

**Disturbance dynamics in west central British Columbia: Multi-century relationships of fire, western spruce budworm outbreaks and climate**

by

Jillian E. Harvey  
B.Sc., University of Victoria, 2004  
M.Sc., University of Victoria, 2011

A Dissertation Submitted in Partial Fulfillment  
of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

in the Department of Geography

© Jillian E. Harvey, 2017  
University of Victoria

All rights reserved. This dissertation may not be reproduced in whole or in part, by photocopy or other means, without the permission of the author.

## **Supervisory Committee**

### **Disturbance dynamics in west central British Columbia: Multi-century relationships of fire, western spruce budworm outbreaks and climate**

by

Jillian E. Harvey  
B.Sc., University of Victoria, 2004  
M.Sc., University of Victoria, 2011

## **Supervisory Committee**

Dr. Dan J. Smith, (Department of Geography)  
**Supervisor**

Dr. Olaf Niemann, (Department of Geography)  
**Departmental Member**

Dr. Thomas T. Veblen (University of Colorado)  
**Additional Member**

Dr. Brad Hawkes (Canadian Forest Service, Retired)  
**Additional Member**

## **Abstract**

### **Supervisory Committee**

Dr. Dan J. Smith, (Department of Geography)  
**Supervisor**

Dr. Olaf Niemann, (Department of Geography)  
**Departmental Member**

Dr. Thomas T. Veblen (University of Colorado)  
**Additional Member**

Dr. Brad Hawkes (Canadian Forest Service, Retired)  
**Additional Member**

Future climate changes will alter disturbance regimes worldwide with important implications for many ecological and social systems. In west central British Columbia, Canada, fire and insect disturbances have shaped the historic character of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* Beissn. Franco) dominated forests. However, since AD 1900 fire suppression and other forest management practices have led to denser forests and conifer encroachment into grasslands. Considering climate changes in interior British Columbia are expected to result in warmer and drier conditions, understanding the influence of climate on forest disturbances is crucial for land managers tasked with both mitigating the effects of disturbance and promoting resilience in forest ecosystems. This research focused on developing multi-century, annually-resolved records of fire and western spruce budworm outbreaks to evaluate: the historic climate conditions related to these disturbances; the influence of grassland proximity on disturbance-climate relationships; and, whether western spruce budworm outbreaks were related to fire activity.

At the landscape scale, a detailed study in the Churn Creek Protected Area revealed spatially variable stand structure and fire-climate relationships at a low elevation forest-grassland ecotone over the interval AD 1600 to 1900. This finding suggests the site was characterized by fires of mixed-severity dominated by frequent, low-severity, fires related to positive antecedent moisture conditions punctuated by widespread fires of moderate to high severity related to intervals of persistent drought. At the regional scale, the influence of interannual climate variability and large-scale patterns of climate variability (e.g. El Nino Southern Oscillation) was evaluated using new and existing records of fire history and multiple climate pattern reconstructions. Regional fire activity was shown to be significantly related to interannual climate variability, and no consistent patterns between regional fire years and the individual phases or phase combinations of large-scale patterns of climate variability were detected. The findings suggest that the spatial expression of large-scale climate patterns translates into weak and undetectable terrestrial effects related to fire activity in this region. The influence of grassland proximity on disturbance history was investigated using site-level and regional tree-ring reconstructions of western spruce budworm outbreaks and fire activity based on four sites adjacent to grasslands and four sites not adjacent to grasslands between AD 1600 and 1900 (fire) and AD 1600 and 2009 (western spruce budworm). Fires affecting grassland proximal sites were more frequent than fires occurring in forests not adjacent to grasslands, and the character of western spruce budworm outbreaks was generally consistent among all sites. Fire activity was related to both warm, dry and cool, wet conditions in the fire year and/or year(s) preceding the fire depending on proximity to grasslands, suggesting climate conditions associated with both fine fuel growth and

drying are key determinants for fire activity. The initiation of western spruce budworm outbreaks was significantly related to drought and this relationship was enhanced at sites adjacent to grasslands. At the site-level and regional scale, no consistent association was found between the initiation of western spruce budworm outbreaks and fire years indicating the historic interaction between these disturbances is weak or non-existent.

## Table of Contents

<b>Supervisory Committee .....</b>	<b>ii</b>
<b>Abstract.....</b>	<b>iii</b>
<b>Table of Contents .....</b>	<b>vi</b>
<b>List of Tables .....</b>	<b>ix</b>
<b>List of Figures.....</b>	<b>x</b>
<b>Acknowledgments .....</b>	<b>xv</b>
<b>Dedication .....</b>	<b>xvi</b>
<b>Chapter 1 Introduction .....</b>	<b>1</b>
1.1 Natural disturbances in the Cariboo Forest Region.....	1
1.2 Climate-disturbance relationships .....	3
1.3 Research motivation .....	4
1.4 Organization of dissertation .....	5
<b>Chapter 2 Mixed-severity fire history at a forest-grassland ecotone in west central British Columbia, Canada .....</b>	<b>7</b>
2.1 Article information.....	7
2.1.1 <i>Authors' names and affiliations</i> .....	7
2.1.2 <i>Author's and coauthor's contributions</i> .....	7
2.2 Abstract .....	8
2.3 Introduction.....	9
2.4 Methods.....	12
2.4.1 <i>Study area</i> .....	12
2.4.2 <i>Site selection, field sampling and sample processing</i> .....	16
2.4.3 <i>Fire history, frequency and severity</i> .....	18
2.4.4 <i>Climate data</i> .....	20
2.4.5 <i>Fire-climate relationships</i> .....	20
2.5 Results.....	21
2.5.1 <i>Fire history, frequency and severity</i> .....	21
2.5.2 <i>Fire-climate relationships</i> .....	26
2.6 Discussion .....	30
2.6.1 <i>Fire history</i> .....	30
2.6.2 <i>Fire severity</i> .....	31
2.6.3 <i>Fire-climate relationships</i> .....	33
2.6.4 <i>Mixed-severity fire from stand structure and fire-climate relationships</i> .....	34
2.6.5 <i>Management implications</i> .....	35
2.7 Conclusion.....	37
<b>Chapter 3 Interannual climate variability drives regional fires in west central British Columbia, Canada .....</b>	<b>39</b>
3.1 Article information.....	39
3.1.1 <i>Authors' names and affiliations</i> .....	39
3.1.2 <i>Author's and coauthor's contributions</i> .....	39

3.2	Abstract .....	39
3.3	Introduction .....	40
3.4	Materials and Methods .....	45
3.4.1	<i>Study region</i> .....	45
3.4.2	<i>Site selection, data collection, sample processing</i> .....	47
3.4.3	<i>Fire history chronologies</i> .....	49
3.4.4	<i>Climate data</i> .....	50
3.4.5	<i>Fire-climate analyses – PDSI</i> .....	53
3.4.6	<i>Fire-climate analyses – ENSO, PDO, PNA</i> .....	54
3.5	Results .....	55
3.5.1	<i>Fire history chronologies</i> .....	55
3.5.2	<i>Fire-climate relationships – PDSI</i> .....	56
3.5.3	<i>Fire-climate relationships – PDO, ENSO and PNA</i> .....	58
3.6	Discussion .....	62
3.6.1	<i>Persistent drought synchronizes regional fire activity</i> .....	62
3.6.2	<i>Antecedent moisture promotes fire activity at local scales</i> .....	64
3.6.3	<i>Inconsistent relationships detected between regional fires and proxy records of ENSO, PDO and PNA</i> .....	65
3.6.4	<i>Future climate implications</i> .....	67
3.7	Conclusions .....	68
<b>Chapter 4 The influence of grassland proximity on insect and fire activity in interior British Columbia.....</b>		<b>70</b>
4.1	Article information .....	70
4.1.1	<i>Authors' names and affiliations</i> .....	70
4.1.2	<i>Author's and coauthor's contributions</i> .....	70
4.2	Abstract .....	71
4.3	Introduction .....	72
4.4	Methods .....	75
4.4.1	<i>Study area and site selection</i> .....	75
4.4.2	<i>Disturbance history reconstructions</i> .....	78
4.4.2.1	<i>Fire</i> .....	78
4.4.2.2	<i>Western spruce budworm</i> .....	79
4.4.3	<i>Disturbance-climate relationships</i> .....	81
4.5	Results .....	84
4.5.1	<i>Disturbance history reconstructions</i> .....	84
4.5.2	<i>Disturbance-climate relationships</i> .....	88
4.5.2.1	<i>WSB outbreak initiation</i> .....	88
4.5.2.2	<i>Fire</i> .....	92
4.5.3	<i>Fire-insect disturbance interaction</i> .....	96
4.6	Discussion .....	97
4.6.1	<i>Disturbance histories</i> .....	97
4.6.3	<i>Enhanced fire-climate sensitivity at grassland sites</i> .....	101
4.6.4	<i>Fire and WSB outbreaks occur independently</i> .....	102
4.6.5	<i>Management and implications</i> .....	103
4.7	Conclusion .....	105
<b>Chapter 5 Conclusion .....</b>		<b>107</b>
5.1	Introduction .....	107

	viii
5.2 Summary of main research results .....	107
5.3 Management implications .....	108
5.4 Future research .....	110
<b>References</b> .....	<b>112</b>
<b>Appendices</b> .....	<b>131</b>

## List of Tables

Table 2.1. Fire record characteristics for the 27 plots in the study area. ....	24
Table 3.1. Fire history sites developed in this study. ....	48
Table 3.2. Results of correlation analysis between different PDO, ENSO and PNA reconstructions. ....	52
Table 4.1. Site locations in the Cariboo Forest Region, British Columbia. Tree-ring chronologies are divided between those collected from non-grassland and grassland sites, and are arranged from east to west (Figure 4.1). The number of samples collected, number of fire years and mean return interval are presented by individual site. ....	77
Table 4.2. Properties of western spruce budworm host chronologies in the Cariboo Forest Region of British Columbia, Canada. Chronologies are divided into non-grassland and grassland sites and then arranged from east to west (See Figure 4.1). The reconstructed number, duration and return interval of outbreaks by individual sites. ....	86

## List of Figures

- Figure 2.1. The Churn Creek Protected Area study site located in west central British Columbia showing the location of 92 sampled fire-scarred trees and 27 age-structure plots (Google Earth 2016). The hatched network is the 500 m grid used to locate the age-structure plots. White circles with numbered boxes represent plot locations and numbers, black circles mark fire-scarred trees sampled in this study and stars indicate spot elevations in the study area. .... 13
- Figure 2.2. (A) Landscape view of the study site looking southeast towards Plots 16 and 17. (B) Sample collected from a standing dead Douglas-fir tree at Plot 4. The tree was located about 200 m from expansive grasslands and within a closed canopy forest. This tree records twelve fire events from AD 1620-1896 with an average return interval of 25 years. .... 14
- Figure 2.3. Widespread (A) and grassland fire (B) chronologies between AD 1600 and 1900 used in these analyses. Widespread fire years were identified when fire was recorded by at least 25% of recording samples over the entire research area. Grassland fires were identified as fires that scarred at least 10% of recording samples (and  $\geq 2$  samples) within 400 m of grasslands. All fires recorded in the study area between AD 1600 and 2010 (C). All fires that occurred between AD 1901 and 2010 were not included in the analyses and were not widespread. Widespread fires are thicker lines. .... 22
- Figure 2.4. Fire history reconstructed from fire scars and post-fire even-aged cohorts for the 27 plots. The x-axis of each histogram records the year of tree establishment in 30-year bins and the y-axis measures the number of live and dead trees crossdated from each plot (total number of trees in each plot given in parentheses). Cohorts are marked by the establishment date of the youngest tree in the cohort. .... 25
- Figure 2.5. Fire and climate relationships from AD 1600-1900. Widespread fire years (large triangles) were identified where fire was recorded by at least 25% of samples over the entire research area. Small triangles mark localized fires within 400 m of grasslands (where at least 10% of recording samples (and  $\geq 2$  samples) were scarred). Lines designate annual tree-ring reconstructed Palmer Drought Severity Index (Gridpoint 30; Cook et al. 2008a) and precipitation (Big Creek; Watson and Luckman 2004) anomalies. General gradients of climate conditions associated with each climate reconstruction are on the right-hand axis (Watson and Luckman 2004; Cook et al. 2008a). .... 27
- Figure 2.6. Lagged interannual relationships of climate and fire from AD 1600-1900, showing mean departures (standard deviations) from climate during 14 years with widespread fire, 28 years with localized grassland fire, and 238 years with no fires for years before ( $t = -4$  to  $-4$ ), during ( $t = 0$ ) and after ( $t = +4$  to  $+4$ ) fire or no fire years. Climate records included in analysis include the Palmer Drought Severity Index (Gridpoint 30; Cook et al. 2008a), and precipitation (Big Creek; Watson and Luckman 2004). Temporal autocorrelation was removed from the PDSI time series using an ARMA model of an order determined based on Akaike's Information Criterion. Dark grey shading shows the fire relationships with statistically significant (at the 95%

confidence interval) anomalies. Stars indicate statistical significance at the 99% confidence interval..... 28

Figure 2.7. Bivariate event analysis of the temporal association of extreme negative and positive Palmer Drought Severity (Gridpoint 30; Cook et al. 2008a) and precipitation (Watson and Luckman 2004) years with fire in CCPA (AD 1600-1900). Extreme climate events were defined using a threshold based on  $\pm 1$  SD. Black solid lines indicate  $L$ hat values ( $L$  function with stabilized mean and variance) for  $t$  years before the fire events ( $t=0$ ). Dotted lines indicate the upper and lower confidence intervals (95%).  $L$ hat values outside the confidence intervals indicate synchrony with fire, and values between the confidence intervals indicate a random relation of fire and climate events. Grey shaded bars highlight statistical significance ( $P<0.05$ )..... 29

Figure 3.1. The eight fire history sites presented in this study and the locations of existing fire histories used to develop the regional fire chronology. The grey polygon covers the area with the 31 sites examined by Iverson et al. (2002). Reconstructed Palmer Drought Severity Index from Gridpoint 30 (Cook et al. 2008a) used in fire-climate analyses. The site names were abbreviated as TL=Tatlayoko Lake, RS=Redstone, CH=Chilko, BC=Bull Canyon, HV=Hanceville, DI=Dante's Inferno, FC=Farwell Canyon, ML=Meadow Lake. .... 46

Figure 3.2. Fire histories at eight sites in the Cariboo Forest Region, British Columbia (a). Existing fire histories from nearby sites (b). Each narrow vertical line marks a fire event recorded by  $\geq 2$  trees. The grey vertical bars highlight a regional fire year when fires burned at  $\geq 3$  sites. .... 50

Figure 3.3. Fire and interannual climate relationships in west central British Columbia during local (AD 1600-1900), moderate and regional fire years (AD 1700-1900). (a) Lagged interannual relationships of reconstructed values of the Palmer Drought Severity Index (PDSI; Gridpoint 30; Cook et al. 2008a) and fire showing mean departures (standard deviations) from PDSI during years when fire burned at only one site ( $n=46$ ), years when fire burned at 2 or more sites in this study ( $n=16$ ) and when fire burned at 3 or more sites (region fire chronology;  $n=17$ ) for years before ( $t = -4$  to  $-1$ ), during ( $t = 0$ ) and after ( $t = +1$  to  $+4$ ) fire years. Dashed lines represent the 99% and 95% confidence intervals. Bivariate event analysis of the temporal association of extreme negative PDSI years (warm, dry) (b), and extreme positive PDSI years (cool, wet) (c), with fire in local, moderate and regional fire years. The number of extreme PDSI years was adjusted based on the temporal interval of analysis (see Methods for details). Black solid lines indicate  $L$ hat values ( $L$  function with stabilized mean and variance) for  $t$  years before the fire events ( $t=0$ ). Dotted lines indicate the upper and lower confidence intervals (95%).  $L$ hat values outside the confidence intervals indicate synchrony with fire, and values between the confidence intervals indicate a random relation of fire and climate events. Grey shaded bars highlight statistical significance. .... 57

Figure 3.4. Positive (white) and negative (black) phases of PDO (a), ENSO (b) and PNA (c) as estimated from the proxy reconstructions. Hatched areas indicate the reconstruction

does not span that interval. Regional fire years are noted and are marked by dashed lines.  
 ..... 58

Figure 3.5. Observed (black bars) and expected (white bars) number of regional fire years for single phases of PDO (a), ENSO (b) and combinations of warm and cool phases of each PDO reconstruction and ENSO (Li et al. 2011)(c). Warm (positive) phases of these oscillations are represented by + symbols, and cool (negative) phases are represented by – symbols. Significant departures from the expected fire occurrence was evaluated by chi square tests. .... 59

Figure 3.6. Results from bivariate event analysis showing the temporal association of extreme positive and negative PDO(a) and ENSO(b) years and regional fire years. The relationships between regional fire years and combined years with the highest PDO and ENSO index values are also presented for each PDO reconstruction and the ENSO reconstruction from Li et al. (2011)(c). See Figure 3.3 and Methods for further explanation. .... 60

Figure 3.7. Results from bivariate event analysis showing the temporal association of extreme positive and negative PNA years and regional fire year (a). Observed and expected number of regional fire years for the PNA reconstruction presented in Trouet and Talyor (2010) with intervention analysis (b) and without intervention analysis (c), and in Starheim et al. (2012b) (d). See Figures 3.3 and 5.5 for further explanation. .... 62

Figure 4.1. Location of eight study sites presented in this study. .... 76

Figure 4.2. Tree-ring reconstructed chronologies of western spruce budworm outbreaks (black line) and fire (vertical grey bars) at non-grassland (a) and grassland (b) sites over the period AD 1600 to 2010. Horizontal dashed lines are the 40% threshold used to identify outbreak periods. Sites are arranged from west to east (top to bottom). Site name abbreviations: RS=Redstone, CH=Chilko, BC=Bull Canyon, HV=Hanceville, DI=Dante’s Inferno, FW=Farwell Canyon, BD, Black Dome, ML=Meadow Lake. .... 85

Figure 4.3. Comparison of the number number of years recording  $\geq 40\%$  defoliation (top plots) and cumulative percent defoliation (lower plots) within 100 year periods at non-grassland (a) and grassland (b) sites over the interval AD 1610 to 2009. See Figure 4.2 caption for site abbreviation descriptions. .... 87

Figure 4.4. Cumulative percent defoliation from AD 1700 to 2010 at non-grassland (black line) and grassland (grey line) sites. .... 87

Figure 4.5. (Previous page) Superposed epoch analysis indicating the direction of reconstructed climate anomalies (Palmer Drought Severity Index (Cook et al. 2008a) and precipitation (Watson and Luckman 2004)0 for an 11-year window centered on outbreak initiation dates at the four non-grassland (a) and four grassland (b) sites. Descending bars indicate a negative association with the climate variable (i.e., droughty conditions), ascending bars indicate a positive association with the climate variable (i.e., wetter conditions). Dashed lines mark the 95% and 99% confidence intervals and dark grey

shading highlights statistically significant (95% confidence intervals) anomalies. See Figure 4.2 caption for site abbreviation descriptions..... 90

Figure 4.6. Superposed epoch analysis indicating the regionalized direction of reconstructed climate anomalies (Palmer Drought Severity Index (Cook et al. 2008a) and precipitation (Watson and Luckman 2004)) for an 11-year window centered on outbreak initiation dates from all non-grassland (a) and all grassland (b) sites. Descending bars indicate a negative association with the climate variable (i.e., droughty conditions), ascending bars indicate a positive association with the climate variable (i.e., wetter conditions). Dashed lines mark the 95% and 99% confidence intervals and dark grey shading highlights statistically significant (95% confidence intervals) anomalies. .... 91

