0.08	0.52	0.16
avg total lgt strikes/year per 100km^2	54	101	167
avg positive lgt strikes/year per 100km^2	6	8	12

Figure 3-6 *Above: example of historical Montane landscape from 1890. Photograph of the Bow Valley taken by surveyor James J. McArthur (Mount Yamnuska in the background). Below: example of Foothills landscape (Jumpingpound watershed) from 1897, photographed by surveyor Arthur O. Wheeler. (source: http://mountainlegacy.ca/)*

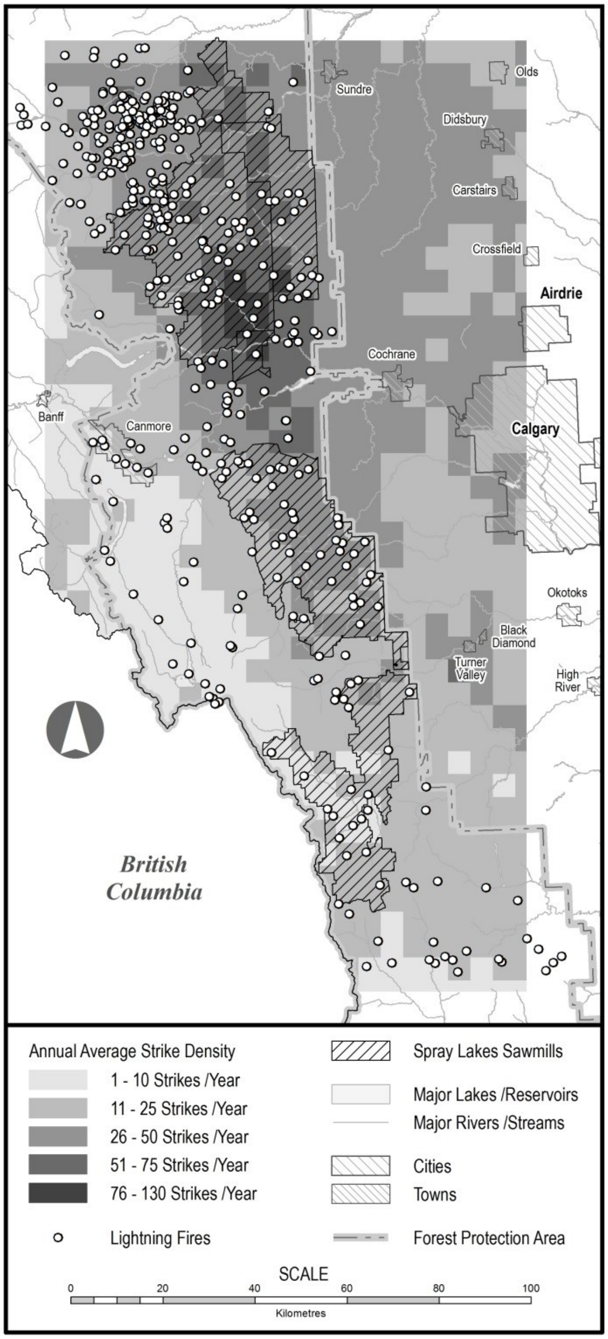

Figure 3-7 *Distribution of lightning-caused fires (1961 - 2003) on to a lightning strike density map plotted over 5 km x 5 km grid cells.*

3.5 DISCUSSION

3.5.1 Spatial variation in fire frequencies

We rejected our null hypothesis and concluded historical FRIs and the overall fire regime vary spatially. Similar to the work by Rollins *et al.* (2002), we observed a strong correlation between the fire environment (Countryman 1972, Pyne *et al*. 1996) and the elements of terrain, fuel and weather that define a natural subregion. Fire frequency distributions and probability median FRI statistics associated with each subregion were found to be statistically different during the pre-1948 period of data analysis. While there can still be spatial differences in the mean or median probability FRI within a natural subregion, as detected by our sampling units, broadly speaking each subregion has a distinct fire regime notably when other elements such as severity, cause and seasonality are considered. However, conflicting results in detecting significance between the probability median FRIs of the Montane and Upper Foothills indicated it is possible at times for these two subregions to have similar fire frequencies. Both the Montane and Upper Foothills are largely composed of lodgepole pine forests and exhibit a continuous forest cover that can lead to large size fires. The similarity in the results could be explained in part by a recent re-categorization of natural subregions by the Government of Alberta. Prior to 2005, we noted the sampling unit Montane-East (ME) used to be labelled Lower Foothills. Like the Upper Foothills sampling unit (UF), ME is composed of rolling hills, which is unlike the other two Montane sampling units (MG, MH) that form valley bottoms below subalpine mountain conditions.

Results from the two Subalpine sampling units were both significantly different from the Montane and Upper Foothills due to their higher elevations which lead to cooler temperatures and a longer period of snow coverage. Marked differences were also noted between the Subalpine-Highwood (SH) and Subalpine-Elbow (SE). Contiguous Subalpine watersheds without extensive rocky barriers produce good fuel connectivity for fire spread (Turner and Romme 1994) and can also be connected with Montane forests. Such is the case of SH and this combination of terrain type and fuel connectivity explains the shorter probability median FRI of 65 yr. In contrast, SE has adjacent watersheds separated by important rocky ridge barriers segregating the forest cover. These conditions produce smaller size fires and vastly different fire histories between watersheds. Coupled with even cooler temperatures, from a mean elevation 242 m higher than SH, the probability median FRI of 85 yr calculated for SE was the longest on this landscape.

A fire regime interaction was anticipated between the Montane, Subalpine and Upper Foothills as these three natural subregions share ecotonal boundaries. However, it was unexpected to observe a reverse edge effect between the rolling foothills landscape composed of continuous forest cover and the rugged (segregated fuels) subalpine landscape (Fig. 4). It appears foothills fires tend to move against the flow of prevailing westerly winds and spread (sometimes deeply) in to the rugged mountains. The high fire frequency recorded in the Montane, coupled with this reverse fire spread pattern, greatly influence FRIs at the mouth of Subalpine watersheds. While fires burning in the Montane or the Upper Foothills can affect the burning rate in the Subalpine, the opposite condition appears to be rare as we were unable to detect a west to east spread pattern from a subalpine valley into the open rolling foothills. This east to west fire spread on the edge of the Rocky Mountain front ranges can be explained in part by day time valley and upslope winds that draw flames from the head or flank of an active fire when it coincides with the mouth of a valley. Another explanation is the breakdown of high pressure upper level ridges with the invading low pressure systems (Johnson and Wowchuk 1993) creating wind from the south-east driving fires into the mountains.

3.5.2 Subalpine fire regime conditions

Fifty percent of sampling sites recorded a single stand replacing fire in SE, indicating full severity burning was frequent in the rugged region of the Subalpine. This is explained by steep slopes that increase the rate of fire spread and terrain complexities creating erratic wind patterns conducive to crown fire behavior (Werth *et al.* 2011). The remainder of stands sampled had evidence of two to three fires implying mixed-severity burning was also historically common, notably for areas in proximity to the Montane.

The late snow melt found at higher elevations limits the tree growing season to Jul. and Aug. (personal field observations). While many fire scars were positioned in the EEW, the late start to the growing season still suggests summer fires. For scars positioned in the dormant period, burning would logically correspond to a fall burning period, likely on warmer aspects, before snow accumulates (Sep. – Oct.). Spring (May) burning on warm facing slopes located at low elevation, and when the grass is cured, is also a possibility. It was noted fire scarring in the EEW and dormant periods for SE were found at the interface with the Montane as a result of burning encroachment from a subregion that experiences an earlier start to the burning season.

The Subalpine is within the lightning strike shadow and is lightning ignition limited. According to provincial fire records from the contemporary era, lightning-caused fires form 25% of the prevailing source of ignition. With the added evidence of summer burning during a short fire season coinciding with the peak period of lightning activity, these observations suggest the role of lightning may still have been important in shaping the fire regime. Any effect of historical anthropogenic burning deep in the mountains, nearing headwaters of watersheds, may have been localized to meadows and warmer aspects.

3.5.3 Montane and Foothills fire regime

Short probability MdFRIs, ranging from 26 to 39 yr, were unexpected in this boreal lodgepole pine ecosystem largely regulated by stand replacing fires. In terms of forest-age mosaic complexity associated with the level of fire severity, there was a predominance of multiple fires at sampling sites. Such evidence included a combination of scars dating different fires and multi-structured stands representing more than one age cohort. The Upper Foothills and a vast area of the Montane showed 16 to 17% of sampling sites detected more than 4 fires to a maximum of 6 to 9 fires. For the Montane-Highwood (MH) region, 31% of sites had more than 4 fires. Approximately half of the sampling sites visited comprised evidence of 2 to 3 fires, but there was still a significant portion of sites (32% for UF, 37-38% for MG and ME) signaling single, high severity stand replacing fires. Only the MH had a low incidence of high-severity fires (15% of sites). It is possible the fire history sampling design, which targeted island remnants and stands appearing to have evidence of multiple fires, may be distorting our perception of the pervasiveness of mixed-severity burning on this landscape. Further analysis focused on mapping and quantifying historical fire severity conditions spatially are recommended.

This combination of fire frequency and severity observed is normally attributed to shrub and grassland (Schmidt *et al.* 2002). Our results show lodgepole pines can be effective adapters of fire through cone serotiny (Lotan 1967, Lotan *et al.* 1985) even at an early age and can supply an abundant new crop of trees. Field observations of cone serotiny on 6 to 10-year old pine trees, as well as open cones as on-going recruitment mechanism (Kashian *et al.* 2005), diverge with findings from Subalpine landscapes regulated by longer fire intervals where abundant cone serotiny is linked with mature trees (Schoennagel *et al.* 2003). Our findings and definition of mixed-severity burning also contrast with that of Amoroso *et al.* (2011) in central Alberta. They identified a small number of mature lodgepole pine stands bearing hundreds of fire scars as a result of low severity burning (likely from localized cultural burning) within a longer regime of stand replacing fires. In spite of a targeted sampling approach, we did not find such stands within our landscape.

A revealing factor from the fire history study (see Chapter II) was the discovery of internal fire scars (Fig. 8) on small diameter trees as young as 4 years old and up to 20 to 30 years of age. Lodgepole pines have a thin bark and do not survive fire well (Lotan *et al.* 1985). Hence, the survival of saplings was the outcome of low fire intensities due to light ground fuels, which in turn were the result of short fire intervals. Supportive lines of evidence of short fire intervals were captured by the moderate to high intricacy of age mosaic complexity from fire identified on the c.1950 aerial photography and Mountain Legacy Project photography from the turn of the 19th century.

The subsiding lightning shadow east of the front ranges and notably over the Upper Foothills, give rise to more strikes and lightning fires across this subregion. However, despite the increase in lightning fire activity, current fire occurrence reports show contemporary anthropogenic ignitions play an influential role (42% of ignitions) on fire frequencies.

Figure 3-8 *Examples of internal fire scars found on lodgepole pines.*

The position of fire scars within an annual tree-ring suggests historical fires occurred more frequently during the early-early-wood or dormant periods of trees. While an exact correlation with the timing of the growing season is not possible, it appears burning often took place outside of the peak lightning season of July and August.

The combination of these factors: relatively short fire intervals, low fire intensity burning, coupled with fire scarring evidence during the cured vegetation period (outside of the lightning season), and further emphasized with tree genetic adaptability to frequent fire occurrence, point to a strong influence of anthropogenic burning in southern Alberta. Traditional territory use in southern Alberta as well as intentional or escaped indigenous burning, have been reported numerously (Coues 1897; Department of the Interior 1904-1942; Spry 1963; Lewis 1977; Francis and Langemann 1993). Some of the popular documented fire uses, as per First Nations interviews from northern Alberta and the northern American Rockies, were to enhance meadows for grazing purposes, to reduce fuels for ease of travels in forested areas and to promote berry crops (Lewis 1977; Barrett and Arno 1982; Lewis and Ferguson 1988). Mountain Legacy photographs appear to support the notion of broader landscape level indigenous burning. The continued effect of anthropogenic burning has been carried through by unquantified careless fire incidence from forest explorers and users during the 1800s and early part of the 1900s, which are part of our tree-ring data set.

According to macrocharcoal paleoecological studies, which can record close proximity fires, the frequent macrocharcoal presence confirmed a steady rate of burning of 46 ± 5 yr for the last 1000 years in a nearby mountain range (Hallett *et al.* 2003). Charcoal accumulation was at its maximum between 9400 and 8400 years BP, but has been constantly present in significant amounts up until present, along with fire related vegetation species (MacDonald 1989). A thick charcoal layer embedded in the sediments of Johnson Lake in the nearby Montane region of Banff National Park was attributed to high fire frequency that denuded the landscape around 6800 BP (Beierle and Smith 1998). Of interest, Schweger and Hickman (1989) concluded the climate has been similar to recent times for the last 5000 years based on vegetation pollen counts. Assuming the effect of the lightning shadow has been in place for thousands of years due to orographic mountain effects on storm tracking patterns, indigenous cultural burning in southern Alberta has likely shaped the vegetation mosaic for hundreds and possibly thousands of years.

3.5.4 Departure from historical conditions

We rejected our null hypothesis and concluded fire exclusion significantly changed the fire regime in the Montane and Foothills, but we accepted the null hypothesis for the rugged Subalpine (SE unit). Post-1948 MdFRIs from all Montane sampling units range from 84 to 104 yr and are over 200% departed from historical FRI 95% confidence limits, followed closely by UF with a 170% departure (104 yr). The Subalpine units show variable departure levels. SH is 128% departed (149 yr) due to its fuel connectivity among watersheds and with the Montane, whereas the rugged SE exhibits a modest departure of 42% (121 yr). Forest conditions for the most rugged portions of the Subalpine are still considered within their historical range of variation.

Using wildfire burn area data between 1961 and 2003 (Rogeau 2004), the contemporary rate of disturbance was estimated at 0.16% for the Upper Foothills, and 0.02% for the Subalpine and Montane subregions. At these rates, the fire cycle or rotation period (i.e. time required to burn an area equivalent to the size of the study area) is projected at 625 yr for the Upper Foothills, and 5000 yr for the Montane or Subalpine subregions. Each passing year without significant area burned creates an annual burn deficit which adds to the existing burn debt and in turn, lengthens the fire cycle.