Figure 4.7. Bivariate event analysis of the temporal association of extreme negative and positive Palmer Drought Severity Index (Cook et al. 2008a) and precipitation (Watson and Luckman 2004) with the non-grassland (a) and grassland (b) regionalized histories of outbreak initiation. Black solid lines indicate  $L$ hat values ( $L$  function with stabilized mean and variance) for  $t$  years before the fire events ( $t=0$ ). Dotted lines indicate the upper and lower confidence intervals (95%).  $L$ hat values outside the confidence intervals indicate synchrony with fire, and values between the confidence intervals indicate a random relation of fire and climate events. Grey shaded bars highlight statistical significance ( $P<0.05$ ). ..... 92

Figure 4.8. (Previous page) Superposed epoch analysis indicating the direction of reconstructed climate anomalies (Palmer Drought Severity Index (Cook et al. 2008a) and precipitation (Watson and Luckman 2004)) for an 11-year window centered on fire years at the four non-grassland (a) and four grassland (b) sites. Descending bars indicate a negative association with the climate variable (i.e., droughty conditions), ascending bars indicate a positive association with the climate variable (i.e., wetter conditions). Dashed lines mark the 95% and 99% confidence intervals and dark grey shading highlights statistically significant (95% confidence intervals) anomalies. See Figure 4.2 caption for site abbreviation descriptions..... 94

Figure 4.9. Superposed epoch analysis indicating the regionalized direction of reconstructed climate anomalies (Palmer Drought Severity Index (PDSI; Cook et al. 2008a) and precipitation (Watson and Luckman 2004)) for an 11-year window centered on fire years from all non-grassland (a) and all grassland (b) sites. Descending bars indicate a negative association with the climate variable (i.e., droughty conditions), ascending bars indicate a positive association with the climate variable (i.e., wetter conditions). Dashed lines mark the 95% and 99% confidence intervals and dark grey shading highlights statistically significant (95% confidence intervals) anomalies. .... 95

Figure 4.10. Bivariate event analysis of the temporal association of extreme negative and positive Palmer Drought Severity Index (Cook et al. 2008a) and precipitation (Watson and Luckman 2004) with the non-grassland (a) and grassland (b) regionalized fire histories. Black solid lines indicate  $L$ hat values ( $L$  function with stabilized mean and variance) for  $t$  years before the fire events ( $t=0$ ). Dotted lines indicate the upper and lower confidence intervals (95%).  $L$ hat values outside the confidence intervals indicate

synchrony with fire, and values between the confidence intervals indicate a random relation of fire and climate events. Grey shaded bars highlight statistical significance ( $P < 0.05$ ). ..... 96

Figure 4.11. Synchrony of fire occurrence and the initiation years of western spruce budworm outbreaks, analyzed using bivariate event analysis at each of the eight sites. See the caption for Figure 4.7 for more details and Figure 4.2 caption for site abbreviation descriptions. .... 98

Figure 4.12. Synchrony of regional fire occurrence and regional initiation years of western spruce budworm outbreaks analyzed using bivariate event analysis. See the caption for Figure 4.7 for more details. .... 99

## Acknowledgments

The findings and contributions presented in this dissertation are supported by hundreds of thousands of tree-ring width measurements, and hundreds of tree cores, cookies and fire-scar samples. I wish that those that read this could also smell the freshly sanded Doug-fir samples, feel the soft crunch of the dry Cariboo forest floor, and the music that accompanied hours in pickup trucks, sanding and writing.

First I would like to thank my supervisor Dan Smith for encouraging me to pursue my passion in fire research. In addition to research and science, I have learned so much from you in the areas of leadership, academic citizenship, teaching and country music. You truly are a great mentor and I am so grateful. To my committee members Brad Hawkes, Olaf Neimann and Thomas Veblen, thank you for your time and interest in guiding my research program. A special thanks to Thomas Veblen, who welcomed me to Boulder, and mentored me in fire-climate approaches. At the University of Victoria Tree-Ring Laboratory for their field assistance, I thank Ansley Charbonneau, Bethany Coulthard, Bryan Mood, and Cedar Welsh. A special thank you to Airell Klopp for volunteering for the 2013 field season, and to Vikki St. Hilaire for joining me for two Chilcotin summers. I am grateful to Kristi Iverson and Emma Watson for providing fire history (Iverson) and precipitation reconstructions (Watson) for use in my research.

I am eternally grateful to my family and friends. First, one of my grandmothers said that you can measure your life in dog chapters. Two chapters of dogs are intertwined in this journey; Buddy and Neko brought me love and companionship without words. That takes a big heart, a dog's heart. Second, Marina I will always be grateful for your arrival into my life during my PhD. The joy, wonder and laughter you have brought to my life reminds me daily of the importance of love, balance and building forts. Third, to my parents, your support is endless and I am so grateful and indebted. Lastly, Brandon you held my hand and my heart on this journey. You truly are my partner in life and I share this success with you.

Support for this research was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) and an NSERC Michael Smith Foreign Study Award.

**Dedication**

*For Brandon*

## Chapter 1 Introduction

### 1.1 Natural disturbances in the Cariboo Forest Region

The Cariboo Forest Region (CFR) is located within the Chilcotin Plateau physiographic region of west central British Columbia (B.C.), Canada (Church and Ryder 2010). Deeply incised by the Fraser, Nicola, Thompson and Chilcotin rivers, extensive natural grasslands characterize the arid river valley-bottoms etched below the plateau surface. Above 700 m above sea level (asl) a forest-grassland ecotone marks a dynamic ecological boundary demarcated by a gradual transition from grasslands to montane forests (Tisdale 1947; Tisdale and McLean 1957). Forests in the lower and middle montane ecosystems are dominated by Douglas-fir (*Pseudotsuga menziesii* var. *glauca* Beissn. Franco) and lodgepole pine (*Pinus contorta* Dougl.) trees. Multiple variables control the position of the ecotonal transition from grasslands to forests including climate, fire and grazing history (Hansen and di Castri 2012; Risser 1995; Staver et al. 2011).

Numerous abiotic and biotic natural disturbances affect forest ecosystems in the CFR (Daniels and Watson 2003; Axelson et al. 2010, Axelson et al. 2015). These disturbances are defined as relatively discrete events that change the structure and function of forest ecosystems and the physical environment (White and Pickett 1985). Most of these disturbances are influenced by complex feedbacks related to ecological legacies, climate variability and disturbance interactions. Typically, they are distinguished by type (e.g. insect outbreak, fire, windthrow), spatial and temporal characteristics, and severity.

Prior to European settlement and contemporary forest management programs, fire was the dominant ecological process that shaped forest ecosystems and grasslands in the CFR. In this and similar settings in the Pacific Northwest, historically frequent fires maintained open forests adjacent to grasslands and controlled the encroachment of conifers into grasslands (Bai et al. 2004). Beginning around AD 1900, reduced fire activity driven by land use changes and fire suppression activities, resulted in denser forests and the encroachment of woody vegetation into native grasslands to decrease their resiliency (Halpern et al. 2012; Halpern et al. 2016). These changes negatively impacted habitat quality for native ungulate species and agricultural grazing (Bai et al. 2004), increased the risk of dangerous and severe fire activity (Klenner et al. 2008) and promoted the synchronicity of insect outbreaks (Swetnam and Lynch 1993; Raffa et al. 2008; Maclauchalan and Brooks 2009).

In the Douglas-fir dominated forests of the CFR, western spruce budworm (WSB) (*Choristoneura occidentalis* Freeman) is the most widespread and destructive defoliating insect (Alfaro et al. 2014; Axelson et al. 2015). Tree-ring records show that since AD 1500 the spatial and temporal characteristics of WSB outbreaks in the Pacific Northwest have been characterized by significant variability in intensity and severity (Flower et al. 2014a, Axelson et al. 2015; Flower 2016). The increased temporal and spatial outbreak synchrony since AD 1900 is attributed to increasing forest density and host connectivity (Flower et al. 2014a; Flower 2016). Stand-level studies in B.C. reveal that outbreaks of moderate to high intensity are associated with overstory and understory mortality (Maclauchalan and Brooks 2009), impacting forest ecosystem functioning and economic value.

## 1.2 Climate-disturbance relationships

Climate influences the frequency and severity of insect disturbances by altering environmental conditions to directly promote or inhibit the survival of insects, or by indirectly affecting the distribution and quality of food and habitat resources (Rhoades 1983; White, 1984; Mattson and Haack 1987; Campbell 1993). Historical WSB outbreaks in the inland northwest and southwest United States (U.S.) have been linked to intervals of transitional climate, where outbreaks were triggered by drought conditions and then maintained by positive moisture conditions (Swetnam and Lynch 1993; Flower et al. 2014a). Flower et al. (2014a) postulated that warm, dry years in the Pacific Northwest promote insect survival and dispersal, while wet and cooler years following outbreak initiation increase the quantity and quality of food resources.

Large-scale climate fluctuations also influence the spatial and temporal impact of forest fires (e.g. Westerling et al. 2003; Westerling et al. 2006; Heyerdahl et al. 2008). During intervals of persistent drought reduced fuel moisture preconditions forested landscapes for widespread fire activity (Burgan 1979; Westerling et al. 2006). In contrast, intervals of positive moisture conditions impact fine fuel growth and influence the character of ignition and fire spread in environments with a significant component of fine fuels (Westerling et al. 2003; Gartner et al. 2012; Rother and Grissino-Mayer 2014). Research in B.C. documents a positive relationship between fire activity and interannual moisture stress as recorded by the Palmer Drought Severity Index (PDSI) (Daniels and Watson 2003; Heyerdahl et al. 2012). Shoennagel et al. (2007) and Heyerdahl et al. (2008) also show that anomalously warm, dry, large-scale periods of intradecadal and decadal climate variability are directly correlated to intervals of enhanced fire activity.

### 1.3 Research motivation

Future changes in climate, land-use and population will impact disturbance regimes in all global biomes to result in changes that will have important consequences for ecological and social systems (Turner 2010). The forest ecosystems of B.C. are the most varied of any province in Canada and are a valuable ‘natural laboratory’ for studying the past, current and future effects of climate variability on ecosystem structure and function. While uncertainty surrounds the magnitude of future climate changes in this region and the associated ecological effects, high-resolution proxy records of historic climate and disturbances present an exceptional opportunity for examining past disturbance-climate relationships to better inform future predictions.

This dissertation examines the historic influence of climate variability on both fire activity and WSB outbreaks, and assesses the influence of WSB outbreaks on the occurrence of fire. It also seeks to determine whether proximity to grasslands affects these relationships.

Long-term spatially explicit information on historic fire activity is poorly documented in the CFR (Iverson et al. 2002; Daniels and Watson 2003; Axelson et al. 2010). The few published studies suggest that causal historical relationships exist between climate fluctuations and both fire activity and WSB outbreaks in the region (Heyerdahl et al. 2008; Flower 2016). Understanding the historic character of disturbances and disturbance-climate relationships will better inform forest and grassland management strategies related to activities such as prescribed fire and thinning. Therefore, the specific objectives of the research were to:

1. determine the relationship(s) between historic fire activity and interannual climate variability, and characterize the severity of past fire activity at grassland forest ecotone in the Churn Creek Protected Area (CCPA);
2. develop multi-century reconstructions of fire activity at a number of representative sites in the CFR, and determine the climate drivers (interannual, intradecadal, decadal) of local, moderate and regional fire years; and,
3. develop multi-century reconstructions of WSB outbreaks at representative sites in the CFR, and incorporate existing outbreak reconstructions to determine if grassland proximity influences the relationships between climate, fire and WSB outbreaks.

#### 1.4 Organization of dissertation

Following this chapter, Chapters 2, 3 and 4 present the main results of the dissertation. These results are presented in the dissertation as individual manuscripts written and formatted for refereed journal submission. Chapter 2 is presently in revision for *Ecological Applications* and presents a detailed characterization of grassland and widespread fire activity (frequency and severity) in the CCPA. Chapter 3 is currently being revised for resubmission to the *Journal of Geophysical Research Biogeosciences*. It describes eight new fire history reconstructions that were used in conjunction with several existing fire histories to identify regional fire years and significant relationships with large-scale patterns of climate variability in the CFR. Chapter 4 is formatted for submission to the journal *Forest Ecology and Management*. It presents new and existing reconstructions of WSB outbreaks and existing fire histories in order to document

disturbance-climate relationships and disturbance interactions at eight sites in the CFR. The dissertation concludes with Chapter 5, where the main contributions of the research are identified and presented with linkages to specific management applications. In Chapter 5, I also identify four future research themes that stem from the research presented in the dissertation. Appendix I has supplementary information relevant to Chapter 2.

## **Chapter 2 Mixed-severity fire history at a forest-grassland ecotone in west central British Columbia, Canada**

### 2.1 Article information

Chapter 2 consists of a manuscript accepted for publication by *Ecological Applications*. The text and figures are from the accepted manuscript but have been renumbered and reformatted for consistency within the dissertation. The citation style has been reformatted for consistency throughout the dissertation.

#### *2.1.1 Authors' names and affiliations*

Jill E. Harvey<sup>1\*</sup>, Dan. J. Smith<sup>1</sup>, Thomas T. Veblen<sup>2</sup>

<sup>1</sup> University of Victoria Tree-Ring Laboratory, Department of Geography, University of Victoria, PO Box 3060, STN CSC, British Columbia V8W 3R4, Canada

<sup>2</sup>Department of Geography, University of Colorado, Boulder, Colorado 80309, USA

\*Corresponding Author Email: [jeharvey@uvic.ca](mailto:jeharvey@uvic.ca)

#### *2.1.2 Author's and coauthor's contributions*

Harvey developed the study and hypothesis, conducted and led field and laboratory work, statistical testing, wrote the manuscript and produced all tables and figures. Smith provided guidance in forming the study design, reviewed and edited the manuscript. Veblen provided guidance on analytical approaches, reviewed and edited the manuscript.

## 2.2 Abstract

This study examines spatially variable stand structure and fire-climate relationships at a low elevation forest-grassland ecotone in west central British Columbia, Canada. Fire history reconstructions were based on samples from 92 fire-scarred trees and stand demography from 27 plots collected over a 7 km<sup>2</sup> area. Historical chronologies of widespread fires and localized grassland fires between AD 1600 and 1900 were documented. Relationships between fire events, reconstructed values of the Palmer Drought Severity Index and annual precipitation were examined using superposed epoch and bivariate event analyses. Widespread fires occurred during warm, dry years and tended to be preceded by multiple years having similar conditions. Localized fires that affected only grassland-proximal forests were more frequent than widespread fires. These localized fires showed a lagged, positive, relationship with wetter conditions. The landscape pattern of forest structure provided further evidence of complex fire activity with multiple plots shown to have experienced low, mixed and/or high-severity fires over the last four centuries. The findings indicate that historically this forest-grassland ecotone was characterized by fires of mixed-severity dominated by frequent, low-severity, fires punctuated by widespread fires of moderate to high severity. This landscape-level variability in fire-climate relationships and patterns in forest structure has important implications for fire and grassland management in west central British Columbia and similar environments elsewhere. Forest restoration techniques such as prescribed fire and thinning are oftentimes applied at the forest-grassland ecotone on the basis that historically high frequency, low severity fires defined the character of past fire activity. This study provides forest managers and policy makers important information on mixed

severity fire activity at a low elevation forest-grassland ecotone, a crucial prerequisite for the effective management of these complex ecosystems.

### 2.3 Introduction

Extensive natural grasslands characterize the arid valley-bottoms of the Fraser, Nicola and Thompson rivers of interior southern British Columbia (B.C.). At elevations over 700 m above sea level (asl) in these valleys, however, there is often sufficient moisture to support trees allowing for a gradual transition to forests (Tisdale 1947; Tisdale and McLean 1957; Nicholson et al. 1991). Like forest-grassland ecotones elsewhere, this transition is recognized as a dynamic natural boundary controlled by a complex suite of abiotic and biotic factors including fire, climate and grazing (Hansen and di Castri 1992; Risser 1995; Staver et al. 2011). An important ecological legacy in the forest-grassland ecotones of interior southern B.C. is the spatial and temporal pattern of historical fires, as the severity of past fires is retained in the demographic patterns of forest structure.

High-frequency, low-severity, fires are presumed by many to be responsible for the historical character and extent of the forest-grassland ecotones of interior B.C. (Lepofsky et al. 2003, Bai et al. 2004). However, mixed-severity fire regimes are increasingly recognized as integral to the long-term ecology of similar dry forests and forest-grassland ecotones in western North America (Arsenault and Klenner 2005; Hessburg et al. 2007; Sherriff and Veblen 2007; Klenner et al. 2008; Perry et al. 2011; Odion et al. 2014, Sherriff et al. 2014). ‘Mixed-severity’ is used to describe both the variability in fire severity over multiple fires at one site, and the variation in burn severity in one fire (Perry et al. 2011). These mixed-severity regimes are generally the product of

interactions between top-down climate forcing and bottom-up controls of fuel and topography (Perry et al. 2011; Marcoux et al. 2015; Chavardes and Daniels 2016). Moderate to severe fires kill overstory trees and characteristically allow for the establishment of patchy even-age cohorts under conditions of sufficient seed source and post-fire climate suitable for tree establishment (Oliver and Larson 1990). The resulting heterogeneous forest structure supports diverse habitat, greater species diversity and demonstrates resiliency to disturbance (Reich et al. 2001; Petersen and Reich 2008; Heyerdahl et al. 2012). While the same fires are presumed to play a key ecological role in maintaining the adjacent grasslands (Tisdale and McLean 1957; Turner and Krannitz 2001; Sherriff and Veblen 2007), the historical encroachment of trees into these grasslands and the conifer infilling of meadows in the forest-grassland ecotone is of growing ecological and economic concern (Covington and Moore 1994; Bai et al. 2004; Klenner et al. 2008).

Native grasslands and the forests adjacent to these grasslands are economically important forage areas for livestock grazing within interior B.C. (Bai et al. 2004). In the absence of 20<sup>th</sup> century fires trees such as Douglas-fir (*Pseudotsuga mezesii* var. *glauca* Beissn. Franco), ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws) and Rocky Mountain juniper (*Juniperus scopulorum*) are advancing beyond the forest-grassland ecotone to encroach into the adjacent upper elevation grasslands (Strang and Parminter 1980, Turner and Krannitz 2001; Lepofsky et al. 2003; Bai et al. 2004). This encroachment has significantly reduced the available forage area (Turner and Krannitz 2001; Bai et al. 2004) and has many advocating for the application of enhanced management practices to restore their historical character (Klenner et al. 2008; Hessburg

et al. 2016). With recent research indicating that prescribed fire and mechanical treatments applied heterogeneously across similar landscapes assists in the restoration of historical multi-scale structural complexity (Ryan et al. 2013; Hessburg et al. 2016), there is an acute need to establish reference conditions of the prevailing fire regime prior to the initiation of modern land-use practices in the mid- to late-1800s (Landres et al. 1999; Swetnam et al. 1999; Keane et al. 2009).

The goal of this study was to describe landscape-level variability in fire occurrence, stand structure and fire-climate relationships at a forest-grassland ecotone in west central B.C. The intent of the research was to: (1) use dendroecological methods to describe tree establishment histories in forested areas of the study area; (2) characterize wildfire activity in terms of frequency and severity; and, (3) document fire-climate relationships. Ecological data derived from dendrochronological investigations and stand demography methods is used to reconstruct past fire regimes (Falk et al. 2011).

Fire-scarred trees preserve an annual and sometimes seasonal record of fire events (Arno and Sneek 1977) and documentation of stand age structure provides insights on the severity of past fires (e.g. Marcoux et al. 2015; Chavardes and Daniels 2016). While the term ‘fire severity’ can encompass both aboveground and belowground ecological changes that arise from fire activity (Keeley 2009), in this study the term ‘fire severity’ is used to describe only the effects of fire activity on forest structure.

Comparable baseline ecological data for historical fire regimes in central interior B.C. is limited (Daniels and Watson 2003; Heyerdahl et al. 2007, 2008, 2012). Given this, it was hypothesized that frequent, low severity fires would affect grassland proximal forests (fuel-limited ecosystems) and have a positive relationship with antecedent

moisture conditions. It was also postulated that historically widespread fires occurred with greater severity across the entire study area and were climatically-related to persistent drought-like conditions.

This research provides valuable insight into the response of interior forest-grassland ecosystems to changing climates. Furthermore, the research findings provide information essential for developing future forest management strategies and for designing restoration treatments appropriate to changing climate-fire regimes.

## 2.4 Methods

### 2.4.1 *Study area*

The study area is located in the Churn Creek Protected Area (CCPA) on the Fraser Plateau in west central B.C., Canada (Figure 2.1). The CCPA was established in 1995 primarily for the conservation of native low, middle and high elevation bunchgrass grasslands (B.C. Parks 2000). The adjacent Empire Valley Ranch area was added to the CCPA in 1998. The CCPA now covers almost 37,000 ha of grasslands and interior Douglas-fir forests, and is the largest area of protected native grassland in B.C. (Reid 2008, 2010).

The study area encompasses an area of approximately 7 km<sup>2</sup> within the central CCPA and ranges in elevation from 850 to 1300 m asl (Figure 2.2). The CCPA is located within the rainshadow of the Pacific Ranges of the B.C. Coast Mountains. It typically experiences warm, dry summers and cold, dry winters (Moore et al. 2010). Climate normals (AD 1971-2000) at Big Creek (60 km northwest of the study area) average 13°C in July and -10°C in January. Precipitation totals range from 51 mm of rain in the

summer months to 25 cm of snowfall in winter months, with 337 mm of precipitation falling annually (Environment and Climate Change Canada 2016).

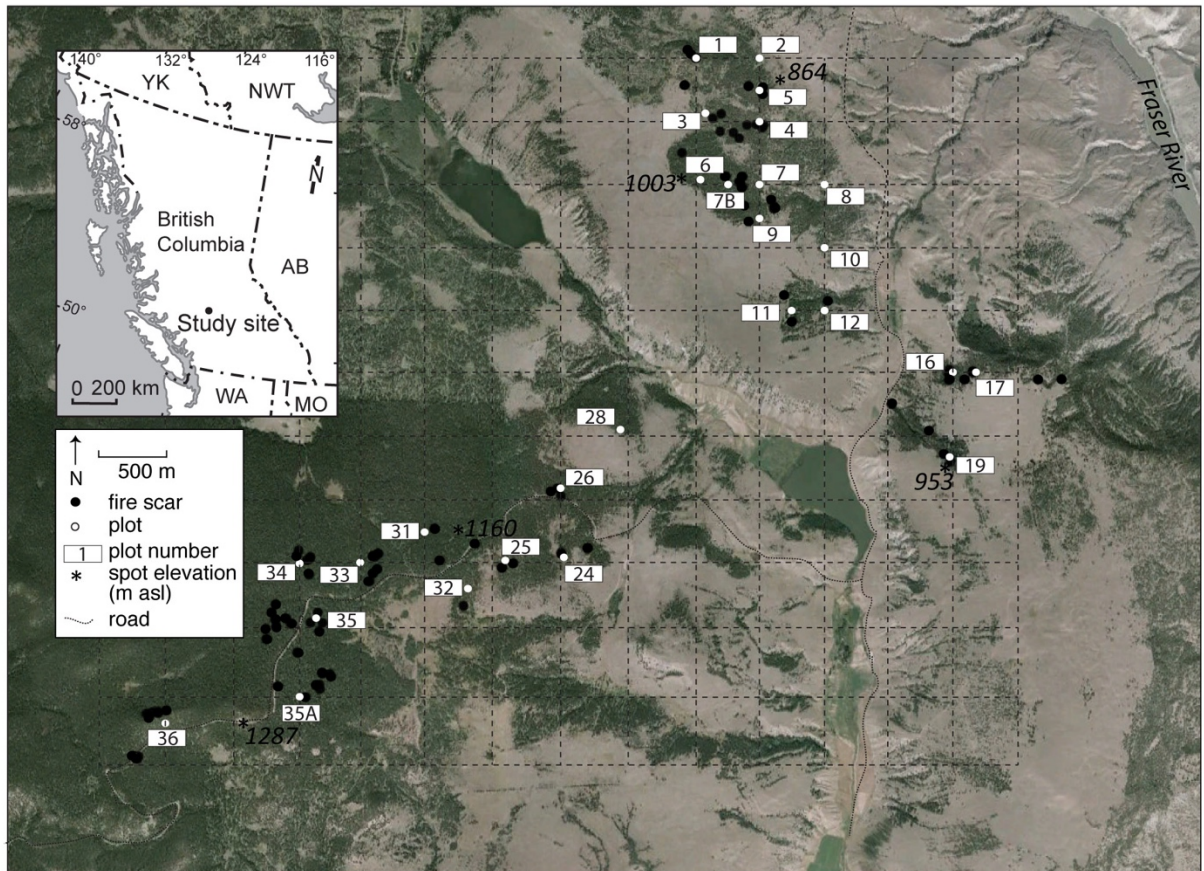


Figure 2.1. The Churn Creek Protected Area study site located in west central British Columbia showing the location of 92 sampled fire-scarred trees and 27 age-structure plots (Google Earth 2016). The hatched network is the 500 m grid used to locate the age-structure plots. White circles with numbered boxes represent plot locations and numbers, black circles mark fire-scarred trees sampled in this study and stars indicate spot elevations in the study area.

The CCPA landscape is characterized by relatively flat terrain or gentle east to southeast-facing slopes at elevations ranging from 850 to 1100 m asl. The vegetation is dominated by a mosaic of grasslands and Douglas-fir forests that shift in composition in response to local site-specific changes in climate, site or historical impacts (B.C. Parks 2000). Grassland vegetation is characterized by bluebunch wheatgrass (*Elymus spicatus*),

short-awned porcupine grass (*Hesperostipa spartea*) and spreading needlegrass (*Acnatherum richardsonii*). Forested areas are dominated by Douglas-fir trees, with small pockets of trembling aspen (*Populus tremuloides* Michx.) found in moist depressions.

From 1100 to 1300 m asl, the CCPA landscape is generally flat with a slight southeast-facing aspect. At 1000-1100 m asl the upper grassland transitions to a vegetation cover consisting increasingly of Douglas-fir trees. At elevations close to 1300 m asl Douglas-fir forests dominate, with aspen at moister sites and infrequent lodgepole pine (*Pinus contorta* Dougl.). At elevations above 1300 m asl and outside the study area, lodgepole pine intermixes with Douglas-fir and then becomes the dominant montane tree species above 1500 m asl.



Figure 2.2. (A) Landscape view of the study site looking southeast towards Plots 16 and 17. (B) Sample collected from a standing dead Douglas-fir tree at Plot 4. The tree was located about 200 m from expansive grasslands and within a closed canopy forest. This tree records twelve fire events from AD 1620-1896 with an average return interval of 25 years.

During the twentieth century, Douglas-fir trees in the CCPA encroached into many middle and upper grasslands. The character of this encroachment is similar to that recorded elsewhere in B.C. (Strang and Parminter 1980; Turner and Krannitz 2001; Lepofsky et al. 2003; Bai et al. 2004) and in the western United States (Soulé and Knapp 2000; Heyerdahl et al. 2006). Previous research shows this conifer encroachment into grasslands occurs during sporadic seedling establishment events and/or by a process of steady infilling. The factors influencing the nature of this infilling include the reduction in fire occurrence since the early 1900s (Turner and Krannitz 2001; Heyerdahl et al. 2006), and warmer spring temperatures and reduced spring snow depth since the 1970s (Lepofsky et al. 2003). More broadly, twentieth-century conifer encroachment into grasslands is oftentimes ascribed to a combination of factors including climate, domestic livestock grazing and the cessation of frequent fire (Bai et al. 2004; Heyerdahl et al. 2006).

Limited archeological evidence shows First Nations activity in the region dates to before 5000 years ago (Cybulski et al. 2007; Reid 2008, 2010). Cultural depressions at Big Bar Lake indicate winter occupation of pithouse villages, as well as the procurement of food from local sources (Wilson 1998). Oral histories suggest a traditional use of grassland fires in the region to promote ungulate browsing. Fires were deliberately set in spring to thin understory brush and suppress encroaching sagebrush and conifer seedlings (Turner 1999; Blackstock and McAllister 2004).

Early gold explorers passed through the CCPA in the early to mid-1800s and small placer mines operated in the Empire Valley through the late 1800s (Parminter 1978). Cattle ranching began at Gang Ranch north of the study area in the 1860s, and

small herds of cattle have been grazing in the Empire Valley since the end of 19<sup>th</sup> century. The number of cattle in the Empire Valley varied through the early 1900s, peaking in the 1960s with 2000 head of cattle (B.C. Parks 2000). Historical logging occurred within parts of the study area in the early 1900s and led to patches of higher-density second growth stands.

#### *2.4.2 Site selection, field sampling and sample processing*

A 7000 ha area within the CCPA was identified for study in 2013 (Figure 2.1). The area was selected to avoid sites influenced by historical and contemporary logging, as well as areas likely to have been influenced by prescribed fire and thinning activities (B.C. Parks 2000). As previous research indicates that forest-grassland adjacency is useful for extracting climate-fire relationships in grassland environments (Sherriff and Veblen 2008; Gartner et al. 2012), a study area was selected that included mature, grassland-adjacent forests. Field reconnaissance showed that beyond approximately 400 m from the expansive grasslands characterizing the CCPA, elevation and forest density typically increased.

Plots to determine tree establishment histories in forested areas were located based on a 500 m grid over the study area (Figure 2.1). At sites with minimal forest cover, the density of plots was increased and a 250 m grid used. Plots were randomly adjusted 50 or 75 m when grid intersection points occurred in areas affected by seasonal roads, absence of forest cover, very steep slopes and/or evidence of historical logging. A n-tree density adapted plot sampling strategy was employed (Lessard et al. 2002; Brown and Wu 2005) where the plot size varied and the nearest 30 standing dead trees, snags or living trees  $\geq 1.7$  m in height to the plot centre were sampled. Increment borers were used

to take two cores ~25 cm above the ground surface from trees with a diameter at breast height (dbh)  $\geq 7$  cm. Basal disks were taken from all trees with a dbh of  $< 7$  cm. At Plot 7 basal sections were taken from 30 seedlings approximately 25 cm tall to establish a site-level coring-height correction factor (Wong and Lertzman 2001).

To reconstruct fire history records at each plot, 1-6 fire-scarred trees with the greatest number of scars were identified within circular 1 ha search areas surrounding the centre of each plot (Arno and Sneek 1977; Amoroso et al. 2011; Chavardes and Daniels 2016). Scar samples were collected from living trees and standing dead trees, as well as from fallen logs, stumps and coarse woody debris. In addition, fire-scarred trees with well-preserved fire records outside the 1 ha search areas were opportunistically sampled.

Increment cores and fragile cross sections were glued to wooden mounts and allowed to air dry. The samples were sanded with progressively finer grits until the xylem cellular structure was visible under magnification. Both visual and statistical methods (Grissino-Mayer 2001) were used to crossdate all samples against a previously developed master chronology (AD 1490-2009) from nearby Farwell Canyon (Axelson et al. 2015).

Fire scars were dated based on their year of record in crossdated annual rings (Dieterich and Swetnam 1984). Whenever possible the fire season was assigned on the intra- or inter-ring position of the scar. Each fire was classified as having occurred: during the dormant season; during the time of early-, middle-, or late-earlywood cell development; or, during the formation of latewood cells (Baisan and Swetnam 1990). I interpreted dormant season scars to represent fires that occurred in the late summer or fall following the cessation of seasonal latewood growth (Caprio and Swetnam 1995). The modern season of peak fire activity supports this convention.

The establishment date of individual trees (living and dead) within each plot was determined from the increment cores or basal disks by annual ring counts and crossdating (Grissino-Mayer 2001). Correction factors were used to account for cores that missed the pith and to adjust for sampling height error (Sigafos and Hendricks 1969). In the case of off-centre cores, a geometric model was used to estimate the number of rings to the pith (Duncan 1989). To correct for coring height, the average age of 30 seedlings 25 cm tall was added. No correction factors were applied to the basal disks.

#### *2.4.3 Fire history, frequency and severity*

Two fire chronologies were reconstructed. One chronology was constructed from fires that scarred at least 25% of recording samples across the entire study area where at least 2 trees recorded a fire event (referred to hereafter as ‘widespread fires’). Fire dates from samples located within 400 m of grasslands and that scarred at least 10% of recording trees (and that has at least 2 trees recording the fire event) were composited into a second chronology (referred to hereafter as ‘grassland fires’). The grassland fire chronology included all fire years that affected the forest-grassland ecotone. To exclude modern human influences on local fire regimes, fire events after AD 1900 were excluded from the fire chronologies.

Fire severity was inferred from stand demography reconstructed from the establishment plots. The establishment of even-aged Douglas-fir forest cohorts within interior B.C. characteristically follows disturbance resulting from fires, insect outbreaks and windthrow events (Heyerdahl et al. 2012). For this study, a cohort was identified if five or more trees established within a 20 year period, preceded by a 30 year period over which no trees established (Heyerdahl et al. 2012; Chavardes and Daniels 2016). Fire

events recorded on samples within 150 m of a plot were then compared to the intervals of establishment (cohorts) for that plot (Brown et al. 2008; Heyerdahl et al. 2012). I found that including samples taken from fire-scarred trees within 150 m of each plot improved the length and replication of fire events for the plot-level fire history reconstructions. Due to the abundant presence of fire scars, soil charcoal and charred coarse woody debris viewed within the even aged cohorts examined, it was postulated that all developed following fire events. While cohorts can establish following other disturbances (Axelson et al. 2009), no evidence of historical stand-altering insect or windthrow events was found. Following Heyerdahl et al. (2012) I visually compared cohort establishment dates with those captured by the Palmer Drought Severity Index (PDSI) reconstruction to determine whether seedling establishment events followed intervals of cool and (or) wet climate conditions.

The presence of fire scars and even-aged cohorts were used to assign each plot to one of three classes of fire severity (Heyerdahl et al. 2012; Chavardes and Daniels 2016). Low-severity fire plots were distinguished: (1) where there was scar evidence of multiple fire years and the presence of a cohort originating after only the last fire; or, (2) when a plot contained trees with variable establishment dates and no visible fire scars. Criteria for identifying historic mixed-severity fire plots included: (1) the presence of multiple fire scar years and two or more even aged-cohorts; or, (2) the presence of multiple fire scar years and a cohort that was affected by subsequent fires. High-severity fire activity was identified at plots with no fire-scarred trees and an even-aged cohort.

#### *2.4.4 Climate data*

Tree-ring derived proxy indices of the PDSI and precipitation were used to analyze fire-climate relationships from AD 1600-1900 (Cook et al. 2008a; Watson and Luckman 2004). Negative PDSI values in June-August describe warm and dry conditions, whereas positive values indicate wet, cool conditions (Cook et al. 2008a). In the analyses that follow, reconstructed PDSI values from Gridpoint 30 (120 km north of the study area, 805 m asl)(Cook et al. 2008a) were used. Autocorrelation from the PDSI time series was removed by fitting an autoregressive integrated moving average model of an order determined based on Akaike's Information Criterion (Heyerdahl et al. 2008; Flower et al. 2014a). A reconstruction of annual precipitation (previous June to current July) at Big Creek, B.C., was also employed (Watson and Luckman 2004). Big Creek is located 55 km northwest from the study area and at a similar elevation (1130 m asl). Autocorrelation was not detected in the precipitation time series.

#### *2.4.5 Fire-climate relationships*

Superposed epoch analysis (SEA) and bivariate event analysis (BEA) were used to evaluate for associations between the fire chronologies and climate variability. Climate-fire studies commonly use SEA to elucidate interannual relationships between fire occurrence and climate over short intervals (3-5 years) (Grissino-Mayer and Swetnam 2000; Trouet et al. 2010). BEA has also been employed in fire-climate research (e.g. Gartner et al. 2012; Rother and Grissino-Mayer 2014) to assess interactions between fire activity and extreme climate events over variable windows of analysis (e.g. 10-30 years; Gavin et al. 2006; Gavin 2010).

SEA was used to determine if the mean value of the climate reconstruction differed significantly in each year before ( $t=-1$  to  $-4$ ), during ( $t$ ) and after fire events ( $t=+1$  to  $+4$ ). Confidence intervals of 95% and 99% were developed using bootstrapping methods to assess statistical significance. The pre-whitened anomalies of PDSI and the precipitation reconstruction were used in the SEA. BEA was conducted in K1D software (Gavin 2010), and extreme climate years were defined as those where the index value was at least one standard deviation (positive or negative) from the mean (Rother and Grissino-Mayer 2014). The bivariate Ripley's K-function was transformed to the  $L$  function to stabilize the mean and variance and improve result interpretation (Gavin et al. 2006; Gavin 2010). Forward selection was used in the K1D software, where fire events were preceded by extreme climate years, and 95% confidence intervals were generated based on 1000 randomized Monte Carlo simulations. Values of the  $L$  function that exceed the upper confidence interval indicate a strong relationship of fire events  $t$  years after the extreme climate years. Values of the  $L$  function that fall below the lower confidence interval indicate fire-climate asynchrony at  $t$  years after the extreme climate years.  $L$  function values between the confidence intervals indicate fires occur independently of extreme climate years.

## 2.5 Results

### 2.5.1 *Fire history, frequency and severity*

Partial cross sections from 98 fire-scarred Douglas-fir trees allowed for identification of 437 individual fire scars. Six samples were excluded from analysis due to substantial decay. The majority of fire scars (73%) were identified at the boundary between latewood and earlywood. The ring position of the remaining scars was

undetermined (16%), within the latewood (7%) or in the late portion of the earlywood (3%). Very few scars were identified in the early or middle portion of the earlywood ( $n=5$ , <1%).

A total of 14 unique widespread fire events and 28 unique grassland fire events were identified from AD 1600 to 1900 (Figure 2.3; Appendix 1). Composited fire return intervals were calculated to broadly characterize fire frequency at the plot level (including 150 m search areas) (Table 2.1). After ~AD 1896 wildfire activity markedly decreased, coinciding with the advent of cattle grazing, fire suppression and mineral exploration in the region.

Twenty-seven stand demography plots were established. Twenty plots were located at or near the intersection points of the 500 m grid and seven plots were located at or near the intersection points of the 250 m grid (Figure 2.1). The locations of 10 plots were adjusted from grid intersection points due to seasonal roads, absence of forest cover, very steep slopes and/or evidence of historical logging.

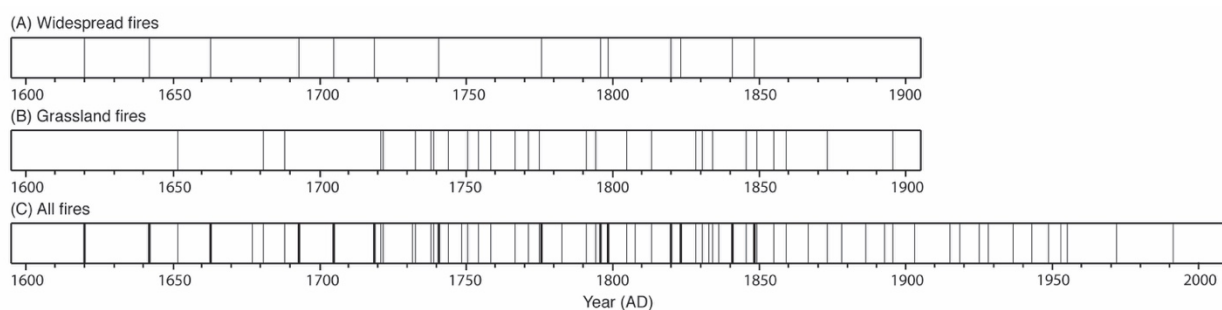


Figure 2.3. Widespread (A) and grassland fire (B) chronologies between AD 1600 and 1900 used in these analyses. Widespread fire years were identified when fire was recorded by at least 25% of recording samples over the entire research area. Grassland fires were identified as fires that scarred at least 10% of recording samples (and  $\geq 2$  samples) within 400 m of grasslands. All fires recorded in the study area between AD 1600 and 2010 (C). All fires that occurred between AD 1901 and 2010 were not included in the analyses and were not widespread. Widespread fires are thicker lines.