3.6 CONCLUSIONS

FRI distributions vary spatially across the landscape and show a strong association with natural subregions. As such, landscape scale fire and forest management policy and activities should initially be developed by subregion. The temporal change in fire occurrence during the contemporary period, which amounts to near fire exclusion on the landscape, has produced a continuous, homogenous cover of mature timber across all natural subregions. This shift in stand conditions is likely to produce extensive, high-severity, stand replacing fires (Gallant *et al.* 2003) in the Montane and Upper Foothills, and could create burning conditions resembling those of the Subalpine. The current lack of diversity in the forest mosaic, seral stages and associated biodiversity has the potential to lead to detrimental ecosystem health conditions, reducing overall resilience to large-scale disturbances such as fire, insect infestations or epidemics (Keane *et al.* 2002), as well as changes in the forest composition (Gallant *et al.* 2003). Fire and forest management actions geared toward ecological restoration should be considered in the Montane and Upper Foothills (Moore *et al.* 1999). The study indicate an important anthropogenic influence on the historical fire regime and restoration goals relying on let-burn policies from lightning ignitions alone would not meet restoration goal objectives (Barrett and Arno 1982; Moritz *et al.* 2014) and are becoming too dangerous to consider during the summer months under a warming climate. While the fire cycle is lengthening in the Subalpine, the current fire regime conditions appear to be within the expected range of historical variation and immediate management actions are not required (Sherriff *et al.* 2001; Sibold *et al.* 2006).

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CHAPTER IV – MANUSCRIPT 3

The effect of topography on fire return intervals in the Canadian Rockies with consideration to forest seral stages

4.1 ABSTRACT

The effect of topography on wildfire distribution in the Canadian Rockies has been the subject of debate. We suspect the size of the study area, and the assumption fire return intervals are distributed as a Weibull distribution used in many previous studies may have obscured the real impact of topography on these fire-regulated ecosystems. The objective of this study was to quantify the effects of elevation, aspect, slope and dominant species on probabilities of burning, and to re-evaluate the same effect when the forest is partitioned by seral stages. The study area covered three natural subregions: Subalpine, Montane, and Upper Foothills of in the Rocky Mountains of southern Alberta, Canada. Fire return interval data from 870 fire history sampling sites were stratified by subregion and analyzed with the non-parametric Kaplan-Meier survival model and Cox Proportional Hazards regression model for survival data. The natural subregions were found to have distinct fire distributions with elevation and aspect being the most important variables affecting the probability of burning. The effect of topography was meaningful for immature forests and very strong for overmature forest types, but was negligible for mature seral stages. The outcome of this study is highly relevant to understanding the ecological role of fire in mountain landscapes and where fire-adapted plant communities prevail. The variable impact of topography on fire frequency based on seral stage is pertinent to forest and fire management activities such as ecological restoration needs, protection of old growth forests, or distribution of

harvest blocks that spatially emulate natural disturbances.

4.2 INTRODUCTION

The effect of topography on fire frequency in mountainous terrain is well recognized. Many fire history studies of northern hemisphere forest ecosystems have found south- and west-facing aspects to have shorter fire intervals (Zackrisson 1977; Clark 1989; Everett *et al.* 2000; Gavin *et al.* 2003) due to increased insolation that results in warmer and drier conditions. It has also been reported that fire frequency exhibits a linear relationship tied to the elevation gradient. This association however varies based on the type of ecosystem. In the drier mountain ranges shorter fire intervals are found at valley bottoms (Rollins *et al.* 2002; Gill and Taylor 2009). In contrast, valley bottoms of coastal ranges experience the most humid forest conditions and contain older forests (Hemstrom and Franklin 1982). Other wildfire related studies have researched the effect of convex (drier) versus concave (wetter) terrain (Romme and Knight 1981), slope gradient (Gill and Taylor 2009), and overall roughness index (Guyette *et al.* 2006) on fire return intervals.

In the Canadian Rockies of southern Alberta and the interior wet-belt of British Columbia, some researchers have concluded that neither topography nor spatial partitioning of the landscape affects the fire cycle in a significant manner (Johnson *et al.* 1990, Masters 1990, Johnson and Larsen 1991). The explanation used is that topography becomes irrelevant when large fire events occur under sustained dry conditions associated with blocking ridges of high atmospheric pressure (Johnson and Wowchuck 1993). Instead, these studies attributed observed differences in burn rates to temporal variations associated with glacial advances during the Little Ice Age (Luckman 1986). While there is some value to these arguments, the outcome from these studies goes against findings from other regional fire history analyses by Hawkes (1979, 1980), Tande (1979), Tymstra (1991), Rogeau (1996) and, Rogeau *et al.* (2004) who have all found significant differences in either fire return intervals or fire cycles between aspect, elevation, watershed, valley orientation, or proximity to the Continental Divide. We believe that these discrepancies in the interpretation of historical fire cycles may have been attributed to the type of data utilized and survival analysis model chosen.

Survival analysis is a method of statistical analysis used in various fields of research involving a duration period. It is applied in engineering to determine the failure rate and reliability of mechanical parts, in oncology to determine the effect of treatments on life expectancy, in biology to understand life expectancy of organisms, and other fields where predictor variables are affected by a time scale. In forest fire ecology, survival analysis is used to describe the probability a forest stand will survive a wildfire. The use of a Weibull survival function has been a popular model with fire ecologists due to its flexibility in fitting life data (Johnson and Van Wagner 1985, Johnson and Gutsell 1994, Grissino-Mayer 1999, Veblen *et al.* 2000, Drobyshev *et al.* 2008). However, some studies have had difficulties fitting the Weibull and opted for a temporal partitioning of the data to force fit the model (Masters 1990, Johnson and Larsen 1991, Weir *et al.* 2000, Van Wagner *et al.* 2006). According to McCarthy and others (2001) there is little reason to choose the Weibull from a biological perspective because the Weibull is unsuitable for forests with a flammability rating that increases with age to an asymptotic level, or a delayed increase in flammability. Moritz (2003) characterises the use of the Weibull as simply phenomenological and recently, Reed (2006) suggested abandoning the use of the Weibull to calculate fire cycles and to restrict its application to fire return intervals to avoid interpretation errors. A survival model that is gaining appeal in recent years for analyzing fire history data is the non-parametric Kaplan-Meier estimator (Drobyshev *et al.* 2008, Scoular 2008). Unlike the Weibull, it does not require any assumption about the stability or the changing forest flammability with age. In combination with the use of the hazard function of the Cox Proportional Hazards model (Cox 1972), covariates that influence the probability of survival of forest stands can also be identified (Cyr *et al.* 2007; Senici *et al.* 2010).

The main goal of this study was to document how spatial partitioning of the landscape affects probabilities of burning by forest fires. We chose to interpret the distribution of point fire return interval data using the Kaplan-Meier estimator (Kaplan and Meier 1958) in combination with the Cox Proportional Hazards model to verify the effect of covariates on fire frequency. The research objectives were to first determine if fire return interval distributions were significantly different among subregions, and to subsequently quantify the effect of topographic variables by subregion. In addition, considering that many forest and wildfire management activities are based on seral stages, and that the Kaplan-Meier model does not make any assumption about changing flammability with aging forests, the fire return interval response to topographic variables was re-assessed by seral stage. In light of the results obtained, a secondary aspect of this paper was to discuss how data type, scale, and chosen model of analysis lead to a vastly different outcome than those obtained for similar, adjacent landscapes.

4.3 STUDY AREA

The study area is located at the interface of the Rocky Mountains front ranges and the Foothills of southern Alberta. The bounding coordinates are 50° 08' 15"N - 115° 23' 37"W and 51° 52' 20"N - 114° 27' 20"W and straddle three natural subregions: Upper Foothills, Montane, and Subalpine (Natural Regions Committee 2006). The area covers 667,673 ha and spans over a distance of 190 km between the Little Red Deer River to the north and Sheep River to the south. The area has a variable width of 5 to 60 km. Within this region, six sampling units were identified for fire history data collection (Fig. 4-1).

The Subalpine is a rugged mountain landscape divided by high rocky ridges (Fig. 4-2A). The area weighted mean elevation in the sampled units range from 1970 to 2210 m, while the treeline is found at ≈2000 m. Climate normals between 1981 and 2010 (Environment Canada 2016) from a weather station located approximately 15 km west of the study area and positioned at valley bottom in the Subalpine subregion (Kananaskis station, 1391 m) report an average annual daily temperature of 3.6°C, with a total annual rainfall of 405 mm, and total annual snowfall of 257 cm. It is not unusual to have snow cover from November until late June in the mountains, especially on cooler aspects and higher elevations. The maximum daily summer temperatures range from 18.3°C to 22.1°C for the months of June, July and August. The Montane (Fig. 4-2B,C) is entrenched in the lower elevation valleys of the Subalpine and also borders the east slopes of the front ranges, notably south of the Trans-Canada Highway (Hwy 1). The area weighted mean elevation in the units sampled ranged from 1500 m to 1750 m.

The Upper Foothills (Fig. 4-2D) is composed of rolling hills with a continuous forest cover and is also located on the east slopes of the front ranges, but north of Hwy 1. The Upper

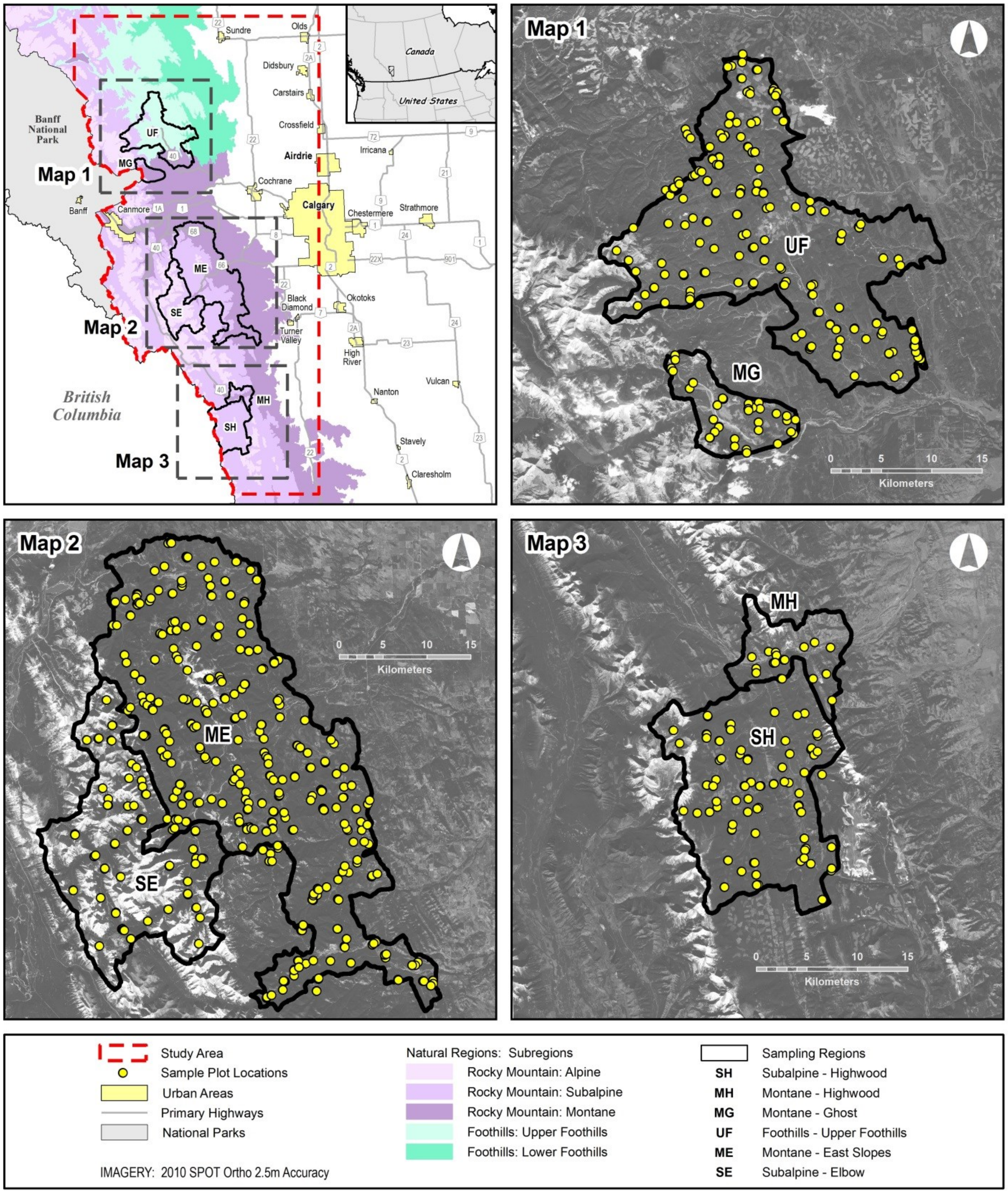

Figure 4-1 *Location of study area and outline of six fire history sampling units overlaid onto the natural subregion map of Alberta. The three map panes show the position of fire history sample plots distributed over six sampling regions.*

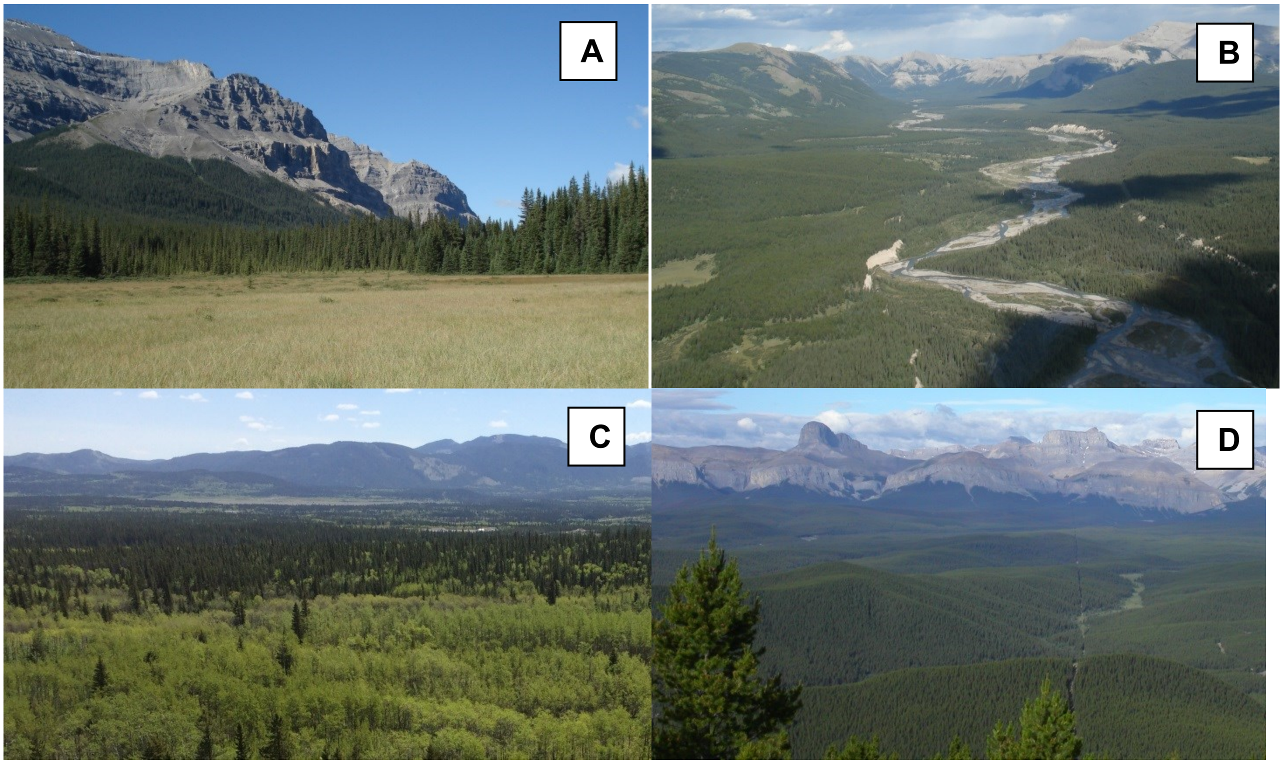

Figure 4-2 *Examples of landscapes within the study area: A) Subalpine natural subregion, B) Montane natural subregion shown as the lower slopes of a subalpine landscape, C) a variation of the Montane near the Foothills, and D) Upper Foothills natural subregion.*

Foothills sampling unit (UF) has an area weighted mean elevation of 1637 m and shares many similar environmental characteristics with the Montane East Slopes sampling unit (ME). The climate for both the Montane and Upper Foothills is transitional between that of the Subalpine and the Prairie. Climate normals for the High River weather station (1219 m), situated east of the study area near the interface with the Montane/Foothills, report an annual daily average temperature of 4.2°C with maximum daily summer temperatures ranging between 19.3°C and 23.1°C. The average annual rainfall is 364 mm, 30% of which falls during the month of June.

The average yearly snowfall of 175 cm is significantly less than in the mountains, but the frost free period remains short and tends to range between the last week of May and last week of August. Across the entire landscape, the diurnal fire weather is influenced spatially by a strong topographic gradient where temperatures vary based on the sun exposed slope and altitude, as well as by protected lee slopes from desiccating winds.

The Montane and Upper Foothills natural subregions along the east slopes of the Rocky Mountains comprise vast extents of fire-adapted lodgepole pine (*Pinus contorta* Loudon) forests (Lotan 1967), which account for 76 to 83% of the forested cover. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and trembling aspen (*Populus tremuloides* Michx.) stands can occasionally be found at valley bottoms and on drier slopes. White spruce (*Picea glauca* (Moench) Voss) stands are numerous, but smaller in size, and tend to be located in mesic type growing conditions such as microtopographic concave features (e.g. draws, depression), higher elevations and cooler aspects. Within the Rocky Mountains Subalpine, 25 to 50% of the forested cover is composed of lodgepole pine that prevails on warmer and well drained sites. In contrast, the cooler aspects and higher elevations host extensive patches of Engelmann spruce (*Picea engelmannii* Parry *ex* Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt). Overall, the prevalence of fire-adapted tree species such as lodgepole pine, Douglas-fir, and trembling aspen (Lotan 1967; Pyne *et al.* 1996; Gom and Rood 1999) throughout the entire landscape is an indication of the important role wildfire plays on these ecosystems.

The pre-industrial fire regime has been documented as high intensity, stand replacing in the rugged Subalpine (Johnson and Larsen 1991, Rogeau *et al. this thesis – Chapters II & III*), and as a mixed severity regime (Rogeau *et al. this thesis – Chapters II & III*) for the remainder of the landscape.

4.4 METHODS

4.4.1 Fire history study

Fire return interval data obtained from an extensive fire history study conducted in six sampling regions positioned in the Montane, Subalpine and Upper Foothills were used for this study (Rogeau *et al. this thesis – Chapter II*). Point location fire intervals (i.e. the time between two fire events at the sampling site) were obtained from 870 targeted fire history sample plots (Fig. 4-1) that represented a variable sampling density of one plot every 100 to 300 ha. A total of 3,446 wide cross-sections sampled from the base (< 20 cm above ground) of live tree specimens were collected and sanded to a smooth reading surface to detect false and missing growth rings. Due to the type of fire regime, the severity of fires obliterates much of the fire evidence over time and it is rare to find tree specimens containing multiple fire scars. A total of 623 fire scars were identified on 522 trees (i.e. 15% of trees samples). Most samples held single scars (450), while 49 trees included double scars, and three or more scars were found on only 23 individuals. Fire dating relied on four sources: archives and fire occurrence reports, fire scars, a sudden and sustained release in the ring growth pattern (Lorimer 1985) supported by evidence of a post-fire cohort, as well as pith origin dates. For even-aged (age spread < 20 yr) lodgepole pine forests, which are a pioneer species following fire, ages were rounded down to the nearest 5-year increment. In uneven-aged stands, typical of older spruce-fir forests, the age of oldest tree sampled was rounded down to the nearest 10-year increment to establish an estimated year of stand origin. The margin of error for dating fire scars was estimated to be 1.07 yr based on known dates of occurrence of 15 fires from the 1900s that burned in southern and central Alberta (Rogeau *unpublished data*). The margin of error is estimated to increase by 2–5 yr as scars depict increasingly older fires (Madany *et al.* 1982). As many forest and wildfire management planning actions are based on seral stages or broad age-classes (20–40 yr classes), such margin of error is inconsequential.

The period of data analysis was truncated at 1948 to cover only the pre-industrialized era. It corresponds to a federal-provincial agreement that established the Eastern Rockies Forest Conservation Board, which resulted in increased protection and management of the Rocky Mountains Forest Reserve (Murphy 1985). Since that time very few fires larger than 200 ha have occurred on this landscape. An interpretation of aerial photography dating from 1948-52 showed that occasional mechanical stand thinning had taken place on the eastern edge of the study area, but that overall the vegetation mosaic had been shaped by forest fires.

Censored observations of fire dates are common in a stand replacing fire regime and must be taken into consideration in the survival analysis and interpretation of results (Moritz *et al.* 2009, Polakow and Dunne 1999). Assuming that all stands were fire initiated, we consider dates from pith origin as an imprecise fire date and not as a left-censored observation (Fig. 4-3 – “a”).

p |----“a”----| X_1 |----“b”----| X_2 |----“c”----1948
p |----------------------“d”----------------------1948

Figure 4-3 *Interpretation of censored and uncensored fire return intervals in a stand replacing fire regime. p: pith origin = fire 1,* X_1 *= fire 2,* X_2 *= fire3, see text on how to interpret a, b, c, d.*

The margin of error from stand origin pith dating is estimated to be less than 10 years based on typical post-fire tree recruitment time. However, we recognize that decade-long or even century-long fire dating errors are possible when using the oldest tree in an uneven-aged old growth forest. An interval calculated between two known fire events (Fig. 4-3 – “b”) is an uncensored observation. Intervals calculated between a known fire event and 1948 (Fig. 4-3 – “c”) or a pith origin and 1948 (Fig. 4-3 – “d”) are right-censored observations as the date of the next fire event is unknown. These open-ended intervals represent the time since the last fire (Johnson and Gutsell 1994). It is essential to combine complete and incomplete (i.e. right-censored observations) fire intervals in the survival analysis as to not under-estimate the length of the mean fire return interval.

4.4.2 Survival analysis

Three separate survival analyses were performed for the Upper Foothills (UF), Subalpine (SUB) and Montane (MT) natural subregions using a total of 289, 233 and 695 fire return intervals (FRI), respectively. The percentage of right-censored observations amounted to 23, 27 and 24%, correspondingly. The minimum FRI documented was 3 for MT and 4 for both SUB and UF, while the maximum FRI was 413, 423 and 258 for UF, SUB and MT, respectively.

The two- and three-parameter Weibull survival models using the weighted Maximum Likelihood Estimate technique developed by Cousineau (2009) to improve fit were initially used, but still failed the Anderson-Darling goodness of fit test (Dodson 2006). The Akaike Information Criterion (Akaike 1974) showed the best alternate model for our FRI data was the log normal distribution, which resembled quite closely the “moisture model” of McCarthy *et al.* (2001) and can be interpreted as young forest ages having a higher mortality rate. However, this interpretation goes against findings from studies undertaken in similar forest types and fire regimes that documented a greater likelihood of large stand replacing fires in older aged forests (Romme 1982; Héon *et al.* 2014). A non-parametric approach of survival analysis was found to be a better alternative, as no assumption is required with regards to the hazard of burning over time, or as forests increase in age. The survival analysis textbook by Kleinbaum and Klein (2012) was used to guide the process, along with the on-line survival analysis guide from Diez (2013). The R survival analysis package developed by Therneau (2016) was used and all statistical analyses were performed in R. The Kaplan-Meier product limit estimator was used to fit FRI distributions. To determine if FRI distributions were significantly different among natural subregions, the *survdiff* log rank function and a permutation test were applied to all paired natural subregions. Subsequent analyses were stratified by those regions found to be significantly different from each other.

4.4.3 Testing for predictive variables

The effect of environmental variables on the hazard function (i.e. chance of burning) was assessed with the Cox Proportional Hazard (PH) model, which is a robust, semi-parametric model that is widely used in survival or mortality analysis (Kleinbaum and Klein 2012), but has rarely been applied in the field of wildfire hazard assessment. Some studies in the boreal forest of eastern Canada (Cyr *et al.* 2007; Senici *et al.* 2010) used this approach, but the PH ratio assumption was not verified, which is an essential step of the process for assessing if the model is meaningful. The Cox PH model analysis, PH ratio testing and interpretation followed techniques fully explained by Kleinbaum and Klein (2012), Fox (2002) and Diez (2013). FRIs were first analysed with the Cox PH baseline hazard model and with a second expanded model containing covariates (formulas are presented in an Appendix for this manuscript). For each predictor variable tested, the PH assumption was assessed using the *cox.zph* function from the R survival package (Therneau 2016). It is a statistical test of the correlation between the scaled Schoenfeld residuals and the ranked survival time. This test makes use of the Kaplan-Meier survival function, but in this case only considers uncensored observations. An additional verification of the PH assumption can be made when the fitted curve through the Schoenfeld residuals against individual failure times (i.e. FRIs) appears to be nearly horizontal. A sloping curve would indicate a time-dependence relationship that does not meet the proportionality assumption.

The predictor variables of interest, and for which data was available, were dominant species, elevation, aspect, slope, and forest seral stages. As to not spread the information too thin for analysis, the number of categories per variable investigated was limited to two or three. Species was divided according to the relationship with fire as either fire-adapted species (lodgepole pine, Douglas-fir, aspen stands) or as fire-independent species (white spruce, Engelmann spruce / subalpine fir mix stands). Aspect was categorized into cool (NW, N, NE, E, flat) and warm (SE, S, SW, W), while elevation was parted into low or high elevation using the median elevation of the sample plots. However, because elevation is a continuous variable, the Cox PH model was run using elevation as a continuous variable, rather than as a dummy variable, in order to obtain a PH ratio for every metre of increased elevation. Following some exploratory analyses on the relationship of slope gradient and FRIs, slope angle recorded in five degree increments was divided into two groups using 20 degrees as the breakpoint value (< 20 and ≥ 20).

The number of predictor variables entered in the Cox PH survival analysis model was minimized by assessing the collinearity among environmental variables (Cyr *et al.* 2007) using a permutation test and the *survdiff* log rank test from the R survival package on a total of 35 paired combinations of variable categories. This step was repeated for each natural subregion to ensure that the effect, or non-response, of some environmental variables was not obscured by the fact that natural subregions have distinct terrain, climate and fire regimes. Variables deemed of interest were entered in the Cox PH model and were tested for their significance on the survivorship function to fire. Lastly, the PH assumption of each significant variable was verified.

Seral stages were used to further stratify the Cox PH model to verify if the effect of predictor variables, and their PH assumption, varied with stand conditions associated with young, mature and overmature / old-growth forests. Because FRI distributions within the study area resemble a log-normal distribution with a heavy positive skew, the median fire return interval (MdFRI) could be used as a guideline to establish three seral stages representative of the evolution of stand structure and fuel accumulation over time following fire. Conveniently, the types of fire regime regulating the study area produce MdFRIs corresponding with the time where young forests transition into a maturing stage. However, it is recognized that the maturation process of forests can be highly variable based on topographic location and species. The rule of thumb was that young forests were determined to be younger than the MdFRI, while mature forests represented ages ranging between the MdFRI value and three times the length of the MdFRI. Overmature forests corresponded to stands older than three times the length of the MdFRI. The three times rule was determined by examining box-and-whisker diagrams of FRI distributions and noting that three times the median would fall within the spread of the upper quartile and would generally represent over-mature stand conditions, or be in a state of departure for a fire regime regulated by a moderately short fire rotation period. For convenience in timber and fire management applications, the median value represented an average from various regions rounded down to the nearest 10-year increment to better capture the initiation period of a maturing forest. A median value of 30 years was used for both the Upper Foothills and Montane, while a value of 60 years was applied for the Subalpine. It is important to understand that seral stages are directly derived from the estimated fire return intervals, which represent the age of the forest at fire mortality. Thus, no correlation analysis can be developed between stand age and length of fire interval (i.e. probability of burning) as they are essentially the same variable.

The last analysis was to compute a log rank comparison (*survdiff* function from R survival package) of the Kaplan-Meir survival curves between the two elevation groups, stratified by aspect, to better understand how aspect and elevation interact with each other and influence FRIs.