I sampled 810 trees in the 27 plots. The plot radius varied from 10 to 17 m and the average plot size was 0.03 ha. Pith was missed on 76% of cores, with between 1 and 15 rings added using the method described (Duncan, 1989). Samples were excluded if more than 15 rings were needed to correct for pith ( $n=31$ ) or if establishment dates of dead trees could not be found using crossdating methods ( $n=56$ ). To correct for coring height, the average age (23 years; range 15 to 33 years; standard deviation 4.6) of 30 seedlings was added to the earliest year of each tree core.

Trees in five plots had multiple fire scar years and a cohort established in the mid- to late 1800s following the last recorded fire located within 150 m of the plot (Figure 2.4). One plot (Plot 6) had no fire scars or even aged-cohorts, but did exhibit variable tree establishment over 400 years (Figure 2.4). Three plots had multiple cohorts and multiple fire scars (Plots 1, 3 and 9). The majority of plots ( $n=13$ ) had a single cohort established in the mid-1800s and a record of multiple fires before and after the cohort established. Three plots had no fire scars and the presence of one even-aged cohort (Plots 2, 10 and 28) or no cohort (Plot 8; Figure 2.4). One plot (Plot 11) had one fire event recorded on one tree and one cohort. None of the cohorts examined showed a relationship between establishment and intervals of cool and wet climate conditions.

Table 2.1. Fire record characteristics for the 27 plots in the study area.

Plot	Fire record (years AD)	Number of fire scar samples	Number of cohorts	Number of fire return intervals	Mean return interval (years)	Range of return interval (years)	Fire regime severity	First fire year (year AD) <sup>a</sup>	Last fire year (year AD) <sup>a</sup>
1	1677-2012	2	2	8	23	7-62	Mixed	1741	1925
2	-	0	1	-	-	-	Not determined	-	-
3	1587-2012	3	2	11	20	4-39	Mixed	1620	1841
4	1588-2012	4	1	19	16	1-33	Mixed	1620	1927
5	1601-1989	2	1	10	18	4-40	Low	1681	1863
6	-	0	1	-	-	-	Low	-	-
7	1592-2012	2	1	7	33	11-70	Low	1663	1896
7B	1600-1983	2	1	15	16	3-29	Mixed	1620	1859
8	-	0	0	-	-	-	Not determined	-	-
9	1712-2012	4	2	16	13	2-41	Mixed	1722	1937
10	-	0	1	-	-	-	High	-	-
11	1719-2012	1	1	*	*	*	Not determined	1859	1859
12	1755-1950	1	1	2	47	46-47	Low	1813	1896
16	1689-2012	4	1	14	11	1-34	Mixed	1699	1859
17	1680-2012	3	1	7	20	1-47	Mixed	1754	1896
19	1550-1964	1	1	2	69	61-76	Low	1722	1859
24	1689-2012	1	1	5	48	26-74	Mixed	1693	1925
25	1609-2012	3	1	8	37	12-104	Mixed	1663	1955
26	1784-2012	3	1	7	6	1-11	Mixed	1820	1863
28	-	-	1	-	-	-	High	-	-
31	1741-2012	2	1	10	11	5-22	Mixed	1776	1886
32	1780-1926	1	1	4	18	10-29	Low	1792	1865
33	1640-2012	4	1	14	16	6-42	Mixed	1642	1897
34	1606-2012	6	1	17	15	3-88	Mixed	1693	1955
35	1520-2012	4	1	17	22	8-58	Mixed	1586	1955
35A	1689-2001	5	1	11	16	2-81	Mixed	1783	1958
36	1665-2012	4	1	8	18	2-36	Mixed	1705	1848

<sup>a</sup> Years when fire was recorded by  $\geq 1$  tree in plot.

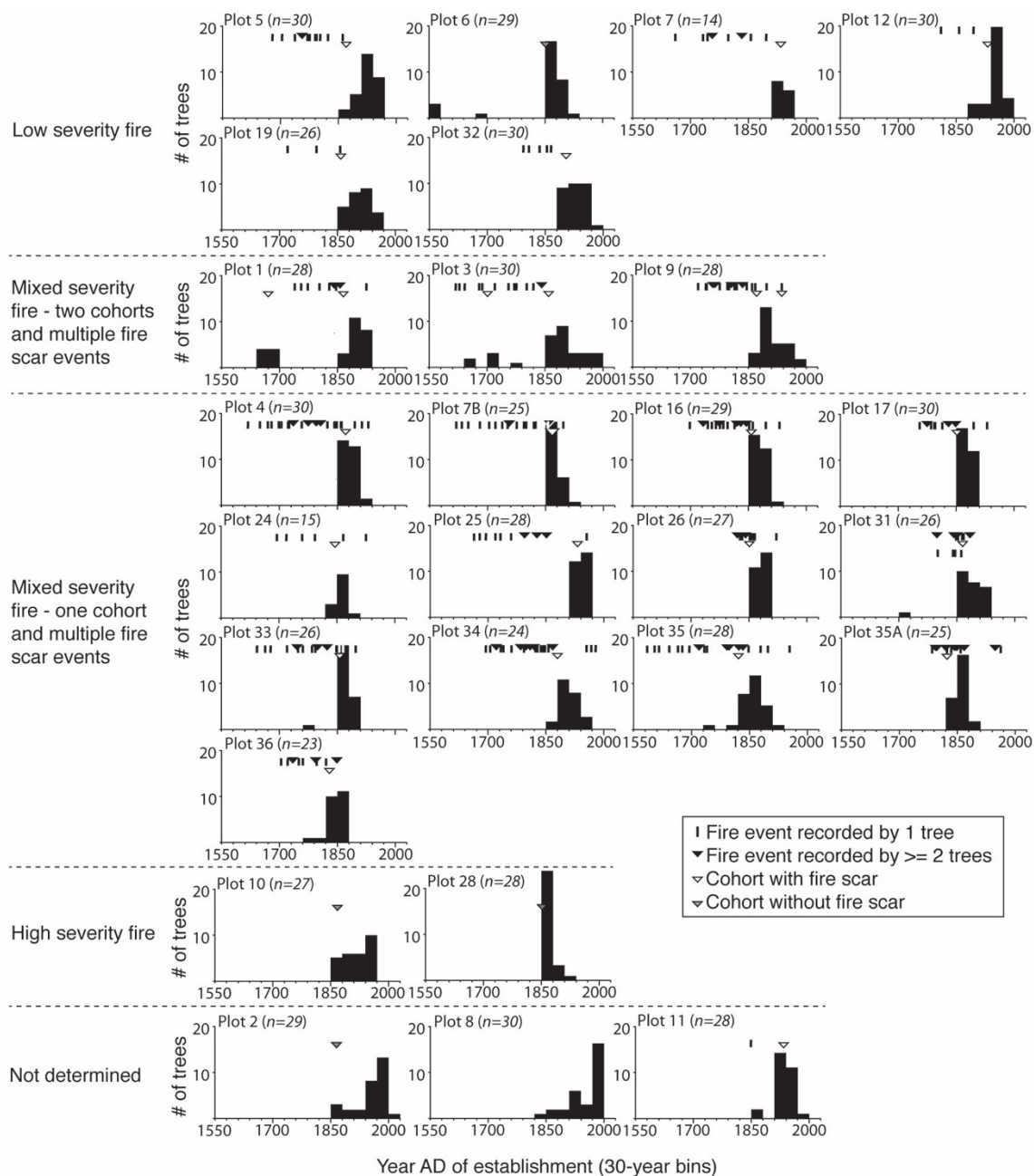


Figure 2.4. Fire history reconstructed from fire scars and post-fire even-aged cohorts for the 27 plots. The x-axis of each histogram records the year of tree establishment in 30-year bins and the y-axis measures the number of live and dead trees crossdated from each plot (total number of trees in each plot given in parentheses). Cohorts are marked by the establishment date of the youngest tree in the cohort.

### 2.5.2 Fire-climate relationships

Statistically significant relationships were identified between fire years, PDSI and precipitation using SEA (Figures 2.5 and 2.6). Years of widespread fires ( $t=0$ ) were significantly associated with dry and warm years ( $P < 0.01$ ; Figure 2.6). Grassland fires were not significantly associated with dry warm years in the fire year ( $t=0$ ), but were significantly associated with cooler, wetter conditions ( $P < 0.05$ ; Figure 2.6) in the year preceding the fire ( $t-1$ ). In years with no fire ( $n=238$ ), SEA indicates conditions were cooler and wetter ( $P < 0.05$ ).

Statistically significant relationships were found using BEA between extreme PDSI and precipitation years, and widespread and grassland fire events (Figure 2.7). Widespread fire years were synchronous with negative extreme PDSI years during the fire year and nine years preceding the fire. Widespread fires were also synchronous with dry conditions (negative extreme precipitation years) in the year of the fire ( $t=0$ ) and the year preceding the fire ( $t-1$ ). While widespread fires were not related to positive PDSI and positive precipitation extreme years, grassland fires were synchronous with positive PDSI extreme years in the year of the fire ( $t=0$ ) and positive precipitation extreme years in the year of the fire and year preceding the fire ( $t=0, t-1$ ). To summarize, BEA revealed that widespread fires were in-phase with negative, extreme PDSI and precipitation years but out of phase with positive, extreme PDSI and precipitation years. Grassland fires were in-phase with positive, extreme PDSI and precipitation years and out of phase with negative, extreme PDSI and precipitation years.

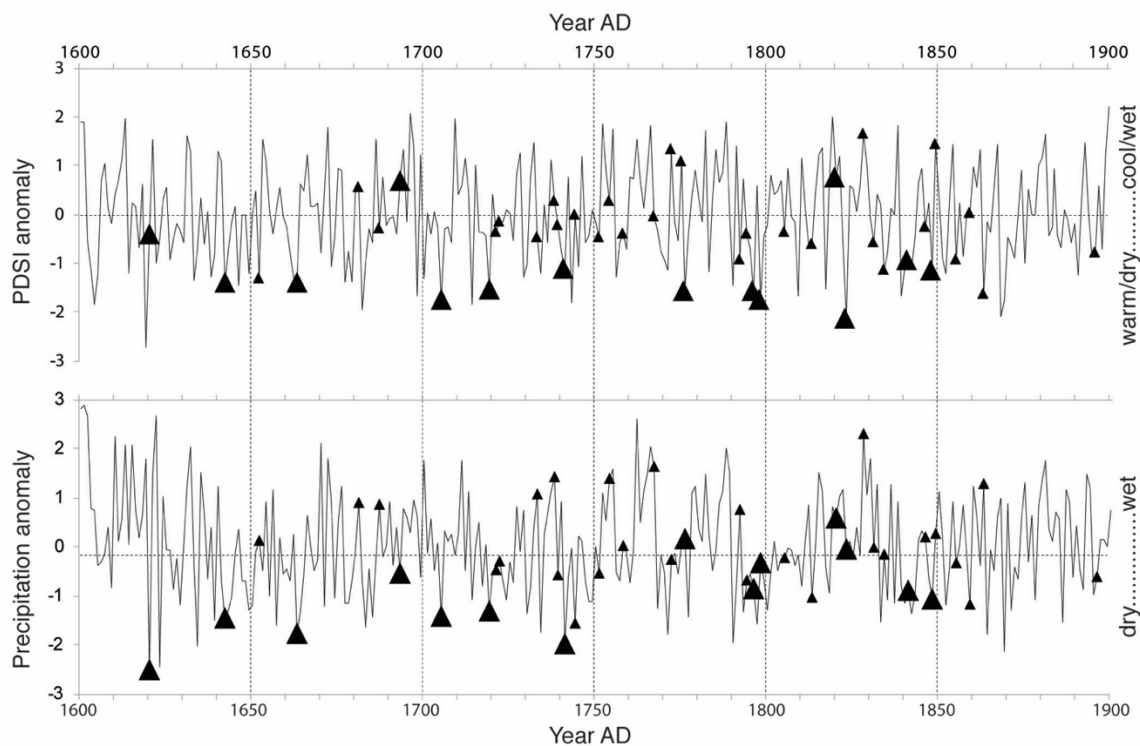


Figure 2.5. Fire and climate relationships from AD 1600-1900. Widespread fire years (large triangles) were identified where fire was recorded by at least 25% of samples over the entire research area. Small triangles mark localized fires within 400 m of grasslands (where at least 10% of recording samples (and  $\geq 2$  samples) were scarred). Lines designate annual tree-ring reconstructed Palmer Drought Severity Index (Gridpoint 30; Cook et al. 2008a) and precipitation (Big Creek; Watson and Luckman 2004) anomalies. General gradients of climate conditions associated with each climate reconstruction are on the right-hand axis (Watson and Luckman 2004; Cook et al. 2008a).

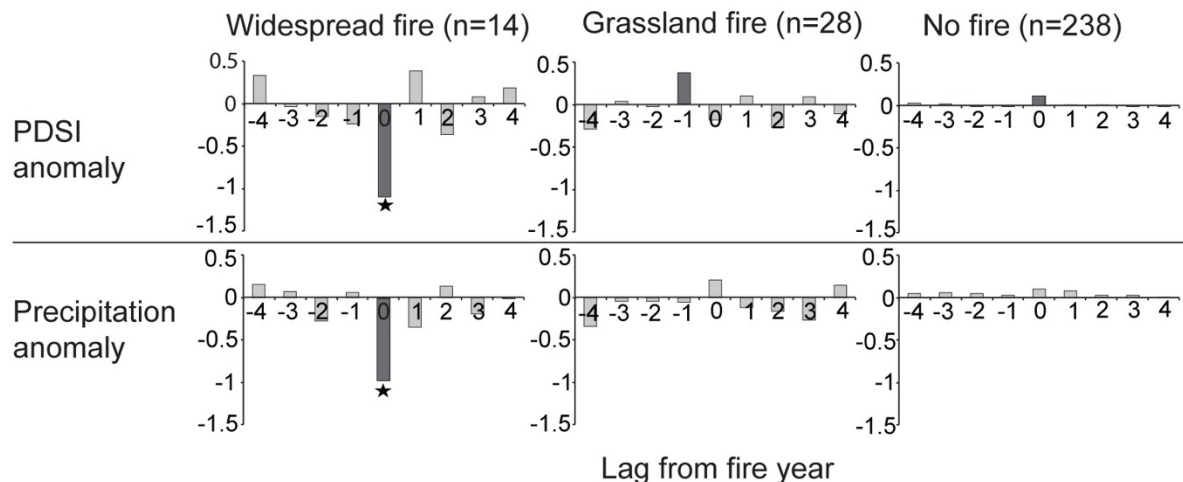


Figure 2.6. Lagged interannual relationships of climate and fire from AD 1600-1900, showing mean departures (standard deviations) from climate during 14 years with widespread fire, 28 years with localized grassland fire, and 238 years with no fires for years before ( $t = -4$  to  $-4$ ), during ( $t = 0$ ) and after ( $t = +4$  to  $+4$ ) fire or no fire years. Climate records included in analysis include the Palmer Drought Severity Index (Gridpoint 30; Cook et al. 2008a), and precipitation (Big Creek; Watson and Luckman 2004). Temporal autocorrelation was removed from the PDSI time series using an ARMA model of an order determined based on Akaike's Information Criterion. Dark grey shading shows the fire relationships with statistically significant (at the 95% confidence interval) anomalies. Stars indicate statistical significance at the 99% confidence interval.

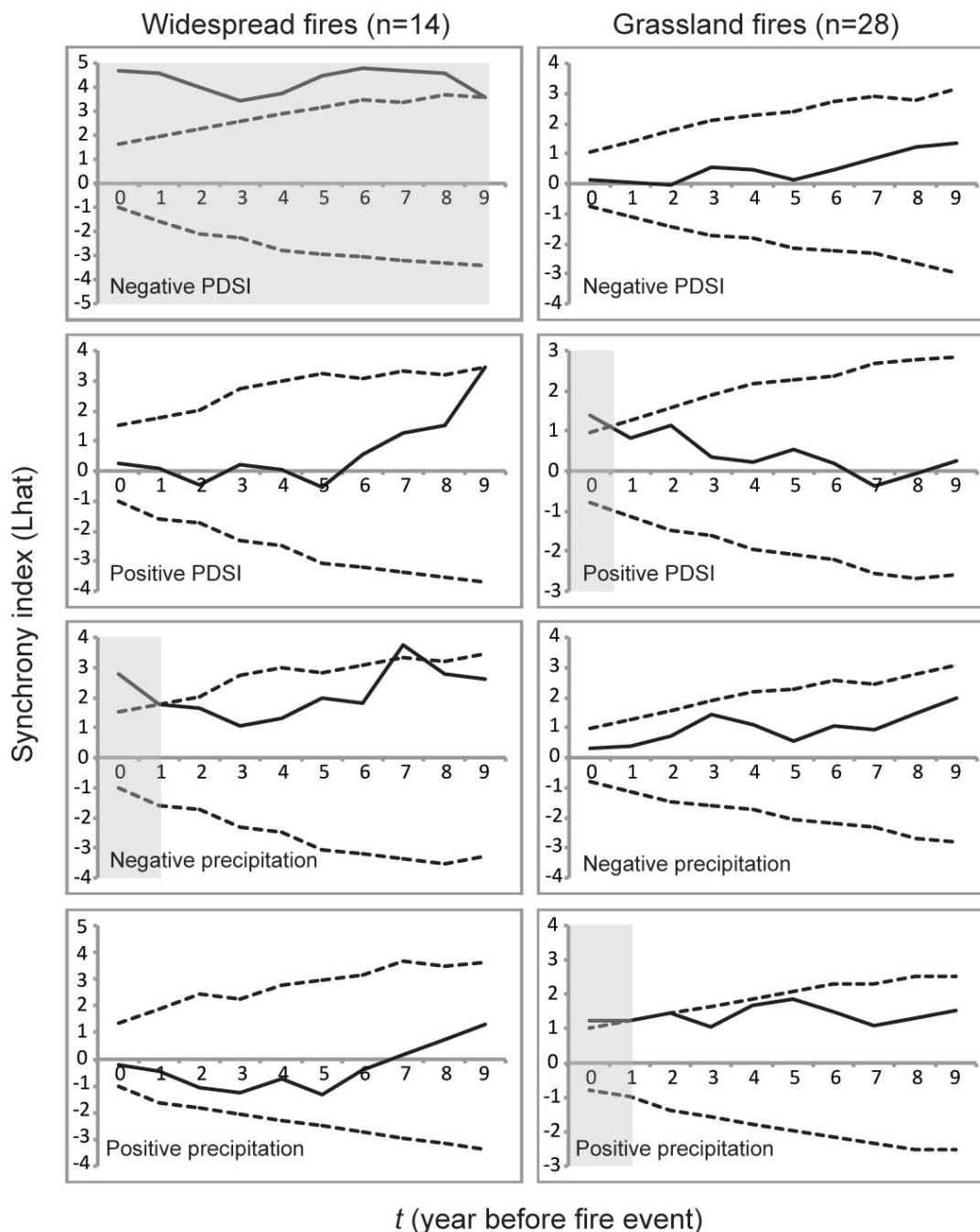


Figure 2.7. Bivariate event analysis of the temporal association of extreme negative and positive Palmer Drought Severity (Gridpoint 30; Cook et al. 2008a) and precipitation (Watson and Luckman 2004) years with fire in CCPA (AD 1600-1900). Extreme climate events were defined using a threshold based on  $\pm 1$  SD. Black solid lines indicate  $Lhat$  values ( $L$  function with stabilized mean and variance) for  $t$  years before the fire events ( $t \neq 0$ ). Dotted lines indicate the upper and lower confidence intervals (95%).  $Lhat$  values outside the confidence intervals indicate synchrony with fire, and values between the confidence intervals indicate a random relation of fire and climate events. Grey shaded bars highlight statistical significance ( $P < 0.05$ ).

## 2.6 Discussion

### 2.6.1 *Fire history*

Between AD 1600 and 1900 the study area was affected by 14 widespread fires. Twenty-eight smaller fires were recorded on at least two scarred trees located at or near grassland areas over the same interval (Figures 2.4 and 2.5). Similar to research in the adjoining Cariboo-Chilcotin region that reported a mean fire interval of 27 years (AD ~1600-1988; ~1 ha search areas; Daniels and Watson 2003), my data describes a mean fire interval of 23 years averaged across the 21 plots with 2 or more fire scars (Table 2.1). The limited number of grassland fires recorded from AD 1600 to 1700 is attributed to the low number of >300 year old fire-scarred trees found within the local forest-grassland ecotone.

The majority of fire scars were identified at the boundary between latewood and earlywood cells. This observation suggests most fires occurred in late July to early August at or near the cessation of the latewood growth season. In contrast, spring fires recorded in the earlywood were very few (4% of scars). One notable exception was the widespread fire of AD 1820 that scarred 32% of the middle to late earlywood or latewood cells of recording samples. As regional fires were scarce in the spring of AD 1820 (Iverson et al. 2002; Daniels and Watson 2003; Heyerdahl et al. 2007, 2008, 2012), and the reconstructed PDSI and precipitation records do not indicate anomalously dry conditions (Figure 2.5), I speculate that First Nations burning or heightened lightning activity may explain this unusual widespread fire event.

### 2.6.2 *Fire severity*

The forest structure data indicates that stands throughout the study area experienced both frequent, stand-maintaining fires and widespread, stand-altering fires. At six plots evidence was found of low-severity fires. In five of the low-severity plots, it appears that a cohort established after the last fire and, in the absence of subsequent fires, grew to dominate the forest structure. These plots were mostly located in low-density forest stands found adjacent to (within 50 m) or surrounded by grasslands (Figure 2.1). Plot 6 exhibited multi-aged stand structure. Although no fire-scarred trees were located within 150 m of Plot 6, consideration was given to multiple fire-scarred trees recording many fire events within 300 m of Plot 6.

The criteria used to identify mixed-severity plots describe a history of frequent fire events (range: 6 to 20 events) between AD 1600 and 1900 generally indicative of low-severity fires, but punctuated by fire(s) of greater severity as reflected by the presence of one or two even-aged cohorts ( $n=16$  Plots; Figure 2.4). Cohorts which established in the mid to late 1800s were affected by subsequent low- to moderate-severity fires. Multiple fire events and single cohorts were identified at 13 plots (Figure 2.4). Multiple cohorts and fire events were documented at three plots (Plots 1, 3 and 9; Figure 2.4) suggesting the occurrence of at least two stand-altering fires of moderate to high severity leading to the establishment of two even-aged cohorts. Instances where fire (recorded by  $\geq 2$  scarred trees) and a cohort were identified in the same plot suggests that three fires (AD 1798, 1841, 1848) were severe enough to cause tree mortality and the subsequent initiation of a new cohort of trees (Figure 2.4).

The fire history of Plots 10 and 28 reflects high-severity fire activity (Figure 2.4). The absence of fire scars and the establishment of a cohort of the oldest trees suggests that a high-severity fire caused substantial overstory mortality. This mortality would have improved the light and nutritional space for survivors, as well as for seedling establishment and growth.

Lastly, the fire severity of three plots (Plots 2, 8 and 11) located next to grasslands was not determined (Figure 2.4). Plots 2 and 8 had variable tree establishment dates and no fire scars. Plot 11 had a single fire event recorded by one tree and an even aged cohort. At these plots the stands contained many young trees suggestive of grassland infilling in the absence of fire and not high-severity fire effects.

The impact of fire suppression on contemporary stand structure was difficult to quantify as fire, with the exception of small isolated fires (e.g. 1925, 1928 and 1955), has generally been absent on this landscape for the past 100 years. In the absence of fire, forest density increased over the past century and the interval between fire events at the end of the 19<sup>th</sup> century lengthened (Figure 2.3). Similar findings have been reported for other forest/grassland ecotones in western North America (Veblen et al. 2000). It is worth noting that the classification of fire severity used in this study could have been affected by this change in forest structure and fire frequency. The result would be underrepresentation in the number of plots dominated by only low-severity fire and inflation in the number of plots classified as mixed-severity fire history. In order to reduce this source of uncertainty I recommend in the future increasing the number of overstory trees sampled in each plot and applying a stratification by age class.

### 2.6.3 *Fire-climate relationships*

The results show that fires affecting the CCPA forest-grassland ecotone are controlled by both climate (top-down factors) and fine fuel development (bottom-up factors). Superposed epoch analysis of PDSI and precipitation indicates that widespread fires occurred during anomalously dry, warm years (Figure 2.6). Bivariate event analysis supports this finding and adds that dry, warm conditions over multiple years precede widespread fires (Figure 2.7). Extended droughts likely reduced the moisture content of forest fuels across the entire study area. The increased availability of dry fuels would have facilitated the spread of fire across the landscape leading to widespread fire events (Miller and Urban 2000). During years of less extreme drought, pockets of vegetation with greater moisture content would have persisted, hindering the spread of fire. The association between extended drought conditions and widespread fires in similar settings is well known (e.g. Collins et al. 2006; Heyerdahl et al. 2008; Morgan et al. 2008). For example, in the southern interior of B.C. and within the inland areas of the northwestern United States, widespread fires from AD 1650 to 1900 characteristically burned in years with above-average warm, dry spring and summer conditions (Heyerdahl et al. 2008). More specifically, Daniels and Watson (2003) found significant relationships between major fire events and below-average precipitation in the year of the fire in southern interior B.C.

Grassland fires in the CCPA were found to be associated with wetter, cooler conditions in the year of the fire and the year preceding the fire. This climatic association suggests that cool, wet spring and early summer conditions may promote the growth and productivity of the herbaceous layer, thereby increasing the availability of fine fuels that

would assist the spread of fire in grassland environments (i.e. Miller and Urban 2000). During the peak fire season (July and August) conditions are generally hot and dry every year, which would dry and cure the denser fine fuels. However, considering that a relationship between dry, warm conditions during the fire year and the occurrence of grassland fires, was not found, it is suggested that pockets of fuel must have remained sufficiently moist to restrict the spread of grassland fires to smaller patches. Similar associations between fires affecting grassland proximal forests and antecedent moisture conditions are documented elsewhere (Westerling et al. 2003; Sherriff and Veblen 2008; Gartner et al. 2012).

#### *2.6.4 Mixed-severity fire from stand structure and fire-climate relationships*

Grassland proximal forests are generally thought to be affected by low severity, high frequency fires (Agee 1996; Swetnam and Baisan 1996; Everett et al. 2000; Hessburg et al. 2005). However, the findings of this study suggest that the contiguous landscape pattern of forest structure in the study area reflects variable fire behaviour and frequency between AD 1600 and 1900. At three plots the presence of multiple cohorts and fire scars was documented, indicating that fires burned with differential severity at the plot level. Evidence was also found of variability in the burn severity of one fire. Plot 28 records the establishment of 21 trees over 19 years beginning in AD 1852. No fire-scarred trees were found within 500 m of Plot 28. By contrast, Plot 26 located ~700 m from Plot 28 contains an even-aged cohort that established from AD 1852 to 1872. Multiple fire-scarred trees within 150 m of Plot 26 record fire events in AD 1820 and 1841. These findings indicate that the behavior of fire in AD 1820 and/or 1841 caused

high-severity, stand replacing fire effects at Plot 28, and moderate-severity fire effects at Plot 26.

The partitioning of widespread fires and grassland fires and the associated respective climate factors illustrates the complex interconnectedness of climate, fuel, fire behaviour and effects. At the site or landscape scale, the documentation of mixed-severity historical fire using the relationships between chronologies of fire events (e.g. widespread and grassland fires) and climate variables has received little attention. The combined insights provided by the landscape pattern of forest structure and fire frequency, and the variable fire-climate relationships, provide convincing evidence of a historic mixed-severity fire history at the CCPA study site.

#### *2.6.5 Management implications*

Lower density forests dominated the CCPA historically. In the study area between AD 1800-1900, 33 fires were recorded on at least 2 fire-scarred trees, whereas only 12 fires were recorded between AD 1900 and 2012. Increased human occupation and fire suppression in the 20<sup>th</sup> century has reduced the number and size of fires affecting the CCPA. As a result, conifer encroachment into the middle and upper grasslands and forest density is increasing since AD 1900 (Figure 2.4) and presents ecological implications for the management of the CCPA and similar environments in west central B.C. Between AD 1965 and 2001 comparisons of aerial photographs suggests conifers encroached on approximately 200 km<sup>2</sup> of grassland, or 11% of grassland areas, in the Cariboo Forest Region of B.C. (Grassland Strategy Working Group, 2001). Grasslands, and forests adjacent to grasslands with important grass understory components, in B.C. and elsewhere are economically important environments for livestock grazing. Conifer

encroachment into grasslands reduces grass forage and grazing area for cattle. In addition to livestock grazing, native ungulate species such as white tailed and mule deer and big horn sheep rely on grasslands and open forests for food and shelter. First Nations in the region use native grasslands for hunting and to harvest traditional foods and medicines (Turner 1999).

The sample in Figure 2.2 was collected from a tree found near Plot 4 and records 12 fire events between AD 1642 and 1896. While the tree is located in a closed canopy forest surrounded by younger trees, the high frequency of fires recorded by the tree suggest Plot 4 was historically open and dominated by a few scattered mature trees with little understory. In the event of fire, dense forests can fuel high severity fires and cause overstory mortality. The loss of mature forests negatively impacts both the economic and ecological forest values including timber resources, habitat and species diversity.

A government-led prescribed burning and thinning program has operated in the CCPA since 2000 (Blackwell et al. 2001). The intent of the program is to promote the health of native grasslands by reducing conifer encroachment, to enhance the habitat of native grass and animal species, and to reduce the spread of noxious weeds (B.C. Parks 2000). The findings of this research document frequent historical fires in the CCPA and lend support to these management activities. However, the record of widespread fires between AD 1600 and 1900 suggests that, in order to maintain the natural range of variability of fire activity and stand structure in the study area, forest and grassland management activities should be expanded to include treatments to mimic patches created by high-severity fire to increase stand-level heterogeneity (Churchill et al. 2013).

Hierarchical forest management plans that incorporate prescriptions at the tree-, patch-, stand- and landscape-levels and are based on promoting disturbances and succession to guide ecological change, will be necessary to increase ecosystem connectivity and capacity for resilience under a changing climate (Hessburg et al. 2015). At the individual tree-level, the CCPA contains many large and old Douglas-fir trees that dominate the canopy and have survived multiple fires and droughts while providing reproductive resources for centuries. Restoration activities should prioritize the preservation of these veteran living and dead trees to promote resilience and protect valuable habitat (Hessburg et al. 2015). The application of patch-level prescriptions to mimic tree clump and gap variability would ensure these dry to mesic mixed- and single-species conifer forests are managed to promote heterogeneity.

## 2.7 Conclusion

Two approaches were used to document historic low, and moderate to high, severity fire events within the CCPA forest-grassland ecotone. The use of both fire-climate relationships and stand structure represents a robust approach to identifying and understanding the factors driving fire severity at the landscape scale. Understanding the relationships between climate and fire in the past, and contextualizing these relationships for the future in the face of climate change, necessitates caution. Patterns identified historically may not directly apply to future climate scenarios, but can provide crucial insights. Given the projected increase in temperature in B.C. and elsewhere over the next 50-100 years, drought and fire will be prevalent on the landscape. Fire suppression and

changes in human land use have led to an increase in forest density, which in turn could lead to more severe fires (Schoennagel et al. 2004).

Managing for heterogeneous forests and landscapes will promote ecosystem and socio-environmental resilience (Hessburg et al. 2016). Considering forest disturbances including fire, forest insects and drought are anticipated to increase in frequency, area and duration (Turner 2010), adaptive forest management frameworks to buffer both climatic- and human-driven ecosystem change are required (Campbell et al. 2009). Efforts to restore forests and mimic natural disturbance history through prescribed burning and thinning are ongoing in Canada and the U.S. (Hessburg et al. 2016). Understanding historical fire-climate-fuel relationships can provide valuable insights to the design and application of restoration strategies such as prescribed fire at the forest-grassland ecotone (Schoennagel et al. 2004; Agee and Skinner 2005).

## **Chapter 3 Interannual climate variability drives regional fires in west central British Columbia, Canada**

### 3.1 Article information

Chapter 3 consists of a manuscript in revision for publication by the *Journal of Geophysical Research Biogeosciences*. The text and figures are those accompanying the submitted manuscript but have been renumbered and reformatted for consistency within the thesis. The citation style has also been reformatted for consistency.

#### *3.1.1 Authors' names and affiliations*

Jill E. Harvey<sup>1\*</sup>, Dan. J. Smith<sup>1</sup>

<sup>1</sup> University of Victoria Tree-Ring Laboratory, Department of Geography, University of Victoria, PO Box 3060, STN CSC, British Columbia V8W 3R4, Canada

\*Corresponding Author Email: [jeharvey@uvic.ca](mailto:jeharvey@uvic.ca)

#### *3.1.2 Author's and coauthor's contributions*

Harvey developed the study and hypothesis, conducted and led field and laboratory work, statistical testing, wrote the manuscript and produced all tables and figures. Smith provided guidance in forming the study design, reviewed and edited the manuscript.

### 3.2 Abstract

The influence of climate variability on forest fire occurrence was investigated at eight sites in west central British Columbia, Canada. Forty-six local fire years affecting a single site and 16 moderate fire years affecting two or more sites were identified (AD

1600-1900). Existing fire history data was incorporated to identify 17 regionally synchronous fire years (fires that affected  $\geq 3$  sites). Interannual and multidecadal relationships between fire occurrence and the Palmer Drought Severity Index (PDSI), El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and the Pacific North American (PNA) pattern were examined. In addition the effects of additive positive phases of ENSO and PDO. Multiple reconstructions of ENSO, PDO and PNA were examined and three methodological approaches were used to characterize climate-fire relationships. The influence of interannual climate, expressed as PDSI, was found to increasingly synchronize fire occurrence when examined from local to regional scales. An association between local fires and positive antecedent moisture conditions suggests moisture-driven fine fuel development and the proximity of some sites to grasslands likely function as key determinants of local-scale fire activity. The relationships between regional fires and ENSO, PDO and PNA suggest that large-scale patterns of climate variability exerted a weak and/or inconsistent influence over fire activity in west central British Columbia between AD 1700 and 1900. Although inconsistent among reconstructions of climate patterns, significant relationships were identified between regional fires and large-scale climate patterns when ENSO and PDO were both in positive phases.

### 3.3 Introduction

The natural dynamics of a diverse grouping of ecological and environmental phenomena in Pacific North America are associated with both short-term (quasi-annual) El Niño-Southern Oscillation (ENSO) driven climatic variability, and to longer term climatic trends linked to the Pacific Decadal Oscillation (PDO) and the Pacific North

American (PNA) pattern. These relationships include those associated with episodic forest insect outbreaks (Stahl et al. 2006; Fauria and Johnson, 2009; Sherriff et al. 2011), changes in the size of fish populations (Mantua et al. 1997; Starheim et al. 2012a; Kilduff et al. 2015), marine bird survival (Bertram et al. 2005), drought severity (Shabbar and Skinner 2004) and regional forest fire incidence (Kitzberger et al. 2007). In the case of the latter, regionally synchronized fires during the twentieth century are attributed to annual extremes in fire season climates (Gedalof et al. 2005), and to particular phases or phase combinations of large-scale climate patterns such as ENSO, PDO and PNA that promote fire activity (Trouet et al. 2006; 2009; Morgan et al. 2008).

Previous research shows that both annual and persistent drought conditions in Pacific North America are associated with positive phases of the PDO and PNA, and El Niño years (Barlow et al. 2001; McCabe et al. 2004; Kitzberger et al. 2007; Cook et al. 2014; Wise 2015). ENSO is characterized by an index reflecting average sea surface temperature (SST) anomalies in the equatorial Pacific Ocean. These anomalies oscillate at frequencies of 2-6 years between tropical El Niño events (warmer than average SST) that favour anomalously dry, warm winters and springs in the continental Pacific Northwest, and La Niña events (cooler than average SST) associated with anomalously cold winters and deep snowpacks (Gershunov et al. 1999; Mantua 2002). The PDO is a decadal mode of North Pacific sea surface temperature variability where the negative, or cool, phase of the PDO is characterized by cooler than average SST along the west coast of North America and in the tropical Pacific, and anomalously warm SST are associated with the positive, or warm, phase of the PDO (Mantua et al. 1997; Mantua and Hare 2002). While Mantua et al. (1997) suggested that positive and negative phases of the

PDO oscillate at 20-30 year frequencies, more recent PDO reconstructions have not consistently captured this periodicity (Gedalof and Smith 2001; D'Arrigo et al. 2001; MacDonald and Case 2005; D'Arrigo and Wilson 2006). The SST anomalies associated with positive and negative phases of PDO are expressed climatically in a manner similar to warm and cool ENSO phases. Previous research shows that the effects of El Niño, particularly temperature impacts, are enhanced when in phase with positive PDO values and diminished with negative PDO values. Similarly, the effects of La Niña years can be amplified during negative phases of PDO (Gershunov et al. 1999; McCabe and Dettinger 1999; Bonsal et al. 2001).

PDO and ENSO patterns are linked to atmospheric circulation over continental North America and the North Pacific Ocean expressed in the PNA index. The temporal expression of PNA is complex with teleconnection effects documented at the seasonal (Barnston and Livezey 1987), interannual (Leathers and Palecki 1992) and multidecadal scales (Yarnal and Leathers 1988). Positive values of the PNA index are related to a deepening of the Aleutian Low and are associated with positive phase PDO and El Niño events (Hsieh and Tang 2001; Yu and Zwiers 2007). The PNA pattern is most strongly expressed in the winter, when positive PNA conditions can result in above average temperatures and below normal precipitation in Pacific North America (Sheridan 2003). During the reverse or negative phase of the PNA pattern, storm activity in the Pacific Ocean and the frequency of polar air intrusion events increase, leading to anomalously high precipitation totals and lower temperatures during the winter months (Leathers et al. 1991).

A causal link exists between drought severity and regionally synchronous forest fires in that warmer spring and summer temperatures, as well as reduced winter snowpacks and spring and summer precipitation, precondition forest landscapes for intensified fire activity (Gedalof et al. 2005; Westerling et al. 2006; Williams et al. 2013). In grassland-proximal forests where fuel abundance and connectivity can limit fire activity, climate conditions conducive to the growth of fine fuels can relate fire activity with phases of ENSO and PDO associated with cool and wet climate conditions (Sherriff and Veblen 2008; Gartner et al. 2012). Therefore, interpretation of fire-climate relationships requires informed consideration of the ecosystem(s) in question and the expression of climate patterns in that region.