4.5 RESULTS

Quantile-quantile plots of sampled FRIs against a three-parameter Weibull fitted FRI distribution demonstrated the generally poor fit of FRI data to a Weibull model (Fig. 4-4). Montane (MT) and Subalpine (SUB) subregions showed a clear departure from the model at around 110–125 yr. While the Upper Foothills (UF) distribution appeared to fit relatively well, all FRI distributions failed the Anderson-Darling goodness-of-fit test for a three-parameter Weibull distribution (Table 4-1). FRI distributions fitted with the non-parametric Kaplan-Meier (KM) survival model are presented individually with their 95% confidence interval bands, as well as a group to ease comparisons between subregions (Fig. 4-5).

The pairwise comparison of KM survival curves using the log-rank test (rho = 1) indicated that MT and UF were not significantly different ($\alpha = 0.5$, $P = 0.116$), but all other paired regions were different at a 0.05 significance level. However, the permutation tests

Table 4-1 Weibull fitting parameters and Anderson-Darling goodness-of-fit test (A^2) for fire return interval distributions of three natural subregions.

	Montane	Subalpine	Upper Foothills
	Weibull parameters		
location	0.98	3.99	3.99
scale	44.15	88.84	46.03
shape	1.24	1.01	1.01
	Anderson-Darling test		
A^2*	8.6476	1.6095	2.3862
N obs.	691	233	289
critical value $\alpha = 0.05$	0.755	0.755	0.755
Reject Weibull	yes	yes	yes

* adjusted for sample size

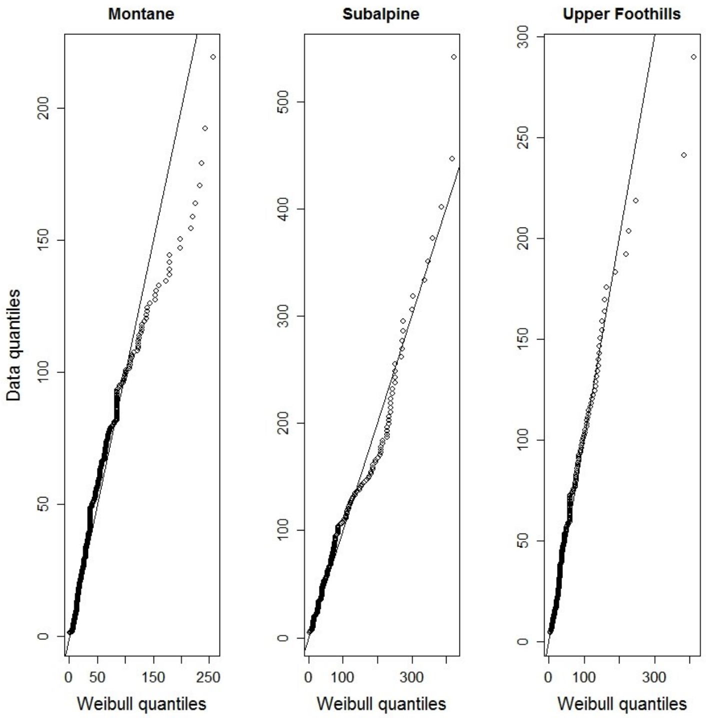

Figure 4-4 *Quantile-quantile plots showing the departure of observed fire return interval data from the Weibull fitted fire return interval distribution.*

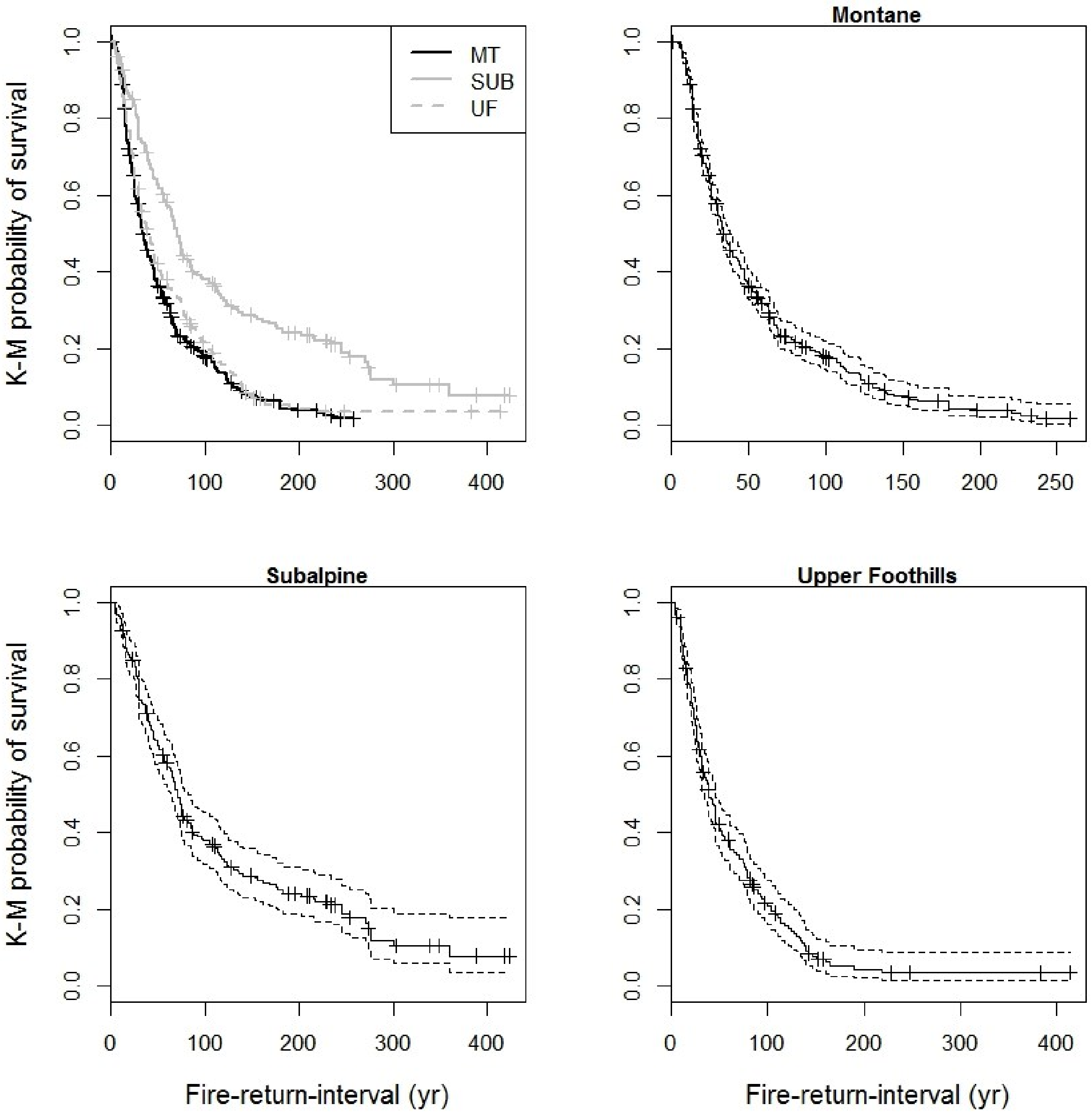

Figure 4-5 *Comparison of Kaplan-Meier survival distributions by natural subregion (upper left) and individual distributions with their 95% confidence bands. Note that the abscissa for the Montane is graduated differently due to the absence of fire-return-intervals longer than 260 years.*

concluded that all paired regions were significantly different ($P \leq 0.007$ for all pairs). Due to known differences in the fire regime, terrain, and age of older forests between MT and UF, coupled with the greater robustness of the permutation test, it was concluded that each natural subregion had a significantly different FRI distribution and hence, fire regime. As to not obscure the effect of environmental covariates on FRIs from the changing fire regimes on the landscape, subsequent analyses were repeated for each natural subregion.

Twenty-eight permutation tests between paired predictor variable classes (Table 4-2) established a strong collinearity (>50%) between a number of variable classes, and identified which variables have significant differences ($p \leq 0.05$) among their categories. For MT, there were particularly strong associations between aspect and slope classes, while both species and elevation were found to have significantly different variable categories. Similar observations were made for UF. In the Subalpine, all variables had categories that were significantly different. Strong associations were found between warm and gentle slopes and, cool steep slopes. The most pronounced collinearity was between cool aspects and high elevations, as well as warm aspects and low elevations. To test for the effect of predictor variables using the Cox PH model, a more limited model including only elevation and aspect was favoured for all natural subregions. Slope was found to generally have a high degree of collinearity with aspect or elevation, and while species was often identified as having significantly different FRIs between the fire- and non-fire-adapted species groups, the fire-adapted group did tend to show strong associations with warm facing slopes and lower elevations for UF and SUB, and the non-fire-adapted group (largely spruce types) was strongly associated with the higher elevations and cooler aspects of SUB.

Table 4-2 Permutation test probability values. Italics: strong collinearity (p ≥ 50%) between paired variable categories; bold: variables with significantly different categories (p ≤ 5%).

	fire-sp.	non fire-sp.	low	high	warm	cool	gentle	steep
Montane								
fire-sp.	1.000							
non fire-sp.	**0.000**	1.000						
low	0.001	0.101	1.000					
high	*0.520*	0.000	**0.031**	1.000				
warm	0.187	0.005	0.217	*0.518*	1.000			
cool	0.015	0.014	*0.474*	0.114	*0.457*	1.000		
gentle	0.070	0.001	0.217	0.266	*0.735*	*0.629*	1.000	
steep	0.065	0.051	*0.556*	0.227	*0.606*	*0.976*	*0.730*	1.000
Subalpine								
fire-sp.	1.000							
non fire-sp.	**0.001**	1.000						
low	0.333	0.002	1.000					
high	0.000	*0.658*	**0.001**	1.000				
warm	0.161	0.006	*0.769*	0.003	1.000			
cool	0.000	*0.851*	0.005	*0.808*	**0.008**	1.000		
gentle	0.079	0.015	0.420	0.007	*0.590*	0.013	1.000	
steep	0.002	0.488	0.000	*0.779*	0.004	*0.633*	**0.005**	1.000
Upper Foothills								
fire-sp.	1.000							
non fire-sp.	**0.000**	1.000						
low	*0.587*	0.000	1.000					
high	0.002	0.403	**0.001**	1.000				
warm	*0.716*	0.007	0.426	0.026	1.000			
cool	0.022	0.071	0.010	0.346	0.111	1.000		
gentle	0.105	0.002	0.053	0.039	0.324	0.314	1.000	
steep	0.072	0.284	0.050	*0.634*	0.183	*0.880*	0.444	1.000

Result interpretation of the Cox PH model and PH assumption test can be elaborate (Table 4-3). Only those variables found to be significant show information pertaining to the PH assumption. Variable regression coefficients are provided, and the validity of the Cox regression model using aspect and elevation as predictor variables is verified by significant p values (< 0.05) of the likelihood ratio and score tests. Under the PH assumption test, a rho close to zero is desirable as it indicates the relationship among the predictor variable categories through time is absent and the proportional hazard is stable regardless of fire interval length. The PH p value is meaningful when greater than 0.05 (5%), but in reality a high p value ($> 50\%$) is desirable as it shows that the PH is maintained for at least 50% of the time. The PH ratio corresponds to the exponentiated regression coefficient and is interpreted as the proportional difference in hazard (failure) rate between the two dummy variable classes tested in model one (M1). Model two (M2) made use of continuous elevation data, rather than classes. In M2, the PH ratio represents the proportional chance of burning for every metre of increased elevation, while M1 offers a PH difference between low and high elevation, using the median elevation as the dividing line. As an additional tool to verify the stability of the PH ratio over time, Schoenfeld residuals were plotted (Fig. 4-6). A horizontal line is the most desirable outcome and was subjectively rated as good, marginal or poor. For data interpretation, preference was given to the PH ratio statistic.

Table 4-3 Output results of Cox regression model and PH assumption test for three natural subregions. M1 model uses elevation classes and M2 model using continuous elevation data. Bold: significant covariate ($p < 0.05$). Underline: PH assumption is respected as rho values consistently near zero more than 50% of the time.

	Cox model				PH assumption test		PH ratio			
Variable	reg. coef.	p. value	likelihood ratio test p value	score test p value	rho	p.value	exp(coef)	lower .95	upper .95	Schoenfeld residuals fit
					Montane					
M1:elevation	0.1954	**0.0285**			0.0080	0.8544	1.216	1.022	1.448	good
M1:aspect	0.1087	0.2195								good
Model1 GoF			0.0477	0.047						
M2:elevation	-0.0012	**0.0003**			0.0151	0.7507	0.999	0.998	1.000	good
M2:aspect	0.0874	0.3237								good
Model2 GoF			0.0006	0.0008						
n = 695, number of failure (uncensored) events = 525										
					Subalpine					
M1:elevation	0.648	**4.82E-05**			0.0571	0.4520	1.912	1.399	2.613	marginal
M1:aspect	0.6498	**4.35E-05**			-0.0310	0.6910	1.915	1.402	2.615	good
Model1 GoF			2.47E-07	1.96E-07						
M2:elevation	-0.0033	**-5.50E-08**			0.0123	0.8700	0.997	0.996	0.998	good
M2:aspect	0.7197	**4.50E-06**			-0.0186	0.8130	2.054	1.501	2.811	good
Model2 GoF			9.30E-11	8.97E-11						
n = 233, number of failure (uncensored) events = 170										
					Upper Foothills					
M1:elevation	0.4417	**0.0016**			-0.0132	0.8420	1.555	1.182	2.048	good
M1:aspect	0.1687	0.2288						0.899	1.558	good
Model1 GoF			0.0015	0.0014						
M2:elevation	-0.0021	**0.0003**			0.0187	0.7880	0.998	0.997	0.999	good
M2:aspect	0.1598	0.2532								good
Model2 GoF			0.0002	0.0003						
n = 289, number of failure (uncensored) events = 222										

For all three natural subregions, elevation was found to be a significant predictor variable, while aspect was found to be relevant only in the Subalpine. PH ratios were strong for all significant variables. With a decreased PH rate of burning of 0.12 % and 0.21 % per metre of elevation gained for MT and UF, respectively, lower elevations had a much greater chance of burning than higher elevations. For SUB, a 0.33% decrease rate per meter, a 300 m elevation gain corresponds to a 99% decrease in chance of burning, which indicated valley bottoms used to burn twice as often as upper-mountain reaches. As for aspect, the PH ratio obtained from the M2 model indicated a 105% greater chance of burning (i.e. twice as likely to burn) on warm aspects over the cooler ones.