Understanding pre-instrumental period relationships between large-scale climate patterns and years of widespread, synchronized fires necessarily relies upon proxy reconstructions of ocean-atmospheric teleconnection patterns. While there are numerous tree-ring based reconstructions of ENSO and PDO (e.g. Gedalof and Smith 2001; D'Arrigo et al. 2001; Cook et al. 2008b; D'Arrigo and Wilson, 2006; Li et al. 2011; and references in D'Arrigo et al. 2005 and Kipfmüller et al. 2012), only a limited number of tree-ring based PNA reconstructions are available (Trouet and Taylor 2010; Starheim et al. 2012b). While good agreement exists between proxy reconstructions of ENSO prior to the instrumental period (D'Arrigo et al. 2005), putative regime periods and phase shifts displayed by different PDO reconstructions are inconsistent (Cook 2009; Kipfmüller et al. 2012). This disagreement is attributed to seasonality issues, temporal instability in regional teleconnections of the PDO, and uncertainties in the different reconstruction methods (McAfee 2014; St. George 2014). As a result, the selection of PDO

reconstruction(s) for fire-climate analysis necessitates caution (Kipfmüller et al. 2012) until there is a better understanding of the inherent driving mechanisms (McAfee 2014).

Interannual and multidecadal relationships between regional fire activity and large-scale climate patterns in Pacific North America are documented in the interior forests of the Pacific Northwest (e.g. Hessl et al. 2004, Heyerdahl et al. 2008; Morgan et al. 2008) and within the subalpine forests of the Rocky Mountains (e.g. Schoennagel et al. 2005, 2007; Sherriff and Veblen, 2007, 2008). In British Columbia (B.C.), the relationship between fire and large-scale patterns of climate variability over the twentieth century was described by Wang et al. (2010) who noted positive teleconnections in the interval from AD 1950 to 2006 between province-wide fire occurrence and indices of the PDO, ENSO and the Arctic Oscillation. Meyn et al. (2010) reported that fire variability from AD 1920-2000 was better related to summer drought than large-scale climate patterns, and that the sensitivity of fire-climate relationships is most pronounced in southeastern B.C.

Heyerdahl et al. (2008) examined proxy data from interior B.C., Washington and Oregon spanning the interval from AD 1651-1900. They found that interannual drought episodes were a strong driver of regional fire activity and that large-scale climate patterns were comparatively weaker drivers (Heyerdahl et al. 2007). More recently, Daniels et al. (2011) reports that from ~ AD 1500-2000 a strong relationship exists between PDO and regional fire events in southeastern B.C., but noted that there was no relationship between fires, ENSO or the Atlantic Multidecadal Oscillation.

The goal of this study was to infer the climate drivers of historical fire activity in the Cariboo Forest Region of west central B.C. The relationships between tree-ring

derived reconstructions of forest fire activity, regional climates, and the indices of regional climate patterns were explored. Identification of the climate elements that contribute to historical fire activity offers the opportunity to provide insights essential for forest managers concerned about the severity of future fire seasons and highlights the importance of designing climate-sensitive fuel mitigation practices.

### 3.4 Materials and Methods

#### 3.4.1 Study region

The Cariboo Forest Region (CFR) is located between 51°00' to 52°30' North latitude and 120°30' to 125°45' West longitude in west central B.C. (Figure 3.1). The Fraser and Chilcotin plateaus dominate the regional physiography and are characterized by level to rolling landscapes ranging in elevation from 800-1500 m asl. The B.C. Coast Mountains flank the Chilcotin Plateau to the west and generate a rain shadow over the region expressed by average annual precipitation totals that range from 1632 mm in Bella Coola on the Pacific coast, to 436 mm at Tatlayoko Lake (western Plateau) and 451 mm at Williams Lake (eastern Plateau) (1980-2010 Climate Normals; Environment and Climate Change Canada 2016). Similar to much of the central interior of B.C., summers in the CFR are hot and dry, and winters cold and dry (Steen and Coupé 1997). Particularly in the summer months, convective storms are responsible for lightning strikes that regularly ignite fires (Klenner et al. 2008).

Douglas-fir (*Pseudotsuga menziesii* var. *glauca* Beissn. Franco) and lodgepole pine (*Pinus contorta* Dougl.) trees are dominate components of forests in the CFR. Ponderosa pine (*Pinus ponderosa* Dougl. ex P. &C. Laws) is found at lower elevations in the southern portion of the region, and interior spruce (*Picea engelmannii* x *glauca*)

grows at higher elevations. Extensive natural grasslands characterize the arid river valleys and adjacent terraces of the Fraser, Thompson, Nicola and Chilcotin rivers. A reduction in fire frequency since the late 1800s has led to increased forest density and promoted the encroachment of conifers into grasslands (Turner and Krannitz 2000; Bai et al. 2004).

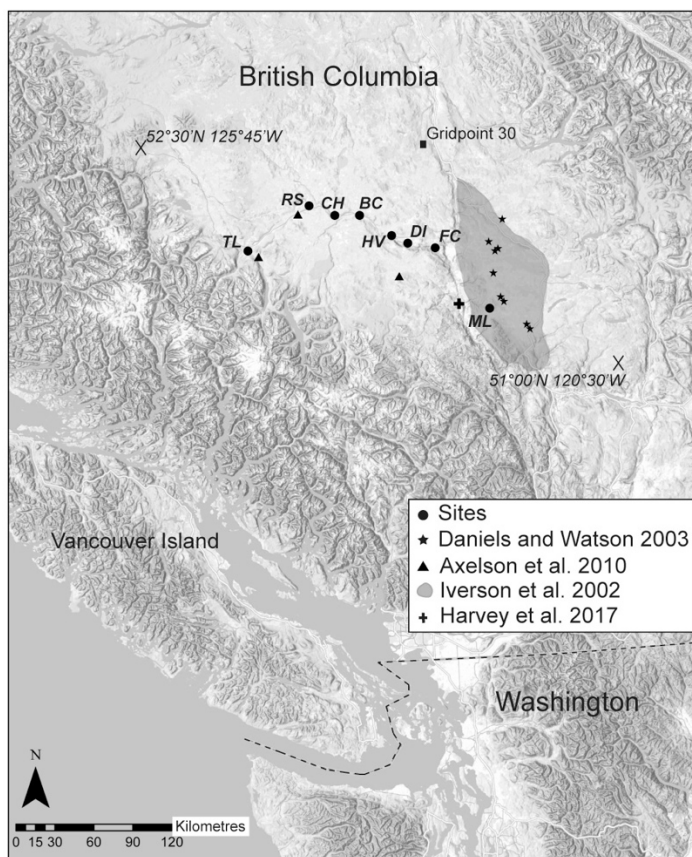


Figure 3.1. The eight fire history sites presented in this study and the locations of existing fire histories used to develop the regional fire chronology. The grey polygon covers the area with the 31 sites examined by Iverson et al. (2002). Reconstructed Palmer Drought Severity Index from Gridpoint 30 (Cook et al. 2008a) used in fire-climate analyses. The site names were abbreviated as TL=Tatlayoko Lake, RS=Redstone, CH=Chilko, BC=Bull Canyon, HV=Hanceville, DI=Dante's Inferno, FC=Farwell Canyon, ML=Meadow Lake.

First Nations occupation of the CFR began prior to 5000 years ago (Cybulski et al. 2007). Fire was traditionally used to thin understory vegetation to encourage ungulate browsing and promote the growth of *Camas* spp. (Turner 1999; Blackstock and

McAllister 2004). In the early to mid-1800s gold explorers passed through the region and by the 1860s cattle ranching was underway at Gang Ranch, the first cattle ranch in B.C. (Thistle 2015). Historic logging occurred within parts of the study region in the early 1900s and contemporary logging is ongoing, especially salvage logging following the recent mountain pine beetle outbreak.

#### *3.4.2 Site selection, data collection, sample processing*

Douglas-fir trees are found throughout most interior forest regions of the Pacific Northwest, where they commonly live for 400 to 500 years (Tisdale and McLean 1957). While thick bark protects the tree from low to moderate severity fires, fire can cause partial cambial death resulting in a scar in the vascular cambium. Subsequent fires can repeatedly scar the tree preserving an annual and sometimes seasonal record of fire events (McBride 1983).

To construct a fire history record for the CFR eight contiguous forest sites dominated by mature Douglas-fir trees and accessible by vehicle were identified (Figure 3.1, Table 3.1). At each site, fire-scarred trees were located within 30-40 ha search areas. Samples were collected with a chainsaw from living and standing dead trees, as well as from fallen logs, stumps and coarse woody debris. Fragile cross sections were glued to wooden mounts and all samples were sanded with progressively finer sandpaper until the xylem cellular structure was visible under 40x magnification. Both visual and statistical methods (Grissino-Mayer 2001) were used to crossdate the samples against previously developed master chronologies from nearby Farwell Canyon (AD 1490-2009) and Redstone (AD 1385-2009) (Axelson et al. 2015). Fire scars were dated based on their year of record in crossdated annual rings (Dieterich and Swetnam 1984).

Table 3.1. Fire history sites developed in this study.

Site	Latitude (N)	Longitude (W)	Elevation (m asl)	No. of samples collected	No. of fire years <sup>1</sup>	First scar (year AD)	Last scar (year AD)	Average return interval (years)
Tatlayoko	51° 51.817'	124° 36.617'	1010	7	2	1843	1911	NA <sup>2</sup>
Redstone	52° 09.867'	123° 54.683'	1031	26	16	1682	1945	18
Chilko	52° 05.575'	123° 37.450'	897	22	6	1727	1883	31
Bull Canyon	52° 05.181'	123° 20.762'	788	19	11	1540	1952	30
Dante's Inferno	51° 52.908'	122° 49.151'	1022	18	12	1627	1896	24
Farwell Canyon	51° 50.525'	122° 31.051'	915	20	14	1693	1896	16
Hanceville	51° 56.418'	122° 59.939'	1075	15	9	1769	1896	16
Meadow Lake	51° 24.234'	121° 56.761'	1125	24	17	1682	1945	16

<sup>1</sup>Fire years were identified when at least 2 trees were scarred by a fire

<sup>2</sup>Too few fire events were identified to calculate the return interval

### 3.4.3 *Fire history chronologies*

Site-level fire histories were compiled from fire dates recorded by  $\geq 2$  samples, and then region-level fire chronologies were composited. Initially, a local fire chronology was constructed from all fire years that burned at only one site (referred to hereafter as ‘local fires’). Following this, fire years that affected  $\geq 2$  sites were compiled into a moderately synchronous fire chronology (referred to hereafter as ‘moderate fires’). Finally, a regional chronology of fire events was constructed by combining the fire records with those reported by Iverson et al. (2002), Daniels and Watson (2003), Axelson et al. (2010), and Harvey et al. (2017).

Iverson et al. (2002) and Daniels and Watson (2003) sampled fire scarred trees at sites east of the Fraser River between Williams Lake and Clinton, and identified 38 (AD 1700-2000) and 33 (AD 1575-1988) fire years, respectively. Axelson et al. (2010) sampled fire scarred trees found at three sites in the CFR and identified nine fire years between AD 1760 and 2000 (Figure 3.1). Harvey et al. (2017) collected fire scars in the Churn Creek Protected Area and identified 65 fires from AD 1600 to 1900.

Following examination of the composite regional fire chronology record, years when fire events were recorded by  $\geq 2$  samples at each site were identified and used to construct study-specific fire histories (Figure 3.2). The eight sites reported in this study were considered to have unique fire history composites (e.g. Tatlayoko, Redstone, Chilko, Bull Canyon; Table 3.1), while the composites created from multi-site pre-existing data were homogenized into single composites (Figure 3.2). To construct the ‘regional fires chronology’ fire years that affected  $\geq 3$  composites across west central B.C. (referred to hereafter as ‘regional fires’) were identified. To exclude historic fire

suppression and management activities (Parminter 1978), fire events after AD 1900 were removed from the fire chronologies.

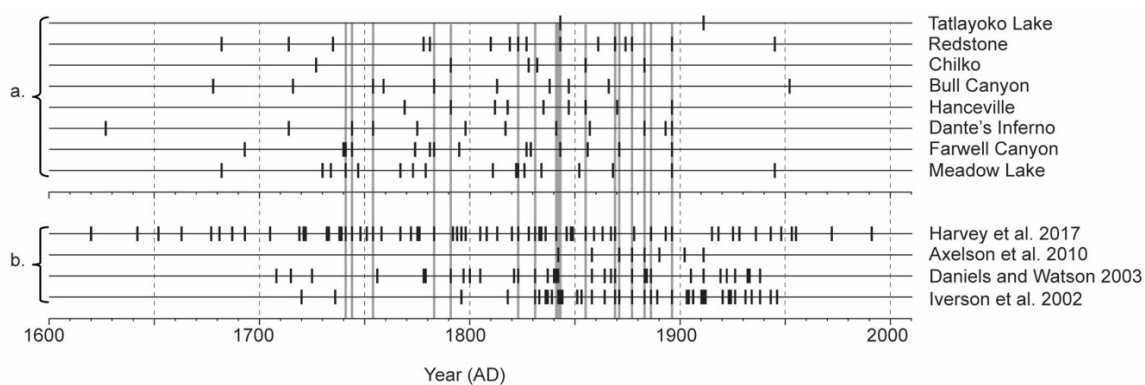


Figure 3.2. Fire histories at eight sites in the Cariboo Forest Region, British Columbia (a). Existing fire histories from nearby sites (b). Each narrow vertical line marks a fire event recorded by  $\geq 2$  trees. The grey vertical bars highlight a regional fire year when fires burned at  $\geq 3$  sites.

#### 3.4.4 Climate data

A tree-ring derived proxy index of the Palmer Drought Severity Index (PDSI) from Gridpoint 30 (Figure 3.1; 805 m asl)(Cook et al. 2008a) was used to analyze interannual fire-climate relationships. Negative values of PDSI indicate warm, dry conditions, while positive values indicate cool, wet conditions. Instrumental PDSI is significantly correlated with the reconstructed PDSI at Gridpoint 30 (pairwise correlation  $r = 0.74$ ,  $P < 0.05$ , AD 1900-1990). Autocorrelation was removed from the PDSI time series by fitting an autoregressive integrated moving average model of an order determined based on Akaike's Information Criterion (Heyerdahl et al. 2008).

Two tree-ring based reconstructions of ENSO were used to test for associations between regional fires and short-term climatic variability. The first consisted of a reconstruction of annual ENSO variability to AD 900 based on the North American

Drought Atlas (Li et al. 2011), a database of drought reconstructions constructed from a regional network of tree-ring chronologies. Second, a reconstruction presented by Cook et al. (2008b) that models annual ENSO variability to AD 1300 was employed. Both of these tree-ring ENSO reconstructions reflect average winter sea surface temperatures in the equatorial Pacific Ocean during December through February.

To examine for any multidecadal relationships between regional fire and large-scale climate patterns, four reconstructions of the PDO were obtained (D'Arrigo et al. 2001; Gedalof and Smith 2001, MacDonald and Case 2005; D'Arrigo and Wilson 2006). The D'Arrigo et al. (2001) annual PDO reconstruction extends to AD 1700. Based on six tree-ring chronologies from Alaska and Oregon, it was constructed using two PDSI gridpoints in northern Mexico. Gedalof and Smith (2001) provide a mean spring (March-May) PDO reconstruction extending to AD 1600 based on six tree-ring chronologies from Alaska, B.C. and Washington. MacDonald and Case (2005) reconstructed an annual PDO record to AD 993 using chronologies from southern California and Alberta. Finally, the reconstructed spring (March-May) annual Asian expression of the PDO extending to AD 1565 was considered (D'Arrigo and Wilson, 2006).

Two reconstructions of winter PNA were used to examine its relationship to regional fire events. The first was presented by Trouet and Taylor (2010) is constructed from a model-based selection of 12 tree ring chronologies from inland sites in the Pacific Northwest and coastal Alaska, and extends to AD 1725. The second reconstruction modeled by Starheim et al. (2012b) extends to AD 1660 and is based on multispecies tree-ring chronologies from west central B.C.

Correlation analyses suggest a moderately positive agreement exists between the two ENSO reconstructions (AD 1700-1900), but reveals there is little agreement between the reconstructions of PDO (AD 1700-1900) and PNA (AD 1725-1900)(Table 3.2). Past research documenting relationships between fires and large-scale climate patterns has oftentimes relied on single proxy reconstructions of PDO and ENSO (eg. Hessler et al. 2004; Schoennagel et al. 2005). More recently, multiple reconstructions of specific climate oscillations were used to provide balanced interpretations of these relationships (eg. Heyerdahl et al. 2008; Kipfmüller et al. 2012; Rother and Grissino-Mayer 2014).

Table 3.2. Results of correlation analysis between different PDO, ENSO and PNA reconstructions.

	PDO1	PDO2	PDO3	PDO4
PDO1 <sup>1</sup>		<i>-0.096</i>	<i>-0.031</i>	<i>-0.083</i>
PDO2 <sup>2</sup>	<i>-0.096</i>		<i>0.152</i>	<i>0.342</i>
PDO3 <sup>3</sup>	<i>-0.031</i>	<i>0.152</i>		<i>0.158</i>
PDO4 <sup>4</sup>	<i>-0.083</i>	<i>0.342</i>	<i>0.158</i>	

	ENSO2 <sup>6</sup>
ENSO1 <sup>5</sup>	<i>0.631</i>

	PNA2 <sup>8</sup>
PNA1 <sup>7</sup>	<i>-0.027</i>

<sup>1</sup>D'Arrigo and Wilson 2006

<sup>2</sup>D'Arrigo et al. 2001

<sup>3</sup>MacDonald and Case 2005

<sup>4</sup>Gedalof and Smith 2001

<sup>5</sup>Li et al. 2011

<sup>6</sup>Cook et al. 2008b

<sup>7</sup>Trouet and Taylor 2010

<sup>8</sup>Starheim et al. 2012b

### 3.4.5 Fire-climate analyses – PDSI

Superposed epoch analysis (SEA) and bivariate event analysis (BEA) were used to evaluate associations between the fire chronologies and climate variability. Climate-fire studies commonly use SEA to elucidate interannual relationships between fire occurrence and climate over short intervals (3-5 years) (Grissino-Mayer and Swetnam 2000; Trouet et al. 2010). BEA has also been employed in fire-climate research (e.g. Gartner et al. 2012; Rother et al. 2014) to assess interactions between fire activity and extreme climate events over variable windows of analysis (e.g. 10-30 years; Gavin et al. 2006; Gavin, 2010).

SEA was used to determine if the mean value of the climate reconstruction differed significantly before ( $t-4$ ), during ( $t$ ) and after fire events ( $t+4$ ) of the local, moderate and regional fire chronologies between AD 1600 and 1900. To assess statistical significance, Monte Carlo simulations that randomly select years for 1000 interactions were used to develop confidence intervals of 95% and 99%. Pre-whitened anomalies of PDSI were used in the SEA.

BEA was conducted in K1D software (Gavin, 2010), and extreme climate events were defined as the years with the 40 most extreme (positive or negative) index values (AD 1600-1900; Gartner et al. 2012). Bivariate Ripley's K-function were transformed to the  $L$  function to stabilize the mean and variance and improve result interpretation (Gavin et al. 2006; Gavin, 2010). Forward selection was used in the K1D software, where fire events were preceded by extreme climate years to generate 95% confidence intervals based on 1000 randomized Monte Carlo simulations. Values of the  $L$  function that exceed the upper confidence interval indicate a strong relationship of fire events  $t$  years after the

extreme climate years. Values of the  $L$  function that fall below the lower confidence interval indicate fire-climate asynchrony at  $t$  years after the extreme climate years.  $L$  function values between the confidence intervals indicate fires occur independently of extreme climate years.

#### 3.4.6 *Fire-climate analyses – ENSO, PDO, PNA*

At the annual scale I tested whether regional fires occurred more often than expected during particular phases (+,-) of the large-scale climate patterns (ENSO, PDO, PNA) using frequency analysis evaluated by chi-square tests. Yearly values of the ENSO reconstructions were classified as either representing positive (El Niño-like) or negative (La Nina-like) conditions depending on whether the reconstructed value was above or below zero. Considering that the PDO and PNA indices exhibit high variance at the decadal or multidecadal temporal scales (Mantua and Hare, 2002; Trouet and Taylor, 2010), intervention analysis (Box and Tiao 1975; Rodionov 2004) was applied to identify persistent warm and cool phases in each of the PDO reconstructions and the PNA reconstruction following the approach described in Rodionov (2004) and Trouet and Taylor (2010). Yearly values of each PDO reconstruction and PNA were then classed as positive (warm phase) or negative (cool phase).

Previous research identifies additive phase combinations of PDO and ENSO are associated with regionally synchronous fires (Hessl et al. 2004; Heyerdahl et al. 2008), so I also considered the influence of combined positive phases of ENSO (Li et al. 2011 reconstruction only) and each reconstruction of PDO. For each test, the expected frequencies of regional fires were customized based on the distribution of all years among the different phases and phase combinations. I restricted the interval of analysis to

AD 1700-1900 for ENSO and PDO, and AD 1725-1900 for PNA, because these intervals captured all regional fire years and were common to the reconstructions employed.

To evaluate longer-term synchronous or asynchronous fire-climate oscillation relationships, I next considered the influence of extreme positive and negative years of PDO, ENSO and PNA independently on regional fire years using BEA. In the analysis 30 extreme years were employed to accompany the shorter windows of analysis (AD 1700-1900 or AD 1725-1900). I also tested for the influence extreme climate interaction events represented by the two-way additive positive phase combinations for each PDO reconstruction and a single ENSO reconstruction (Li et al. 2011) again using BEA. Following the methods of Schoennagel et al. (2007), I ranked the annual values of the reconstructed indices between AD 1700 and 1900 and defined extreme climate interaction events by identifying common years within the highest ranked annual values of each PDO index and the ENSO index. For example, to select extreme positive climate events using the PDO reconstruction from D'Arrigo et al. (2001) and the Li et al. (2011) ENSO reconstruction, years with the 70-80 highest annual values of PDO and ENSO were selected independently, and from these subsets, only years that were common to both subsets were then used in the analysis. Therefore, the total number of climate events selected varied based on the reconstruction used (Schoennagel et al. 2007).

## 3.5 Results

### 3.5.1 *Fire history chronologies*

Partial cross sections of Douglas-fir trees from each of the eight study sites allowed for the identification of 2 to 17 fire years (recorded on  $\geq 2$  samples) between AD 1600-1900 (Table 3.1). The site-level mean fire return interval ranged from 16 to 31

years. Forty-six years when fire burned at only one site were identified, and 16 moderate fire years when fire occurred at  $\geq 2$  of the sites (Figure 3.2). After incorporating data from previous research (Iverson et al. 2002; Daniels and Watson 2003; Axelson et al. 2010; Harvey et al. 2017), 17 years when fires were recorded in  $\geq 3$  regional fire history records were identified (Figure 3.2; Table 3.1).

### 3.5.2 *Fire-climate relationships – PDSI*

Statistically significant relationships were identified between fire years and PDSI using SEA (Figure 3.3). SEA indicates that local fire years were not significantly associated with PDSI in the year of the fire or years preceding the fire. Moderate fire years were significantly related to warm, dry years in the fire year indicated by negative values of PDSI ( $P < 0.01$ ), and with cool and wet years two years prior to the fire indicated by positive values of PDSI ( $P < 0.01$ ). Years of regional fire were significantly associated with dry, warm years in the year of the fire ( $P < 0.05$ ) and the year preceding the fire ( $P < 0.05$ ) (Figure 3.3).

Statistically significant relationships were found using BEA between extreme PDSI years and local, moderate and regional fire events (Figure 3.3). Local fires were synchronous with negative extreme PDSI years during the year preceding the fire, and with positive extreme PDSI years 2-3 years and 6-7 years before the fire. Moderate fires were synchronous with negative extreme PDSI years during the fire year and 3-7 years preceding the fire. Regional fires were synchronous with negative extreme PDSI years in the fire year and 9 years preceding the fire (Figure 3.3). Neither moderate nor regional fire years were associated with extreme positive PDSI years.

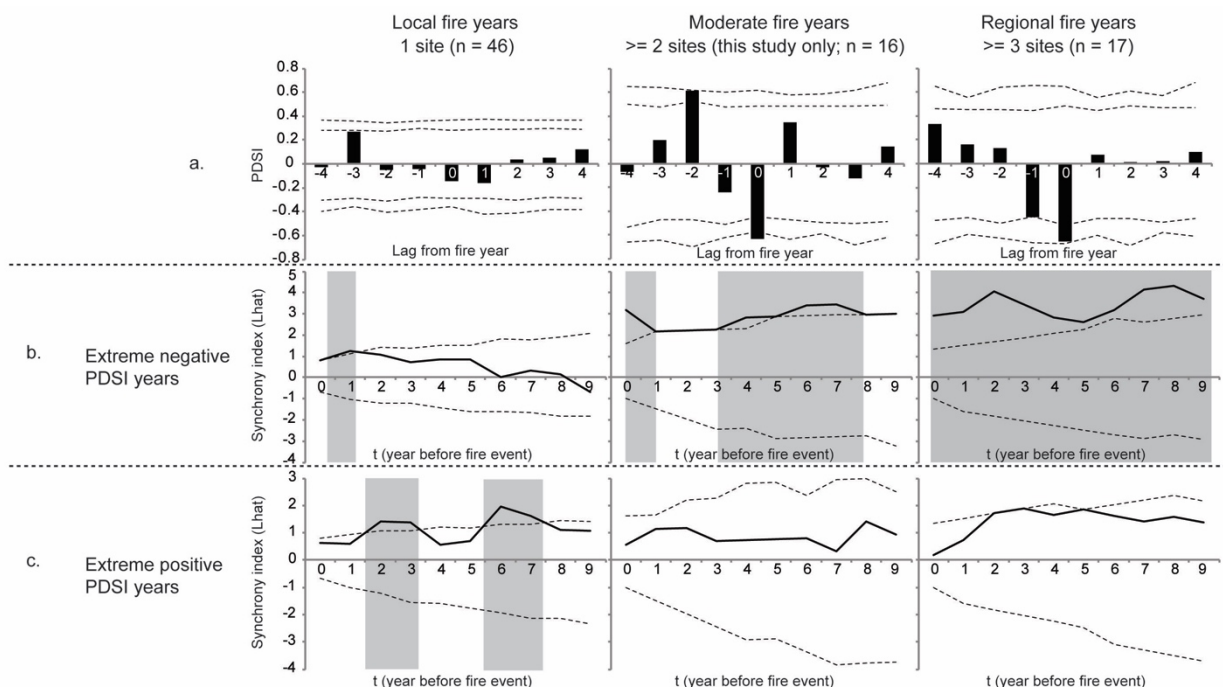


Figure 3.3. Fire and interannual climate relationships in west central British Columbia during local (AD 1600-1900), moderate and regional fire years (AD 1700-1900). (a) Lagged interannual relationships of reconstructed values of the Palmer Drought Severity Index (PDSI; Gridpoint 30; Cook et al. 2008a) and fire showing mean departures (standard deviations) from PDSI during years when fire burned at only one site ( $n=46$ ), years when fire burned at 2 or more sites in this study ( $n=16$ ) and when fire burned at 3 or more sites (region fire chronology;  $n=17$ ) for years before ( $t = -4$  to  $-1$ ), during ( $t=0$ ) and after ( $t = +1$  to  $+4$ ) fire years. Dashed lines represent the 99% and 95% confidence intervals. Bivariate event analysis of the temporal association of extreme negative PDSI years (warm, dry) (b), and extreme positive PDSI years (cool, wet) (c), with fire in local, moderate and regional fire years. The number of extreme PDSI years was adjusted based on the temporal interval of analysis (see Methods for details). Black solid lines indicate  $Lhat$  values ( $L$  function with stabilized mean and variance) for  $t$  years before the fire events ( $t=0$ ). Dotted lines indicate the upper and lower confidence intervals (95%).  $Lhat$  values outside the confidence intervals indicate synchrony with fire, and values between the confidence intervals indicate a random relation of fire and climate events. Grey shaded bars highlight statistical significance.

### 3.5.3 Fire-climate relationships – PDO, ENSO and PNA

Intervention analysis identified six to nine phase shifts in the PDO reconstructions between AD 1700 and 1900 and six shifts in the PNA reconstruction from Trouet and Taylor (2010) between AD 1725 and 1900 (Figure 3.4). The results of the intervention analysis were verified against analyses similar to those previously reported (e.g. Gedalof and Smith 2001; D'Arrigo and Wilson 2006; Trouet and Taylor 2010; Kipfmüller et al. 2012). High frequency variability in the Starheim et al. (2012b) PNA reconstruction precluded the use of intervention analysis on this time series.

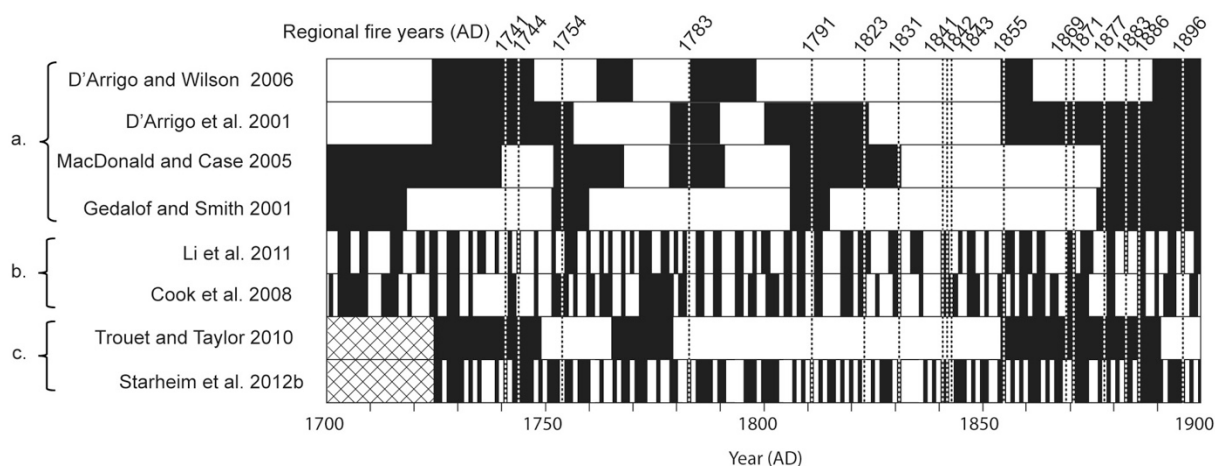


Figure 3.4. Positive (white) and negative (black) phases of PDO (a), ENSO (b) and PNA (c) as estimated from the proxy reconstructions. Hatched areas indicate the reconstruction does not span that interval. Regional fire years are noted and are marked by dashed lines.

Frequency analyses suggest that regional fires occurred more often than expected during positive PDO phases, and less often than expected during negative PDO phases when I considered the reconstruction by D'Arrigo et al. (2001) ( $P < 0.02$ ) (Figure 3.5a). No significant departure between observed and expected distributions of fire years for the remaining three PDO reconstructions were documented, nor were any identified for either ENSO reconstruction (Figures 3.5a and 3.5b). Significant departures from the distribution

of fire years were not detected for combined phases of PDO and ENSO (Figure 3.5c). No significant departure between observed and expected distributions of fire years for the reconstructions of PNA were found (Figure 3.7). The analysis for each PDO and ENSO reconstruction was repeated without applying intervention analysis, and resulted in a similar outcome. When I did not apply intervention analysis to the Trouet and Taylor (2010) PNA index, it was found that regional fires occurred more often than expected during positive PNA index years ( $P < 0.06$ ) (Figure 3.7). In contrast, when considering the Starheim et al. (2012b) PNA index, it was shown that regional fires occurred more often than expected during negative PNA index years ( $P < 0.06$ ) (Figure 3.7).

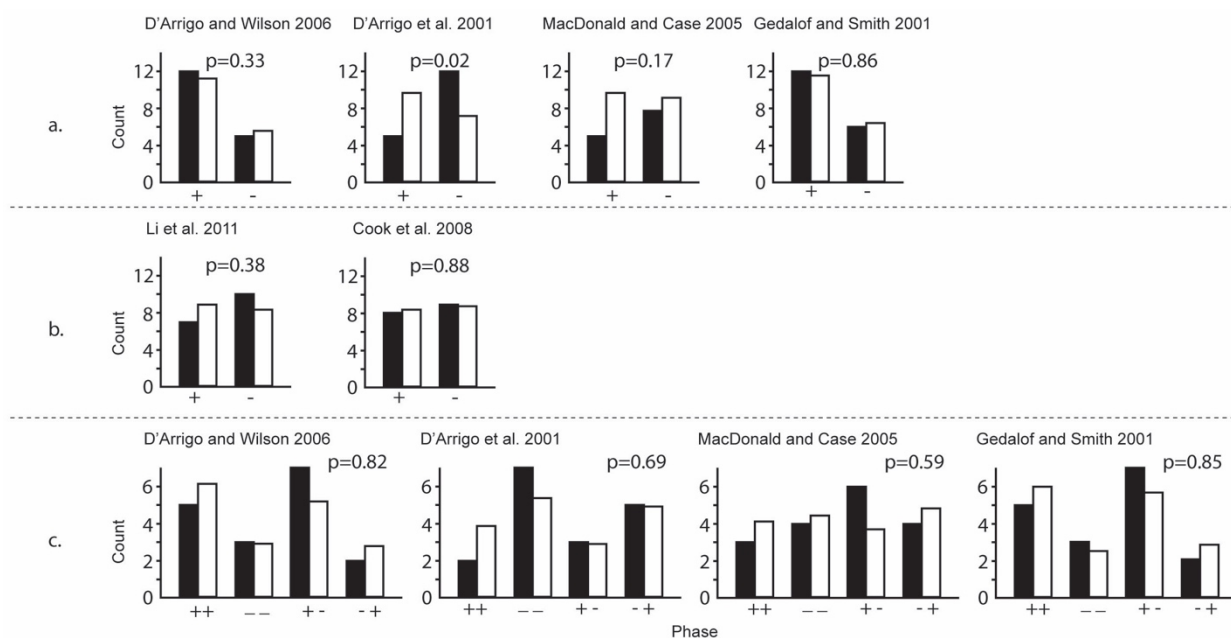


Figure 3.5. Observed (black bars) and expected (white bars) number of regional fire years for single phases of PDO (a), ENSO (b) and combinations of warm and cool phases of each PDO reconstruction and ENSO (Li et al. 2011)(c). Warm (positive) phases of these oscillations are represented by + symbols, and cool (negative) phases are represented by – symbols. Significant departures from the expected fire occurrence was evaluated by chi square tests.

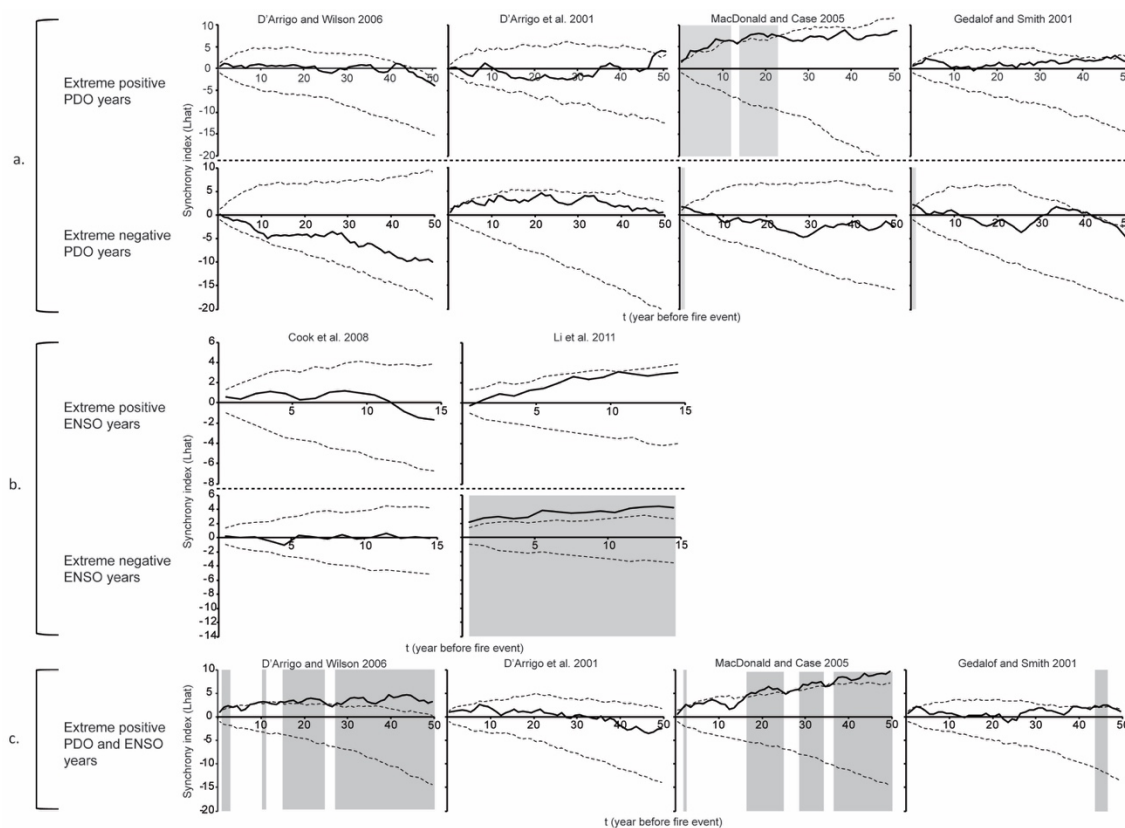


Figure 3.6. Results from bivariate event analysis showing the temporal association of extreme positive and negative PDO(a) and ENSO(b) years and regional fire years. The relationships between regional fire years and combined years with the highest PDO and ENSO index values are also presented for each PDO reconstruction and the ENSO reconstruction from Li et al. (2011)(c). See Figure 3.3 and Methods for further explanation.

Statistically significant relationships between regional fire years and extreme positive PDO years were detected using the MacDonald and Case (2005) reconstruction in BEA (Figure 3.6). Regional fire years were broadly synchronous with extreme positive PDO years in the year of the fire and 23 years prior to the fire. No significant relationships were found between extreme positive PDO years using the remaining three PDO reconstructions (D'Arrigo et al. 2001; Gedalof and Smith 2001; D'Arrigo and Wilson 2006) and regional fire years. Statistically significant relationships between

regional fire years and extreme negative PDO years in the year of the fire with two of the PDO reconstructions were documented (Gedalof and Smith 2001; MacDonald and Case 2005)(Figure 3.6). BEA analysis did not indicate a relationship between regional fire events and extreme positive ENSO years for either reconstruction considered. A significant relationship was found between regional fire years and extreme negative ENSO years in the fire year and multiple years prior to the fire when the Li et al. (2011) reconstruction was considered (Figure 3.6). BEA revealed variable relationships between regional fire years and extreme PNA years (Figure 3.7). As reported in the American West by Trouet and Taylor (2010), statistically significant relationships exist between extreme positive PNA years and regional fire in the year of the fire. When considering the Starheim et al. (2012b) PNA reconstruction, an association between extreme negative PNA years and regional fires in the year of the fire and three years prior to the fire was revealed. This association is preceded by a significant relationship between regional fires and extreme positive PNA years occurring 5-8 years before the fire (Figure 3.7).

BEA analysis indicates combined warm phases of ENSO (Li et al. 2011) and PDO are synchronous with regional fire events when considering two of the PDO reconstructions (D'Arrigo and Wilson 2006; MacDonald and Case 2005). Intervals of synchronicity for positive PDO and ENSO extreme years and regional fire events occurred at 2-3 years, 15-25 years and 28-50 years prior to the fire.