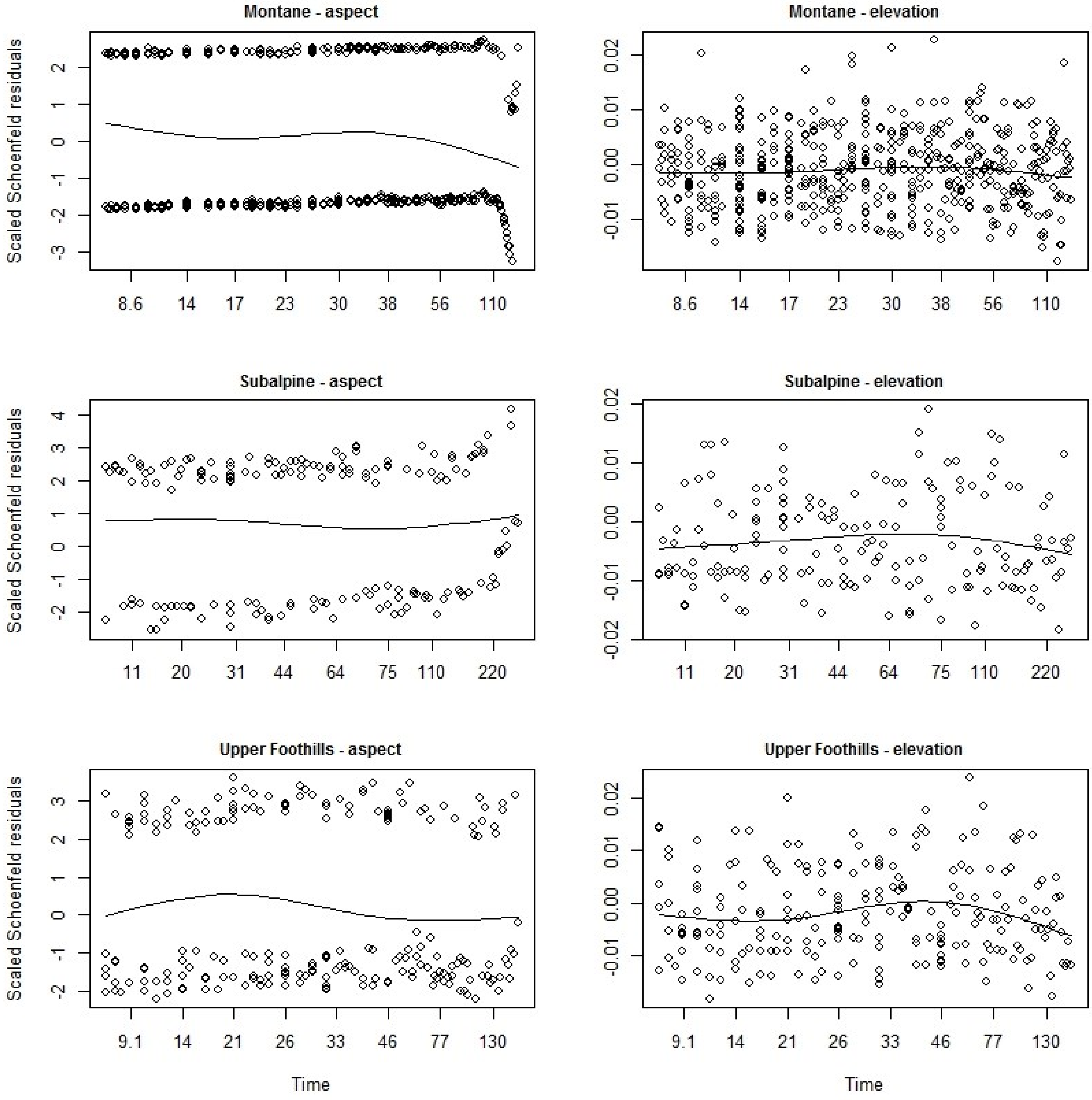

Figure 4-6 *Verification of PH assumption using Schoenfeld residuals and elevation as a continuous variable. The consistent horizontal line shows that Proportional Hazards are mainly constant through time.*

Despite the fact that the PH ratio was found to be consistent through time, when repeating the analysis process by forest seral stage, the effect of topographic variables varied remarkably across seral stages (Tables 4-4, 4-5, 4-6). As a general rule, the variables responses were greatest for overmature (OM) and immature (IMM) forests, while the topographic model was rejected for the mature (MAT) forests of all three natural subregions. Note that the interpretation for OM relied on the M1 model, which makes use of a dummy variable for elevation. Due to the limited number of observations and tendency for older forests to already be found at higher elevation (63 to 77% of data points), too few observations could be evenly distributed across the elevation gradient to obtain an accurate PH rate of burning per increased metre of elevation in model M2. The effect of topography for MT was only relevant for OM forests and indicated a 111% greater chance of burning at lower elevations; a risk that is amplified 5 times over the model using the complete FRI data set. Aspect was also found to be significant for OM, but contrary to expectations, warm aspects fostered a 50% decreased chance of burning. For SUB, continuous elevation data was significant, but only for IMM forests, and indicated a decreased chance of burning at a rate of 0.23% per m. Aspect was found to be highly significant for both IMM and OM forests, and showed a 60% increased chance of burning on warm aspects, which increased nearly three-fold to 171% for OM timber. In contrast, both elevation and aspect were found to be significant for UF IMM forests, but only aspect marginally passed the PH ratio test (P = 0.05). The UF IMM model indicated a 50% increase in the probabilities of burning for warm aspects. For the OM forests of UF, elevation was found to be highly significant (P = 0.009), whereas aspect was insignificant. The chance of burning was found to decrease by 0.33% per increased metre of elevation.

Table 4-4 Output results of Cox regression model and PH assumption test partitioned by forest seral stage, for the Montane (MT) natural subregion. M1 model uses elevation classes, while M2 uses continuous elevation data. Bold: significant covariate ($p < 0.05$). Underline: PH assumption is respected as rho values consistently near zero more than 50% of the time.

	Cox model				PH assumption test		PH ratio			
Variable	reg. coef.	p. value	likelihood ratio test p value	score test p value	rho	p.value	exp(coef)	lower .95	upper .95	Schoenfeld residuals fit
MT - Immature: < 30 yrs										
M1:elev_d	-0.0454	0.6930								good
M1:aspect	0.1024	0.3720								good
Model1 GoF			0.6181	0.6172						
M2:elev_c	-0.0002	0.7050								good
M2:aspect	0.1019	0.3750								good
Model2 GoF			0.6219	0.6216						
n = 347, number of failure events (i.e. uncensored fire intervals) = 306										
MT - Mature: 31 - 89 yrs										
M1:elev_d	-0.3168	**0.0386**			-0.0260	0.7320	0.729	0.540	0.984	good
M1:aspect	0.0067	0.9657								marginal
Model1 GoF			*0.1175*	*0.1142*						
M2:elev_c	0.0009	0.1060								good
M2:aspect	0.0459	0.7680								marginal
Model2 GoF			0.2781	0.2677						
n = 290, number of failure events (i.e. uncensored fire intervals) = 174										
MT - Over mature: >90 yrs										
M1:elev_d	0.7442	**0.0171**			0.0423	0.7460	2.105	1.142	3.881	good
M1:aspect	-0.598	**0.042**			0.1001	0.4490	0.550	0.309	0.979	poor
Model1 GoF			0.0075	0.0054						
M2:elev_c	-0.0025	**0.0056**			-0.0267	0.8390	0.998	0.996	0.999	good
M2:aspect	-0.6759	**0.0238**			0.0531	0.6870	0.509	0.283	0.914	poor
Model2 GoF			0.0019	0.0016						
n = 58, number of failure events (i.e. uncensored fire intervals) = 58*										

* also includes censored fire intervals as too few uncensored observations.

Table 4-5 Output results of Cox regression model and PH assumption test partitioned by forest seral stage, for the Subalpine (SUB) natural subregion. M1 model uses elevation classes, while M2 uses continuous elevation data. Bold: significant covariate ($p < 0.05$). Underline: PH assumption is respected as rho values consistently near zero more than 50% of the time.

	Cox model				PH assumption test		PH ratio			
Variable	reg. coef.	p. value	likelihood ratio test p value	score test p value	rho	p.value	exp(coef)	lower .95	upper .95	Schoenfeld residuals fit
					SUB - Immature: < 60 yrs					
M1:elevation	0.2619	0.2152								good
M1:aspect	0.4248	**0.0533**			-0.0608	0.5530	1.529	0.994	2.353	marginal
Model1 GoF			0.096	0.0981						
M2:elevation	-0.0023	**0.0209**			-0.0087	0.9260	0.998	0.996	1.000	marginal
M2:aspect	0.4706	**0.0323**			-0.0383	0.7120	1.601	1.040	2.464	good
Model2 GoF			0.0129	0.0139						
n = 118, number of failure events (i.e. uncensored fire intervals) = 94										
					SUB - Mature: 61 - 179 yrs					
M1:elevation	-0.4341	0.1180								marginal
M1:aspect	0.0356	0.8930								poor
Model1 GoF			0.2725	0.2661						
M2:elevation	0.0007	0.4920								good
M2:aspect	0.0547	0.8410								poor
Model2 GoF			0.7270	0.7232						
n = 71, number of failure events (i.e. uncensored fire intervals) = 61										
					SUB - Over mature: >180 yrs					
M1:elevation	0.7163	0.0654			0.1365	0.3470	2.047	0.956	4.385	poor
M1:aspect	0.9055	**0.0083**			0.0015	0.9920	2.473	1.263	4.842	good
Model1 GoF			0.0072	0.0037						
M2:elevation	-0.0012	0.3312			0.0488	0.7580	0.999	0.996	1.001	poor
M2:aspect	0.9936	**0.0047**			0.0020	0.9900	2.708	1.357	5.374	good
Model2 GoF			0.021	0.0132						
n = 44, number of failure events (i.e. uncensored fire intervals) = 44*										

* also includes censored fire intervals as too few uncensored observations.

Table 4-6 Output results of Cox regression model and PH assumption test partitioned by forest seral stage, for the Upper Foothills (UF) natural subregion. M1 model uses elevation classes, while M2 uses continuous elevation data. Bold: significant covariate ($p < 0.05$). Underline: PH assumption is respected as rho values consistently near zero more than 50% of the time.

	Cox model				PH assumption test		PH ratio			
Variable	reg. coef.	p. value	likelihood ratio test p value	score test p value	rho	p.value	exp(coef)	lower .95	upper .95	Schoenfeld residuals fit
					UF - Immature: < 30 yrs					
M1:elevation	0.6499	**0.0014**			0.127	0.1462	1.915	1.285	2.855	marginal
M1:aspect	0.4347	**0.0276**			0.169	0.0498	1.545	1.049	2.274	poor
Model1 GoF			0.0016	0.0019						
M2:elevation	-0.0034	**0.0004**			-0.128	0.1259	0.997	0.995	0.999	marginal
M2:aspect	0.4016	**0.0396**			0.168	0.0541	1.494	1.019	2.190	marginal
Model2 GoF			0.0003	0.0009						
n = 129, number of failure events (i.e. uncensored fire intervals) = 115										
					UF - Mature: 31 - 89 yrs					
M1:elevation	-0.0032	0.9890								good
M1:aspect	0.3425	0.1870								marginal
Model1 GoF			0.4017	0.3839						
M2:elevation	-0.0002	0.8870								good
M2:aspect	0.3297	0.2070								poor
Model2 GoF			0.3977	0.3801						
n = 119, number of failure events (i.e. uncensored fire intervals) = 75										
					UF - Over mature: >90 yrs					
M1:elevation	1.0096	**0.0074**			-0.0889	0.5733	2.744	1.312	5.742	good
M1:aspect	0.0633	0.8609								poor
Model1 GoF			0.0209	0.0118						
M2:elevation	-0.0033	**0.0094**			-0.0708	0.657	0.997	0.994	0.999	good
M2:aspect	0.1321	0.7071								poor
Model2 GoF			0.0156	0.0206						
n = 41, number of failure events (i.e. uncensored fire intervals) = 41*										

* also includes censored fire intervals as too few uncensored observations.

Aspect and elevation, the two lead covariates affecting FRI distributions, respond differently to each other when the Cox model is stratified by either aspect or elevations groups (Table 4-7). The model stratified by aspect and adjusted for elevation was more relevant for all natural subregions. This exercise showed that as a general rule, the effect of cool facing slopes is more significant with the exception of the Subalpine where both warm and cool aspects play a significant role. However, the cool aspect of SUB did not respect the PH assumption. In contrast, results showed that a model initially stratified by elevation groups and adjusted for aspect is only significant in the Subalpine (Table 4-7).

Table 4-7 Response of elevation on fire return intervals when the landscape is stratified by cool and warm aspects, and response of aspect when the landscape is stratified by low and high elevations. Bold: highlight significantly different results (p <0.05), underlined: PH assumption is respected. Log rank test compares Kaplan-Meier fire return interval distributions.

			Cox model			PH assumption test		PH ratio			log rank test
NSR	Stratifi-cation	Variable	n / n events	reg. coef.	p. value	rho	p.value	exp(coef)	lower .95	upper .95	p value
MT	warm	elevation	300 / 230	0.1216	0.3670	-0.0145	0.8260	1.129	0.867	1.471	**0.088**
	cool		395 / 295	0.2493	**0.0366**	0.0219	0.7060	1.283	1.016	1.621	
SUB	warm		117 / 97	0.4316	**0.0368**	-0.1090	0.2850	1.540	1.027	2.309	**1.71E-05**
	cool		116 / 73	0.9805	**0.0002**	0.2130	0.0553	2.666	1.597	4.449	
UF	warm		108 / 87	0.3478	0.1220	-0.0770	0.4690	1.416	0.911	2.202	**0.0008**
	cool		181 / 135	0.5495	**0.0021**	0.0124	0.8850	1.732	1.220	2.460	
MT	low	aspect	354 / 266	0.0806	0.5210	-0.0866	0.1580	1.084	0.848	1.386	0.393
	high		341 / 259	0.1351	0.2810	-0.0961	0.1200	1.145	0.895	1.464	
SUB	low		115 / 90	0.4336	**0.0426**	-0.1720	0.1090	1.543	1.015	2.346	**7.77E-06**
	high		118 / 80	0.9191	**0.0002**	0.0992	0.3710	2.507	1.537	4.089	
UF	low		148 / 118	0.0857	0.6470	-0.1390	0.1290	1.089	0.756	1.571	0.204
	high		141 / 104	0.3158	0.1340	-0.0740	0.4540	1.371	0.907	2.073	

Survivorship distributions using FRIs grouped in four combinations of topographic variables between cool and warm aspects, and low and high elevations, showed variable differences between natural subregions (Fig. 4-7). The Montane displayed subtle differences among its distributions, whereas UF depicted slightly more distinct distributions. In contrast, wide differences in the survivorship distributions were captured for SUB notably between low, warm facing slopes of high fire frequency and its antipode cool, high facing slopes fostering infrequent burning. A significant revelation was the high degree of resemblance of FRI distributions between warm-high slopes and cool-low slopes in the Subalpine. Both sets of conditions appear to exert a similar effect on probabilities of survival from fire, an outcome that was not depicted in the permutation test (Table 4-2). Mean fire return intervals (MFRI) and probability median FRI (MdFRI) with their 95% confidence limits further highlight differences between aspect and elevation among natural subregions, as well as between the four combinations of aspect and elevation classes (Table 4-8).

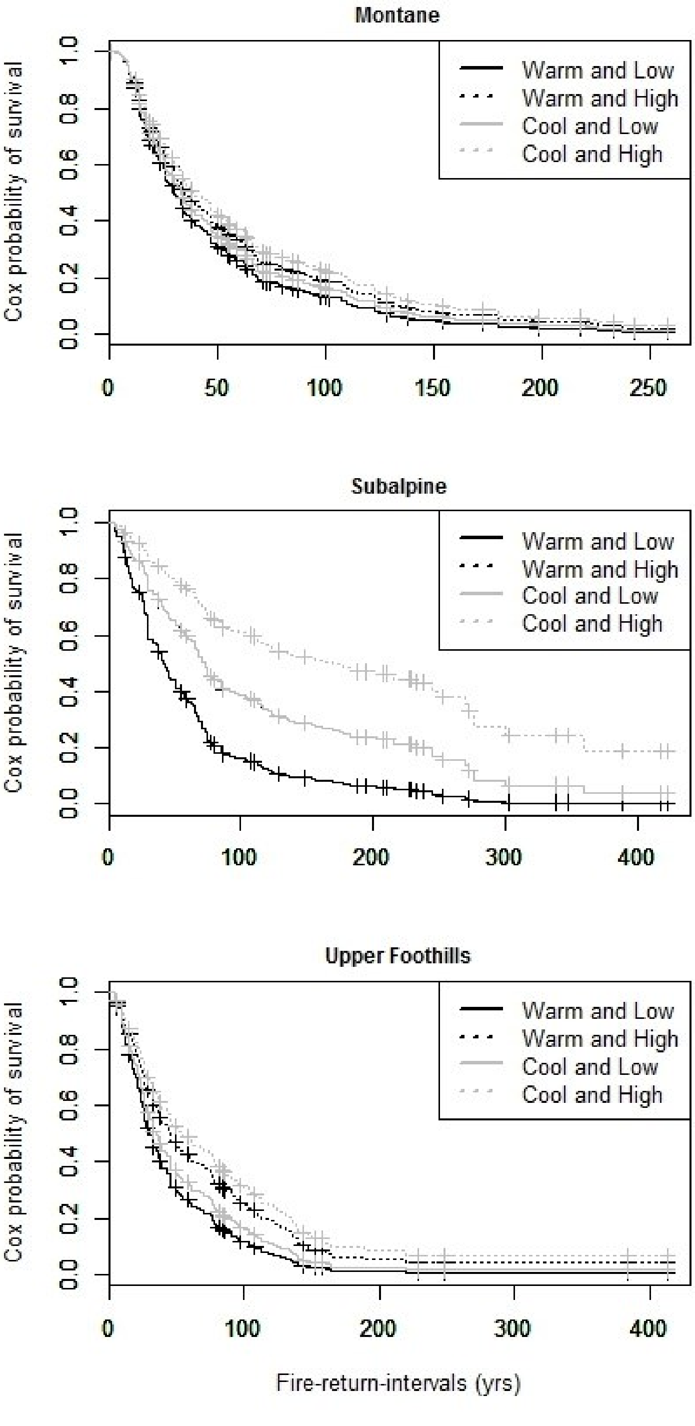

Figure 4-7 *Cox survival distributions adjusted for each combination of lead topographic groups and presented by natural subregion. Cool and warm aspect classes were combined with low and high elevation classes.*

Table 4-8 Mean fire return intervals (MFRI), probability Kaplan-Meier median (MdFRI) with lower and upper 95% confidence intervals. n = number of observations.

Variable class	n	MFRI	MdFRI	Md LCI .95	Md UCI .95
Montane					
Elev: low	354	37.6	33	29	38
Elev: high	341	46.6	36	33	47
Asp: warm	300	40.8	32	26	35
Asp: cool	395	42.9	38	33	45
Subalpine					
Elev: low	117	70.9	64	45	75
Elev: high	116	114.3	76	70	123
Asp: warm	117	76.6	56	45	68
Asp: cool	116	108.5	86	75	136
Upper Foothills					
Elev: low	148	40.1	32	26	46
Elev: high	141	60.0	47	37	70
Asp: warm	108	43.6	32	26	46
Asp: cool	181	53.4	44	37	61

Topographic combinations

	Montane		**Subalpine**		**Upper Foothills**	
	n	**MFRI**	**n**	**MFRI**	**n**	**MFRI**
Cool & High	189	46.7	52	148.8	96	65.8
Cool & Low	206	39.5	64	75.8	85	39.5
Warm & High	152	46.5	66	87.8	45	47.6
Warm & Low	148	34.9	51	62.2	63	40.8

4.6 INTERPRETATION

4.6.1 Role of topography in fire-based ecosystems

The ability of forest stands to avoid fire was strongly tied to topographic elements such as aspect and elevation. Elevation was found to be highly relevant for all three natural subregions. This is a noteworthy finding, considering elevation is one of the factors used in the delineation of subregions and as such, elevation range within a subregion is already bound to a narrower spread. With increased elevation, the probability of fire survival increased and resulting FRIs lengthened. This phenomenon is explained by the adiabatic cooling effect from orographic lifting of an air mass, which increases relative humidity and can eventually lead to precipitation. The dry adiabatic lapse rate of -1°C per 100 m rise in elevation reduces the drying rate of surface fuels, which in turn makes it more difficult for fuels to ignite. Further, the cooler air at higher altitude slows snow melt in the spring, keeping fuels moist for a longer period of time. In contrast, low elevation areas have a greater chance of burning due to warmer temperatures that dry fuels more rapidly and a longer fire season as a result of earlier snow melt (Heyerdahl *et al.* 2001).

Aspect was found to play an important role on fire survival, notably in the Subalpine where mountains are more rugged with long, steep slopes that cast shadows affecting the amount of daily sunlight and potential warming capacity to dry surface fuels. Sun exposed slopes were found to have much shorter FRIs than cooler aspects. The proportional hazard of burning assessment showed stands on cooler aspects were nearly twice as likely to avoid burning in the Subalpine. Results also showed cool facing slopes enhanced the effect of elevation in the Montane and Upper Foothills, yet elevation was not found to be significant for the warm aspects.

Chances of warm facing slopes burning were relatively equal from top to bottom, whereas low elevation-cool aspects were 28% more likely to burn than high elevation-cool aspects in the Montane. A similar, but more pronounced influence was calculated in the Upper Foothills with a 73% greater chance of burning on low elevation-cool facing slopes.

The various combinations of aspect and elevation classes produce different microclimate conditions which tend to be reflected in the FRI distributions, but not always with the prevalence of fire-adapted species. Counterintuitively, a general lack of agreement between FRIs of fire-adapted species (largely pine) and those calculated for low elevation and warm aspect (where pine thrives) was observed. In the Subalpine, low collinearity was noted between fire-adapted species and aspect or elevation in spite of the fact that 81% of pine stands sampled were located at low elevation and 66% on warm aspect. In contrast, the strongest associations were observed between FRIs of non-fire-adapted species (spruce type) and those found at high elevation (66%) and on cool aspect (85%). The distribution of spruce stands sampled was not overly biased toward certain topographic categories with 65% of stands located at high elevation and 57% on cool aspects. In comparison, fire-adapted species in the Upper Foothills and Montane showed various degrees of collinearity with warm facing slopes (72% for UF, 19% for MT) and low elevation (59% for UF and non-existent for MT). Spruce stands were found to have an association of 40% with high elevation in the Upper Foothills. Due to natural successional processes following disturbances, and a shifting forest mosaic based on time-since-fire, understanding past FRI distributions is better achieved using bottom-up, static controls such as topographic elements.

One of the salient findings was the nearly interchangeable effect *low elevation on cool aspects* and *high elevation on warm aspects* have on FRIs in the Subalpine natural subregion.

Both sets of topographic environments foster similar microclimatic forest conditions that in turn produce similar probabilities of burning. As a general rule, the longest fire intervals were found in terrain features that encompassed the coolest and wettest conditions such as high elevation zones on a cool aspect. In contrast, warm aspects of lower elevations had shorter fire intervals as they are more frequently available for burning.

The synergy of fire-topography has far reaching implications from an ecosystem perspective. Fire is an important disturbance and forest renewal agent (Wright and Bailey 1982). Landscape features that favour shorter fire intervals are those where fire-adapted plant communities will thrive, as well as animal life that rely on fire-maintained habitats. Landscapes that have been under fire exclusion policies for several decades are seeing a shift in seral stages with increasingly older forests across the entire land base (Keane *et al.* 2002). Valley bottoms and warm facing slopes with a history of recurrent fire activity should be priority target zones for setting ecological restoration objectives.

At the other end of the spectrum, cool aspects and high elevation have been found to be the lead topographic agents in the formation of fire refugia as they foster the longest FRIs. Other influential landforms in the creation of fire refugia have been documented including headwalls, confluence of streams, flat benches, and valley flats (Camp *et al.* 1997). An interruption in fuel continuity as a result of rock talus or water body can inhibit fire spread, reduce fire size and also protect forest patches from burning (Murray *et al.,* 1998). We defined a fire refugium as a patch of forest that was able to escape, by its spatial location, several fires and is older than three times the length of the mean fire return interval. The contributions of fire refugia to overall ecosystem functions and health are many. Fire refugia are biological legacies that contribute to faster ecosystem recovery following intense, large fire disturbances as they form small ecological pools from which seeds can propagate (Keeton and Franklin 2004). This ecological function is particularly important for mesic sites in high elevation terrain where known pioneer species, such as pine or aspen, are not present to recolonize the forest following a disturbance (Johnson and Fryer 1989). Fire refugia contribute to the overall biodiversity of a watershed by offering a diversified landscape age-class mosaic (Kaufmann *et al.* 1992, 2007) and by providing ecological niches specific to organisms living in old growth forests.

Fire refugia patches are commonly associated with decadent old-growth Engelmann spruce - subalpine fir stands in the Canadian Rockies. The structural complexity and renewal dynamics of these stands are associated with small gap dynamics as a result of mortality of individual trees or a cluster of trees (Veblen 1986; Aplet *et al.* 1988; Rebertus *et al.* 1992). These stands are made up of scattered large diameter trees, standing live and dead, with in-filling of multi-size trees forming a layered canopy (Kaufmann *et al.* 1992, 2007; Moir 1992). The stands often include open pockets that may be vegetated by a shrub layer and small trees, as well as dense pockets of in-filling subalpine fir (Mehl 1992). Large diameter down woody debris in various degrees of decomposition and various states of moss cover are also found scattered through these stands (Moir 1992). In the Montane and Upper Foothills, fire refugia may also correspond to decadent lodgepole pine stands exceeding 150 years of age, as these regions' mean fire return intervals of 42 and 50 years, respectively, are much shorter than the life expectancy of trees.

4.6.2 Topography and forest seral stages

For stand-replacing fire regimes, fire return intervals correspond to stand ages at time of death from fire. Thus a study reviewing the effect of topography on FRIs is by association an analysis on stand ages in this case. Forest seral stages (immature, mature, overmature) were found to respond differently to the effect of aspect and elevation on probabilities of burning. This is a surprising outcome considering the proportional hazard test using the complete data set was significant for all meaningful topographic variables tested, in addition to PH ratios that appeared stable across stand ages, as per the Schoenfeld residual plots.

Fuel load, fuel arrangement, and forest types play an important role in crown fire behaviour (Van Wagner 1977, Cruz and Alexander 2014). Following a disturbance, stand regeneration moves through seral stages where the volume and density of ground and aerial fuels increase over time (Baker, 2009; Hély *et al.* 2000). However, this natural process is highly variable as it is strongly influenced by the frequency of fires, the interval since the last fire, and the severity of the last fire. As a general rule, younger stands have more abundant fast-drying fine and small diameter fuels that can ignite easily after only a short period of precipitation-free days (<1 day, Van Wagner 1987). In contrast, older stands have well-developed duff, understory and canopy layers, which can maintain a higher relative humidity and require a sustained drought for fuels to be available for burning (usually more than 5 to 12 days depending on fuel diameter of the stand).

Our results showed that when forest stands reach mature conditions, their topographic location is irrelevant as they have the same likelihood of burning. This is a condition that held true for all natural subregions. This is in part due to the fact that mature stands have a greater, larger size diameter, fuel load that take longer to dry out and requiring several rain-free days common to sustained drought conditions. At this point, forests of all types and ages, across the entire landscape, have dried out evenly and have become equally available for burning (Johnson and Larsen 1991). However, for immature and overmature seral stages, the response to topography was variable and was not similar across natural subregions.

Probabilities of burning in immature forests of the Montane were also not influenced by aspect or elevation. The light fuel load of immature forests quickly become available for burning in this generally low elevation environment that favour faster drying conditions and a much longer fire season. However, when stands do manage to escape fire for over 90 years, it is twice as likely to happen at high elevation. It is unclear however, why overmature forests have a 50% greater chance of surviving on warmer aspects. This could be the result of an aberration, or from using a small data set (n=58, or 8% of observations) that brings greater variability. To increase the sample size, censored observations had to be included in the overmature class for all subregions, as only a handful of uncensored intervals were available for analysis.

As previously stated, the long, steep slopes from high mountain peaks of the rugged Subalpine can cast extended and prolonged shadows on north facing slopes, notably during the shoulder season when the sun is still at a low angle. This effect is such that immature forests, despite its finer fuels, are 60% more likely to survive fire on cooler slopes, regardless of elevation. Likewise, forests that are older than 180 years are 1.7 times (270%) more likely to be found on cooler aspects regardless of elevation. Despite the fact elevation was not found to play a major role for the overmature class of the Subalpine, fire refugia tend to be found on cool aspects within the highest elevation strata.

The Upper Foothills shares many environmental characteristics with the Montane, but is positioned at lower elevation and outside of the mountain ranges. Unlike in the Montane, the immature forests of the Upper Foothills respond well to the effect of both elevation and aspect, but the PH assumption for aspect is not respected. Thus, aspect does not have a consistent effect across the immature seral stand ages and its predictability is unreliable. Weather conditions in the Upper Foothills are greatly influenced by upslope winds associated with precipitation-bearing low pressure systems. This orographic lifting and cycling of precipitation cells is especially important during April-May when large amounts of precipitation in the form of snow are common. Despite this type of precipitation regime, lower elevations become snow-free early and dry out more quickly. This process allows for immature forests to be available for burning during short periods of rain-free days. Aboriginal fire-use has had a long history in Alberta and has been a contributing factor in shaping the historical fire regime (Lewis 1977; Lewis and Ferguson 1988). It is likely that topographic influence on the fuel drying rate was used intentionally to limit fire spread to low lying areas during the spring and fall seasons. This would explain in part why younger aged forests were twice as likely to be found at low elevations. In contrast, overmature forests (> 90 yr) were 170% more likely to be found at higher elevation, but they did not respond to aspect. We believe the rolling hills of the Upper Foothills are simply not as high as the Subalpine therefore they do not induce a similar effect on overmature forests.

4.6.3 Choice of data and model in interpreting probability of survivorship to fire

Other fire history studies completed in landscapes located in close proximity to our study area (Johnson *et al.* 1990; Masters 1990; Johnson and Larsen 1991) made use of the Weibull survivorship model in spite of the fact it failed the goodness-of-fit test. These studies were unable to identify topographic features as having an effect on the fire cycle or fire return intervals, and the temporal variability identified in the survivorship distribution was eventually attributed to the Little Ice Age, a period of glacial expansion in the Canadian Rockies (Luckman, 2000; Osborne and Luckman, 1988). In contrast, our study captured the important role elevation and aspect play on fire distribution. Given these conflicting conclusions, it is important to discuss how the type of data used and the chosen survivorship model for data analysis can influence result outcomes and affect forest and fire management planning decisions.

The fire cycle is equivalent to the natural fire rotation period (Heinselman 1973; Agee 1993) and is similar to the mean-fire return interval (Van Wagner 1978; Johnson and Gutsell 1994). More specifically, the fire cycle is defined as the number of years required to burn over an area equivalent to the area of interest, allowing for the fact that during one cycle some portions of the area may burn more than once, while others may not burn at all (Van Wagner 1978; Merrill and Alexander 1987). In Canada, fire cycles in stand replacing fire regimes have been commonly estimated by fitting time-since-fire (TSF) data using the Weibull survivorship model, or its special case the negative exponential (Van Wagner 1978; Yarie 1981; Bergeron 1991; Reed *et al.* 1998;Weir *et al.* 2000; Van Wagner *et al.* 2006). TSF data come from a stand or fire origin map drafted following fire history sampling. In a survivorship analysis, the cumulative age-class distribution is weighted by the size of stand age polygons (Johnson and Gutsell 1994).

In spite of its popularity, the use of the Weibull model has been the object of contentious debates as a method for analyzing fire history data and interpreting changes in fire frequency on spatial and temporal scales. Many researchers have demonstrated the pitfalls of the approach and that inflections (or breaks) in the fitted age-class distribution are related to causes other than climate or a change in the fire regime. Finney (1995) attributed the poor fit of the Weibull distribution to the missing old age data, which cannot be accounted for due to obliteration by more recent fires, or to the life expectancy of trees being shorter than the fire interval. Huggard and Arsenault (1999, 2001) argued with Reed and Johnson (1999) that using the reverse cumulative age class distribution is incorrect and that the actual stand age distribution should be used instead to analyse survivorship from which Weibull parameters are estimated. Armstrong

(1999) demonstrated through Monte Carlo simulations that infrequent large fire events create spikes in the age-class distribution, which are carried through time until they are erased by subsequent fire events. Armstrong concluded that burn rates are highly variable and that the constant rate of burning through time portrayed by the negative exponential is an unsuitable model. Li (2002) showed via landscape fire modelling under a constant fire regime, that a series of simulated stand origin maps produce variable fire cycles for the same area. These findings were echoed by Rogeau (1996, 2010) who found that despite maintaining homogeneous fire regime conditions during landscape fire regime simulations, inflections in the survivorship distribution are to be expected due to burning episodes of large areal extent, or as a result of fire refugia in mountainous terrain. In summary, if the data fails the goodness-of-fit test to a Weibull, or any distribution for that matter, the fit should not be forced by having to partition or truncate the distribution.

Beyond the application of the Weibull model to time-since-fire data, further issues have been raised with the approach of using one stand origin map, which amounts to a single snapshot in time of a landscape that has been regulated by fire for thousands of years. A sample of one is insufficient to gauge the natural range of variation in fire frequency of a landscape and the analysis of its single age-class distribution can lead to misleading results (Baker 1989, Rogeau 1996). Furthermore, one of the criteria invoked by Johnson and Van Wagner (1985) to use a landscape that is sufficiently large in comparison to the largest fire events is frequently not respected. The size of some of the study areas (Johnson *et al.* 1990; Johnson and Larsen 1991; Charron and Johnson 2006) were too small and did not contain a large enough array of valley orientations to capture the range of topographic features with a large enough number of observations. Too small of a study area can lead to large peaks in the age-class distribution as a result of large fire events that obliterate much of the other past fire evidence. The conundrum is that in choosing very large landscapes, the criterion of fire regime homogeneity (Johnson and Van Wagner 1985) can rarely be met due to variations in lightning ignition patterns, probabilities of anthropogenic ignitions, or varying fuel types in combination with variable presence of fuel breaks in the form of water bodies or rocky ridges. This is especially problematic for landscapes with a continuous forest cover such as the boreal forest, which can see extremely large size fires (larger than 1 million ha) and would require exceedingly large landscapes to appropriately interpret fire frequency distributions.

As the issues stated above highlight, there were several reasons for time-since-fire data to not properly fit a Weibull distribution. As a result, the method of re-plotting time-since-fire data into different epochs of homogeneous distributions to properly fit the Weibull (Johnson and Larsen 1991; Van Wagner *et al.* 2006) may have potentially been misleading, and may have wrongly attributed a change in burning rate to fluctuations in glacial advances during the Little Ice Age events (Luckman 2000, 1986).

Our data set covered a similar fire regime as nearby fire history studies, and the calculated fire return intervals stemmed from stands having a similar range in tree ages. However, the poor fit of our data to the Weibull distribution could not be tied to a temporal event because fire intervals are timeless on a temporal scale. For example, a 100-year fire interval does not correspond to an event that took place 100 years ago, but to an interval between two fires, which could have taken place between 1832 and 1932, or between 1740 and 1840 for instance. This is the advantage of using fire return interval data rather than time-since-fire data. It clearly demonstrates how the Weibull survivorship model cannot be used to interpret changes in burning rates and less so to tie these changes to temporal events. We believe a non-parametric survivorship model such as the Kaplan-Meir, which does not make assumptions about the hazard rate of burning over time, is a more appropriate model of analysis. The semi-parametric Cox proportional hazard survivorship model used in this study was also found to be an appropriate alternative in testing the effect of topography and plotting survivorship functions.

4.7 CONCLUDING REMARKS

The large fire history data set compiled over a broad and varied landscape clearly demonstrated the effect of topography on fire frequency and probabilities of burning within each of the three natural subregions studied. This is a contradictory outcome to nearby studies and as such, it has important ramifications to how fire history should be interpreted in the Canadian Rockies. The poor fit of fire history data to the Weibull survivorship model cannot be attributed to a temporal change in the burning rate, nor be associated with the Little Ice Age as a contributing factor.

Overmature forests should be dissociated, identified spatially and managed accordingly. Landforms associated with long fire return intervals are those more apt at sheltering the forests from fire and forming fire refugia that fulfill important ecological functions in an ecosystem. Immature seral ages were found to dominate at lower elevations and on warmer aspects and, are zones that can be targeted for ecological restoration needs.

In conclusion, forest and fire management planning should not be a uniform approach but should be adapted for natural subregion, landform type, and historical probability median fire return interval and its 95% confidence interval range. In a fire management context, understanding the spatial variability of forest survivorship to fire will assist with decisions in regards to prescribed burning for ecological restoration needs, fire hazard reduction to protect values at risk, deployment of fire suppression resources, as well as ranking fire suppression priorities. Results from this study will also provide input for fire risk assessment modelling, as well as for computerized fire spread models of mountainous landscapes. From a forest management perspective, information gained from this research can help with the prioritization and distribution of harvest blocks to meet some of the management guidelines for successful forest certification practices.

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4.10 APPENDIX: FORMULAS

The three-parameter Weibull survivorship function describes the probability of survival as a function of time:

$$S(t) = \int_t^{\infty} \frac{\beta(T-\delta)^{\beta-1}}{\theta^{\beta}}\ exp\left[-\left(\frac{T-\delta^{\beta}}{\theta}\right)\right] dT$$

$$S(t) = e^{\left[-\left(\frac{t-\delta}{\theta}\right)^{\beta}\right]}$$

Where:

T = time, β = shape parameter, θ = scale parameter, δ = location parameter

The Kaplan-Meier estimator of S(t), where S(t) is the probability that an entity *i* has a lifetime exceeding time *t*:

$$\hat{S}(t) = \prod_{t_i<T} \frac{n_{i\_}d_i}{n_i}$$

Where:

n_i = number of entities at risk of dying just prior to time t_i
d_i = number of deaths at time t_i
When censored observations are present, n_i is the number of surviving entities minus the censored cases.

The Cox Proportional Hazard (PH) model is composed of the baseline hazard model and the exponential expression e to the linear sum of $\beta_i X_i$, where the sum is over the p explanatory X variables (Kleinbaum and Klein 2012).

$$h(t,\mathbf{X}) = h_0(t)e^{\sum_{i=1}^{p}\beta_i X_i}$$

The baseline hazard is a function of *t* and does not involve the effect of covariates X: $h_0(t)$

The exponential component involves X's but not *t* as covariates are time independent: $e^{\sum_{i=1}^{p}\beta_i X_i}$

The PH ratio:

$$\widehat{HR} = \exp\left[\sum_{i=1}^{p}\beta_i(X_i^{*} - X_i)\right]$$

Where X* is the set of predictors for one variable group perceived to have the largest hazard and X is the set of predictors for the other variable group with a smaller hazard.

CHAPTER V - CONCLUSION

The concluding chapter encompasses two main sections. The first section is a summary of six salient findings that were discussed in the three manuscripts that form Chapters II, III and IV of this thesis. Findings apply to the historical fire regime during the pre-industrial era covering the period between the oldest stands sampled (c.1600) and 1948. The second section is a discussion on how the information from this research can contribute to forest and fire management strategies.

5.1 SUMMARY OF SALIENT FINDINGS

5.1.1 Fire history approach

The statistical analyses and sampling design used were adapted to answer questions related to applied forest and fire management where decisions are based on broad forest age-classes or seral stages. There is no indication the chosen process of by-passing cross-dating impaired the quality and accuracy of the results in a manner that would subsequently affect forest and fire management strategies. The sampling design maximized the number of fires detected by visiting a large number of sample plots (814) and collecting a large number of tree samples (3123). To minimize dating errors associated with false or missing rings, a number of remediation actions were taken and are described below.

A targeted sampling approach that uses the double-plot strategy along a fire boundary ensures a fire interval can still be calculated even when fire scars or fire-releases in the ring growth pattern are absent. Collecting samples only from live specimens provides an accurate year of mortality, and cutting cross-sections in the form of partial (1/3) to full disks presents a wide surface (unlike increment cores) from which to read tree-rings. When present, scarred specimens are normally collected as a complete disk. Samples were also taken at ground level to reduce the number of years missed due to tree growth. A verification process involving 193 fire scar dates from 15 known (i.e. accurately dated) fires from central and southern Alberta in the 1900s showed the average error margin in fire dating is 0.98 yr with 81% of fire scar dates accurate within one year of the actual fire date (Chapter II -Table 2-3). The verification process confirms remediation measures are efficient and can produce a margin of error well below the average minimum fire return interval (FRI) in a stand replacing fire regime.

In summary, the science-based approach used produces a margin of error in fire dating that is more than adequate in the field of applied fire management, where decisions are based on broad age-classes or seral stages. It is suspected that the process of cross-dating would not have enhanced or modified the outcome of this research in a significant manner. However, a limiting factor of not cross-dating tree rings is the imprecision of fire scar dates, notably those older than the 1900s (estimated error of 2 to 5 years). As a result, correlations between past climatic events or drought indices and important fire years are not advised and were not considered in this research.

5.1.2 Natural subregions and fire regimes

There is a strong correlation between the fire environment and the elements that define a natural subregion. While there can be spatial differences in the mean or median probability FRI within a natural subregion, broadly speaking each subregion tends to have a distinct fire regime. This study showed forest fire survivorship distributions associated with each subregion are significantly different. Median FRI statistics are also significantly different, although 95% confidence intervals indicate the Montane and Upper Foothills natural subregions could experience similar FRIs at times.

Fire return intervals in the Montane range from 3 to 226 yr and from 4 to 219 yr in the Upper Foothills, whereas the range is from 4 to 360 yr in the Subalpine. Slight to moderate variations in mean or median FRIs within watersheds of a natural subregion are also expected. Such variations are more pronounced for valleys that historically did not share a similar level of historical anthropogenic land use activity. For instance, main valleys that were well traveled present shorter FRIs than those that are more remote. In that regard, the shortest FRIs in central and southern Alberta are found in all main Montane valleys: Crowsnest, Bow, North-Saskatchewan and Athabasca (unpublished fire history data). Adjacent watersheds that are not separated by rocky ridges and exhibit good fuel connectivity for fire spread, tend to share a similar fire history and hence a similar range of FRIs. In contrast, adjacent watersheds separated by important rocky ridge barriers can display a vastly different fire history and mean FRIs.

A fire regime interaction was anticipated between the Montane, Subalpine and Upper Foothills as these three natural subregions share ecotonal boundaries. However, it was unexpected to observe a reverse edge effect between the rolling foothills landscape composed of continuous forest cover and the rugged (segregated fuels) subalpine landscape. It appears foothills fires tend to move against the flow of prevailing westerly winds and spread (sometimes deeply) in to the rugged mountains. This is likely an outcome of sudden wind shifts associated with a passing front at the time of burning, in combination with erratic wind behaviour common to mountainous environments. Also, once a fire has entered a narrow valley, the mid-afternoon warm rising air encourages fire spread upslope and upstream. The high fire frequency recorded in the Foothills, coupled with this reverse fire spread pattern, greatly influence FRIs at the mouth of subalpine watersheds. Thus, fires burning in the Montane and Upper Foothills affect the burning rate in the Subalpine, but not necessarily the other way around. As a general rule, FRIs recorded at the interface between the rugged subalpine and foothills landscapes are much shorter and contrast with the longer FRIs found upstream, which become increasingly longer near the headwaters. This phenomenon is explained in part by erratic wind patterns due to passing fronts the influence of elevation that increases from the mouth of a valley to its headwaters. The influence of topography is summarized in greater detail is Section 5.1.5.

5.1.3 Strong influence of human activity on the pre-industrial fire regime

The main ranges of the Canadian Rockies are located in a lightning shadow. The effect of the shadow is fewer lightning strikes and lower probabilities of lightning fire ignitions. The shadow subsides towards the east and more lightning strikes and lightning fires occur across the Foothills landscape. Despite the increase in lightning fire activity, current fire occurrence reports show contemporary anthropogenic ignitions play an important role on the fire regime.

The range of pre-industrial median FRIs of 26 to 39 years, associated with the Montane and Upper Foothills, cannot be explained by lightning ignition alone. Results of this fire history study indicate the influence of pre-industrial human activity from settlers, explorers and First

Nations in the Foothills and Montane was significant in shaping the historical fire regime. The ensuing complex vegetation mosaic was observed on the 1950 aerial photography series, as well as photographs taken by surveyors in the early 1900s (*Mountain Legacy Project*).

Additional indicators point to the importance of anthropogenic burning in the past. For instance, the position of fire scars in tree-ring growth tissues suggests historical fires occurred more frequently during the early-early-wood or dormant periods of trees. While an exact correlation with the timing of the growing season is not possible, it appears burning often took place outside of the peak lightning season of July and August.

The short fire intervals identified outside of the rugged mountains do not appear to have been ephemeral and associated only with the arrival of the fur trade, exploration, and land settlements. Field observations of serotinous cones present on lodgepole pine saplings, as young as five years old, suggest trees have genetically adapted to fire-induced mortality occurring at very short intervals. The combination of these factors: few lightning ignitions, early or late season burning when light surface fuels are cured, early-age cone serotiny and, multiple historical accounts from the literature of fire use by aboriginal people, leads to the assumption that aboriginal activities played a significant role on the fire regime of southern Alberta for hundreds of years.

5.1.4 Fire regime departure post-1948

Through the 1900s, fire suppression policies, abolishment of fire use by First Nations, and effective fire awareness campaigns in Alberta resulted in a quasi-exclusion of area burned in southern Alberta by the late 1940s. In 1948, the Eastern Rockies Forest Conservation Board was established and this federal-provincial agreement resulted in increased protection and management of the Rocky Mountains Forest Reserve. This date (1948) was chosen to mark the beginning of the effective fire exclusion period and represents the contemporary era. Fire occurrence reports dating between 1961 and 2003 established the contemporary fire cycle at 5000 years. Each passing year without significant area burned creates an annual burn deficit which adds to the existing burn debt and in turn, lengthens the fire cycle. Based on historical fire return intervals, it is estimated that fire recurrence and associated forest stand conditions are now departed by 197 to 223% in the Montane (from 26 to 35 yr historically to 84 to 104 yr), by 167% in the Upper Foothills (from 39 to 104 yr), and by 42% (from 85 to 121 yr) to 128% (from 65 to 149 yr) in the various regions of the Subalpine. Forest conditions for the most rugged portions of the Subalpine are still considered within their natural range of variation, but the estimated fire cycle of 625 years continues to increase without recent area burned.

As a result of short fire intervals that historically prevailed in the Foothills and Montane, it is assumed that fires were of low fire intensity, as ground and aerial fuels did not have time to cumulate. This assessment is corroborated by a number of internal fire scars that were uncovered in this study. These internal fire nicks and full open-wound scars, marked with charcoal, tend to occur on lodgepole pines aged between 4 to 30 years. As tree saplings and small diameter trees could only survive under conditions of low to moderate fire intensity, this is an indication that mixed-severity fires were historically common in this region. The current presence of mature forests throughout the Foothills and Montane (discounting harvest blocks) have the potential for altering the fire regime to one with more severe and more intense fires that will lead to higher tree mortality rates. In other words a stand-replacing fire regime that is typical of the Subalpine.

5.1.5 Influence of topographic features on fire return intervals

Elevation is the most significant topographic variable influencing the length of FRIs for all three natural subregions studied. This is despite a narrow range between the lowest and highest elevation limits for some of the natural subregions.

Aspect is also significant in influencing FRI, but only for the Subalpine. This is explained by the increased height of mountain ridgelines that cast longer shadows causing north facing slopes to remain cooler. This is compounded by the added effect of higher elevations that are subjected to a decreased temperature of 1°C per 100m of increased elevation.

Slope angle does not appear to have an important effect on FRIs and was not included in the topographic model. This could be an outcome of the distribution of sample plots which was not initially geared to test for the effect of topography. Sample plots collected on steep slopes were found to have a strong collinearity with cool aspects and high elevations.

The most surprising outcome of the topographic effect assessment is the near interchangeable influence of the combined elevation and aspect in the Subalpine. Survivorship distributions, produced using the Cox Proportional Hazard model (adjusting for both elevation and aspect), are similar between low elevation terrain positioned on cool aspects, and high elevation terrain on warm aspects.

The Cox Proportional Hazard ratio (i.e. a ratio between variables of interest that retains its failure rate proportionality through time) is maintained between low and high elevation groups (using the median elevation as the dividing line) of each subregion, and between warm and cool aspects of the Subalpine. Results conclude that the probability of burning decreases by 0.1%, 0.2% and, 0.3% for each metre of increased elevation for the Montane, Upper Foothills and Subalpine, respectively. This corresponds to a decreasing probability of burning of 10%, 20% and 30% per 100 metre of elevation gained. For the Subalpine aspect, warm facing slopes have 92% greater chances of fire recurrence, which means they are nearly twice more likely to burn than cool aspects. In other words, within a similar fire environment, a FRI of 30 years on a warm facing slope is expected to nearly double (57.6 yr) on its opposite cooler face.

5.1.6 Variable effect of topography on FRI when seral stages are considered

There is a variable impact from elevation and aspect on forest fire survivorship when FRI data are examined by seral stage. As the FRI is equivalent to the age of the forest at time of death, FRIs can be partitioned to represent immature, mature and overmature seral stages. The details of the partitioning are explained in Chapter IV – Section 4.3. Despite the fact that Proportional Hazard ratios are maintained across all forest ages (i.e. FRIs), as discussed in Section 5.1.5, the risk of burning in mature forests is for the most part unresponsive to variations in topographic features. An exception is the mature forests of the Montane where elevation significantly affects FRIs, but in an unexpected manner. Mature forests located at low elevations have probabilities of dying due to fire that are 27% less than those at higher elevations. This is contradictory to the common effect of elevation observed in the study area (higher risk at lower elevation) and is likely the result of an anomaly linked to the sampling design which targeted island remnants.

In the Upper Foothills, probabilities of burning decrease by 30% for every 100m of elevation gained for both immature and overmature forests. This decrease in probability of burning is more pronounced than the one calculated when the forest is considered as a whole (30% vs 20%). When the Cox Proportional Hazard ratio is calculated for the below and above median elevation groups, immature and overmature forests are 92% and 174% more likely to burn, respectively. Thus, FRIs above the median elevation line are likely to be 1.9 times longer when the forest is immature, and 2.7 times longer for overmature forests.

In the Subalpine, elevation has significant influence only for immature forests where probabilities of burning are found to decrease by 20% per 100m of elevation gained. In terms of aspect, immature and overmature forests located on warm aspects have 160% and 247% greater chances of burning, respectively, whereas FRIs in mature forests do not respond to aspect changes.

5.2 APPLIED MANAGEMENT STRATEGIES

In light of this study, it is recommended that forest and wildland fire management policies and guidelines be tailored and adapted to each natural subregion, rather than using a global land base approach without ecological reference. Different management decisions that take into account the spatial variability in probabilities of ignition and burning between the different natural subregions are advocated. The significant departure from pre-1948 fire regime conditions also needs to be addressed by all aspects of forest and fire management (Veblen *et al.* 2000). Given that some wildland fires already overwhelm fire suppression efforts, adaptive forest management initiatives that are inclusive of both harvesting and prescribed burning strategies will need to be considered. The option of full fire suppression for an extensive period of time, without some form of fuels management, can have far greater consequences on ecosystems and is discouraged (Agee 2002).

The following two sub-sections outline a number of management strategies in the field of forest and wildfire managements. These are by no means an exhaustive list, but ideas to guide future management decisions, as well as how results of this study could be used.

5.2.1 Forest management

From the results of this study a number of forest management actions can be taken to comply with sustainable forest management practices. For instance, harvest scheduling could adopt a prioritization process based on locations where younger aged forests were historically maintained by higher fire frequencies. In contrast, zones of reduced probabilities of burning that have been successful at harbouring old-age and old-growth forests (fire refugia) should be conserved, or be put on a multi-century long rotation period. Another option is to prioritize salvage logging in recently burned areas that are located in areas with historically short fire intervals.

The common approach of “growing” future stands of old growth forests in zones that typically burned relatively frequently, in an attempt to replace those that have already been harvested, should be discouraged. If not, this practice is likely to be unsuccessful in the long run. Rather, such stands should be designated in areas of historically very low fire frequency and zones considered to be at low fire risk. As all seral stages of the forest play an ecological role, a spatial distribution of each stage throughout the landscape is also favorable to mitigate fire risk. Maturing forests located in higher fire risk zones can receive strategic fuel treatment to reduce their probability of burning.

The 100-year long rotational harvest period, typically applied to boreal forests, needs to be adjusted to a flexible rotation period that is more in-line with the range of historical fire intervals and associated biodiversity. Forest and fire management decisions must also give consideration to fire ecology in terms of wildlife habitats, endangered species and habitats, old-growth forests, and rare ecosystems.

Given the length of the FRI corresponds to the age of the forest at the time of death, the FRI distribution is essentially a surrogate to an age-class distribution and can be used as such to estimate the proportion of forest that should be attributed to each seral age-class. This information can be obtained from the instant failure rate from the Kaplan-Meir survival analysis queried for specific fire interval times (i.e. stand ages).

While this study only looked at fire intervals, different aspects of the fire regime (disturbance size, patch retention size and numbers) and fire effects (retention of coarse woody debris, horizontal and vertical stand structure) should also be considered as part of ecosystem-based forest management strategies.

5.2.2 Wildland fire management

Historically, the burning dynamic at the interface of foothills and mountain landscapes was drastically different. The repeat fire activity of mixed severity burns in the foothills would rarely produce high intensity fires that could propagate deep into mountain valleys towards the headwaters. The current condition, consisting of an extensive and continuous cover of mature forests across the entire landscape, is highly concerning for the protection of valley headwaters and the water quality of streams. This concern is exacerbated when the area of interest includes the water supply of a large city such as Calgary. A mitigation measure to protect the upper reaches of these valleys is to break up the forest cover via harvest blocks near the mouths of valleys where they enter the foothills, as long as significant protective vegetation buffers remain along rivers and creeks. While no fuel treatment is a guaranteed measure against high intensity fires, it has been demonstrated that fuel treatments via mechanized means can reduce fire intensity and spread, and improve firefighting success (Parisien *et al.* 2007). Fire control success is further increased with the use of regular prescribed fires (Stephens and Moghaddas 2005) to reduce fuel load.

With a vision towards a long-term planning process that is on par with the length of the historical median fire-return-intervals and expected range of variation, ecological restoration benchmarks will need to be determined according to the magnitude of departure. Management guidelines and actions will need to take further consideration of small scale variations in fire distribution based on topography and vegetation type associated with a particular subregion. For instance, it is essential that low elevation forests on south facing slopes be favoured for ecological restoration needs and that recurrent burns be considered to maintain shorter fire return intervals associated with these areas.

5.3 CONCLUDING REMARKS

I see the results of this research as the baseline for providing the quantitative measure needed to calculate fire regime condition departure from historical conditions. For instance, in broad landscape management terms, median FRIs obtained from a fire history study can serve as inputs to calibrate fire regime and fire spread computer simulation models. In turn, the outputs from such modelling exercises are used to produce probability of burning maps or stand age distribution maps which capture spatial trends in fire recurrence. Such maps can identify where young seral ages tend to prevail and in contrast, areas where old-aged forests persist.

In conclusion, this was the first detailed quantitative assessment of historical fire regimes done for a broad landscape that straddled a number of natural subregions in southern Alberta. Therefore, it provides a solid baseline and framework for replicating a similar process on other landscapes. Results obtained from this study contributed in part to Spray Lake Sawmills Ltd. (Cochrane, AB) receiving their Forest Stewardship Council (FSC) certification and assisting them with their harvest rotation and block distribution planning. In concert, the Alberta Government is using the same information in their FireSmart initiatives to protect communities and for setting out prescribed burn guidelines as part of fire restoration efforts.

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