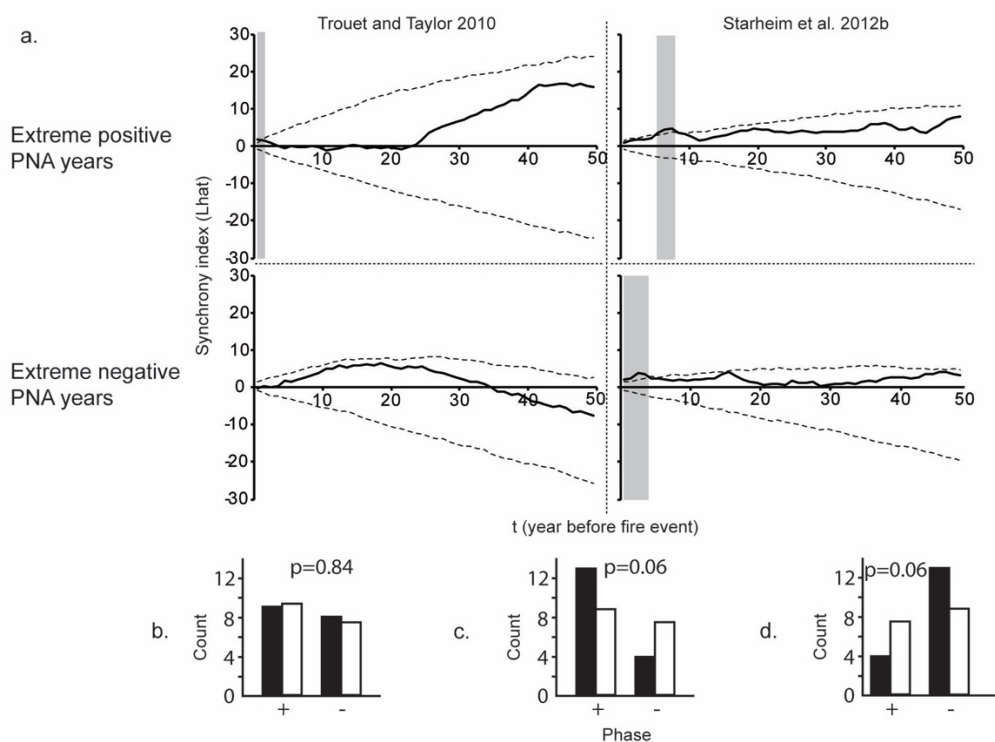


Figure 3.7. Results from bivariate event analysis showing the temporal association of extreme positive and negative PNA years and regional fire year (a). Observed and expected number of regional fire years for the PNA reconstruction presented in Trouet and Talyor (2010) with intervention analysis (b) and without intervention analysis (c), and in Starheim et al. (2012b) (d). See Figures 3.3 and 5.5 for further explanation.

## 3.6 Discussion

### 3.6.1 Persistent drought synchronizes regional fire activity

The findings of these analyses indicate that the influence of summer droughts on prehistorical fire activity in the CFR increases with the spatial recording of fire activity from local to regional fires (Figure 3.3). Anomalously low PDSI in the fire year and in multiple years preceding the fire was an important prerequisite for moderate and regional fires (Figure 3.3b). The effects of persistent drought on environmental conditions include reduced fuel moisture levels improving vegetation flammability (Burgan 1979), reduced winter snowpack and earlier spring snow melt lengthening the fire season (Westerling et

al. 2006) and increased tree mortality leading to greater accumulations of dry forest fuel (Allen et al. 2010; Williams et al. 2013). These effects collectively promote the occurrence and spread of fire in forest ecosystems.

Seventeen regional fire years between AD 1700 and 1900 were discerned within the fire history datasets. Regional fires between AD 1600 and 1700 were not identified, most likely due to missing records associated with the mortality, decay and loss of trees that lived in this century (e.g. Swetnam et al. 1999). Five of the regional fires identified between AD 1700 and 1900 (in AD 1783, 1843, 1869, 1883, and 1886) are common to those described by Heyerdahl et al. (2008). Given this correspondence, it seems likely that fires burned across large expanses of the interior Pacific Northwest region during intervals of persistent anomalously low precipitation and warmer than normal temperatures. Independent proxy reconstructions (not used in this analysis) supporting this interpretation include: the anomalously low annual precipitation records reconstructed by Watson and Luckman (2004) for interior B.C. in AD 1783 and 1869; the higher than average temperatures in south central B.C. described by Briffa et al. (1992) in AD 1831, 1877, 1883 and 1896; and, the below average summer Chilko River streamflows reconstructed for AD 1783, 1841, 1843, and 1877 by Hart et al. (2010). Collectively, these paleoenvironmental records lend support to the relationship between regional fires and anomalously low PDSI values found in this study.

The connection between persistent drought and prehistoric fire activity is recorded in interior B.C., where drier and warmer climate conditions persisted for multiple years prior to widespread fire activity (Daniels and Watson 2003; Heyerdahl et al. 2008). Schoennagel et al. (2007), Heyerdahl et al. (2008), and Sherriff and Veblen (2008) report

that multiple years of spring and summer drought conditions are related to regional fire activity in montane and subalpine forest ecosystems in the inland northwest United States. In the southwestern United States, numerous studies have reported relationships between past severe droughts and large fire years (e.g. Swetnam and Betancourt 1990; Swetnam and Baisan 1996; Rother and Grissino-Mayer 2014).

### *3.6.2 Antecedent moisture promotes fire activity at local scales*

Anomalously cool and wet years were shown to occur 2-3 and 6-7 years before local fire years (Figure 3.3). Positive antecedent moisture conditions can promote the growth of grasses and other fine fuels improving fuel connectivity (Westerling et al. 2003; Gartner et al. 2012). In grassland environments, fire spread is limited primarily by the connectivity of fuel, while in forested environments the spread of fire is largely controlled by the preponderance of fuel moisture over fuel connectivity (Krawchuk and Moritz 2011). Three of the eight sites (Farwell Canyon, Dante's Inferno and Meadow Lake; Figure 3.1) were located within 500 m of expansive grasslands.

Fire activity in forests adjacent to grasslands has been linked to positive antecedent moisture conditions suggesting a relationship between fire and the development of fine fuels at local scales (Gartner et al. 2012). No relationship was detected between positive PDSI years and fire years when I considered the moderate and regional fire chronologies, which suggests the influence of antecedent moisture conditions is not consistent among all the sites and is not a key determinant in regional fire activity in the study region.

### *3.6.3 Inconsistent relationships detected between regional fires and proxy records of ENSO, PDO and PNA*

In Pacific North America, associations between prehistoric regional fire years and El Niño years (Heyerdahl et al. 2002; Kitzberger et al. 2007), positive PDO years (Hessl et al. 2004; Kitzberger et al. 2007), and additive combinations of positive ENSO and PDO years (Heyerdahl et al. 2008) have been documented. In this study, comparisons of observed and expected frequencies broadly suggest that climate patterns characteristic of ENSO, PDO and PNA exert little influence over the incidence of regional fire activity when considered independently or in combination (Figure 3.5). BEA corroborated these findings revealing inconsistent associations between regional fire and the different indices of PDO, ENSO and PNA (Figures 3.6 and 3.7). When considering extreme interaction years of positive PDO and El Niño years with regional fire years, significant associations were detected at several similar intervals within 50 years preceding regional fire years using the D'Arrigo et al. (2001) and MacDonald and Case (2005) PDO reconstructions. This finding suggests that extreme interaction years may precede regional fire years just before the fire year, and around 15-25 and 28-50 years before the fire. The interpretation of these multidecadal-scale associations between regional fire and extreme climate years should consider that the selected climate events used in BEA reflect low frequency trends in the climate record to which fires respond, and that single or combined climate events do not mechanistically affect the occurrence of fire decades later (Schoennagel et al. 2007).

The absence of consistent relationships between regional fires and reconstructed indices of ENSO, PDO and PNA in the analyses could stem from: 1) spatial inconsistencies in the geographical expression of these climate patterns in the Pacific

North America; 2) ecosystem homogenization through regional fire history composites; and, 3) poor agreement between the reconstructions. First, the spatial expression of ENSO and PDO strength and seasonal persistence is most pronounced along the coast and in southeastern B.C. (Fleming and Whitfield 2010). Topographic variability characteristic of the Selkirk Mountains in southeastern B.C. enhances the expression of ENSO and PDO modulated winter temperatures (Meyn et al. 2010) and is reflected by responding snowpack variability (Whitfield et al. 2010). Similarly, negative PNA years have been associated with positive snow water equivalent anomalies, representing winter precipitation variability, in the mountainous regions of the inland Northwest (Hsieh and Tang 2001). In the Cariboo-Chilcotin region, during winter El Niño years (La Nina years) climate conditions are reportedly 3-5°C warmer (1-3°C cooler) with 5-15% less (2-15% greater) precipitation than long-term averages (Dawson et al. 2008). However, the expression of ENSO and PDO in inland areas of south and central B.C., including the study region, is likely somewhat diminished due to the distance from the Pacific Ocean and the effects of Arctic air masses (Whitfield et al. 2010). Additionally, hot and dry summers characterize the region and could overshadow the winter and spring PDO and ENSO driven climate effects.

Second, the homogenization of ecosystem characteristics resulting from compiling fire history chronologies from multiple sites may contribute to the inconsistencies detected in fire-climate pattern relationships. For example, above average antecedent moisture was found to be significantly related to the occurrence of local fires and I postulate that the presence of expansive grasslands close to three sites could explain this association. Site level biogeographical factors, such as proximity to grasslands and

topographic characteristics, could confound fire-climate responses reducing the coherency and strength in regional fire-climate statistical analyses. Lastly, the poor agreement between PDO and PNA indices prior to AD 1900 contributes uncertainty into the relationships between regional fire and large-scale patterns of climate (Kipfmueller et al. 2012; McAfee 2014; Zanchettin et al. 2015). These findings align with those of Kipfmueller et al. (2012), adding support to their argument that the choice of PDO reconstruction can significantly affect the resulting historic fire-climate relationships.

It is worth noting that three consecutive regional fire years were identified in this analysis (AD 1841, 1842 and 1843) that coincide with positive PDO phases in three of the four reconstructions used in this analysis (Figure 3.4). Regional fire activity has been identified by others during this interval in Pacific North America (e.g. Plummer 1900 [referenced in Hemstrom and Franklin 1982]; Bekker and Taylor 2001; Heyerdahl et al. 2008; Gayton 2013).

#### *3.6.4 Future climate implications*

These data describe a mean fire return interval of 24 years between AD 1600 and 1900 that is similar to the mean fire interval of 25 years reported in the adjoining Cariboo-Chilcotin region (Daniels and Watson 2003; Harvey et al. 2017). Fire activity after AD 1900 is comparatively infrequent (Figure 3.2) suggesting fire suppression and forest management activities have extended the fire return interval. A reduction in the frequency of fires affecting montane forests in west central B.C. has led to denser forests and the encroachment of conifers into grasslands. In the recent International Panel on Climate Change assessment (IPCC 2014) increased frequency and severity of drought

stress for the inland Pacific Northwest is predicted, which could lead to more frequent and regionally synchronous fires (McKenzie et al. 2004; Turner 2010).

After nearly a century of fire exclusion in the inland Pacific Northwest, efforts to mitigate the risk of severe fires in B.C. montane forests by thinning and removing deadfall in high-risk forest stands remains limited (Taylor 1998; Ryan et al. 2013). Although the efficacy of forest restoration efforts in similar ecosystems is variable (Rocafort et al. 2010) fire managers should consider past relationships between fire and measures of interannual climate and, in consideration of projected climate change, increase forest management activities to decrease fire risk in the province. The relationships between regional fire and single patterns of large-scale climate variability in west central B.C. are weak at best, but the consideration of additive phases of PDO and ENSO in fire management planning may be more effective and has been suggested by others in the inland Pacific Northwest (eg. Dawson et al. 2008; Meyn et al. 2010; Haughian et al. 2012).

### 3.7 Conclusions

Multiple methodological approaches and climate proxy reconstructions were used to characterize the relationship between fire activity and climate variability in west central B.C. The results show that persistent drought, represented by multiple years of anomalously low reconstructed PDSI values, is clearly related to the regional synchronization of fire activity in west central B.C. between AD 1600 and 1900. I found that antecedent moisture conditions were related to local fires, leading to the suggestion that the presence of fine fuels and proximity to grasslands are important determinants of fire at the site level within the study region. The documentation of inconsistent

relationships between regional fires and reconstructed indices of ENSO, PDO and PNA over the period of AD 1700 to 1900 suggests the spatial expression of these regional climate patterns may be weak in west central B.C. Furthermore, site level ecosystem characteristics (e.g. grassland proximity) could dilute fire-climate relationships when considering regional fire history composites, and the poor agreement of proxy reconstructions prior to AD 1900 adds additional uncertainty. Future studies examining prehistoric regional fire activity and climate patterns should consider the inconsistencies recorded here and cautiously select proxy reconstructions

## **Chapter 4 The influence of grassland proximity on insect and fire activity in interior British Columbia**

### 4.1 Article information

Chapter 4 consists of a manuscript prepared for submission to the journal *Forest Ecology and Management*. The text and figures are from the manuscript but have been renumbered and reformatted for consistency within the thesis. The citation style has also been reformatted for consistency.

#### *4.1.1 Authors' names and affiliations*

Jill E. Harvey<sup>1\*</sup>, Dan. J. Smith<sup>1</sup>, Jodi N. Axelson<sup>2</sup>

<sup>1</sup> University of Victoria Tree-Ring Laboratory, Department of Geography, University of Victoria, PO Box 3060, STN CSC, British Columbia V8W 3R4, Canada

<sup>2</sup>Department of Environmental Science, Policy, and Management, University of California, 130 Mulford Hall # 3114, Berkeley, California, 94702, USA

\*Corresponding Author Email: [jeharvey@uvic.ca](mailto:jeharvey@uvic.ca)

#### *4.1.2 Author's and coauthor's contributions*

Harvey developed the study and hypothesis, conducted and led field and laboratory work, statistical testing, wrote the manuscript and produced all tables and figures. Smith provided guidance in forming the study design, reviewed and edited the manuscript. Axelson provided some data and analytical support.

## 4.2 Abstract

Wildfires and western spruce budworm (*Choristoneura occidentalis* Freeman) (WSB), a native conifer defoliator, lead to natural disturbances that affect the structure and function of montane forests in British Columbia, Canada. Limited research exists describing the climate conditions associated with historical fire activity and outbreaks of WSB, and the interaction between fire and WSB outbreaks. Site-specific and regional characterizations of the relationships between fire, WSB and climate are needed to establish historical baselines to define the range of variability in these relationships. Regionalized chronologies of historical fire activity from AD 1600 to 1900 (fire) and AD 1600 to 2009 (WSB outbreaks) were compiled to inform predictions on how future climates may impact these disturbances, and the implementation of management prescriptions aimed at improving forest resilience.

The relation between fire years, outbreaks of WSB, reconstructed values of the Palmer Drought Severity Index and annual precipitation were examined using superposed epoch and bivariate event analyses, and were used to evaluate the influence of grassland proximity (regionalized grassland and non-grassland chronologies) on these relationships and the disturbance history characteristics. The analyses reveal significant and complex relationships between historic fire and climate in the study area. The findings show that fires affecting grassland proximal sites were historically more frequent than fires occurring in forests not near grasslands. Fire activity was related to both warm, dry and cool, wet conditions in the fire year and/or year(s) preceding the fire depending on proximity to grasslands, suggesting climate conditions associated with both fine fuel growth and drying are key determinants for fire activity. The initiation of outbreaks of

WSB was significantly related to drought and this relationship was enhanced at sites next to grasslands. No associations were discerned between the initiation of WSB outbreaks and fire years. Considering the risk of dangerous fire activity in the future and potential timber losses associated with WSB defoliation, the findings provide important information to forest managers charged with promoting forest health and resilience in the dry conifer forests of interior British Columbia.

### 4.3 Introduction

Forest fires and insect outbreaks are important natural disturbances that directly influence the structure and function of forest ecosystems in the Pacific Northwest of North America (Fellin and Dewey 1982; Agee 1996; Oliver and Larsen 1996; Kurz et al. 2008). In the dry conifer forests of interior British Columbia (B.C.) periodic outbreaks of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (MPB) and western spruce budworm (*Choristoneura occidentalis* Freeman) (WSB) have led to overstory and understory mortality at variable spatial scales (Thompson et al. 1984; Kurz et al. 2008). Reduced fire activity within this region in the 20<sup>th</sup> century resulted in forest infilling and the encroachment of woody vegetation into grasslands historically maintained by low- and mixed-severity fire regimes (Klenner et al. 2008). Periodic droughts add complexity to these disturbance dynamics, with anomalously warm and dry conditions shown to be associated with historic fire and insect activity (Heyerdahl et al. 2008; Flower et al. 2014a, 2014b; Abatzoglou and Williams 2016; Littell et al. 2016; Senf et al. 2016). Considering that more frequent and severe intervals of drought and disturbance are expected in these dry conifer forests as the climate of interior B.C. changes in the next

century (Turner 2010), the disturbance-drought association, as well as the interactions among these disturbances, warrants attention.

A complex suite of factors including climate, land cover and disturbance interactions influence the characteristics (e.g. intensity, severity, return interval and size) and ecological effects of disturbance. A comparison of subalpine and lower montane forests highlights the complexity in relationships between fire, climate, land cover and effects (Krawchuk et al. 2011). Fires affecting subalpine forests are generally large and infrequent, and have significant ecological impact (Agee 1996). These fires are characteristically associated with prolonged and enhanced droughts that reduce fuel moisture (Schoennagel et al. 2007). Fires affecting subalpine forests contrast with fires occurring in lower montane forests where antecedent moisture promotes the growth of fine fuels. Low- and mixed-severity fires are common-place in these montane forests, and characteristically maintain park-like open forests dominated by middle to large canopy classes with little understory vegetation (Agee 1996). Within these forests, mild to moderate droughts in the fire year and/or positive antecedent moisture conditions are shown to be related to historic fires (Agee 1996; Gartner et al. 2012).

Insect outbreak characteristics (eg. synchrony, severity, duration) are linked to climates that promote insect survival and weaken the defenses of the host tree species (e.g. Peltonen et al. 2002; Bentz et al. 2010; Senf et al. 2016), as well as to habitat conditions such as host density and connectivity (Raffa et al. 2008). Warm and dry climates favour forest insect survival, the expansion of natural ranges (Dale et al. 2001; Logan et al. 2003; Bentz et al. 2010), and reduce the effectiveness of tree defense strategies (Mattson and Haack et al. 1987; Dale et al. 2001). The density and age-class of

host species contributes to the transition of endemic to epidemic insect population levels (Maclauchlan et al. 2006; Senf et al. 2016). For example, the abundance of suitable-aged lodgepole pine (*Pinus contorta* Dougl.) in the late 20<sup>th</sup> century within inland regions of the Pacific Northwest is identified as a key determinant in the recent, extensive, MPB outbreak (Raffa et al. 2008). In interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* Beissn. Franco) dominated forests, isolated outbreaks of Douglas-fir beetle (*Dendroctonus pseudotsugae*) are increasing (Maclauchlan and Buxton 2015), and the spatial synchrony of WSB outbreaks has reportedly increased in the 20<sup>th</sup> century (Flower et al. 2014a; Axelson et al. 2015; Flower 2016).

Forest insect outbreaks can inhibit or promote the occurrence of other disturbances, such as fire and disease, creating important ecological feedbacks that affect forest structure and function. Although research on the interaction between WSB outbreaks and fires in B.C. is limited (Lynch and Moorcroft 2008), elsewhere researchers suggest that reduced fire frequency over the past century has led to multi-storied Douglas-fir stands that support widespread and synchronous WSB outbreaks (Anderson et al. 1987; Hadley and Veblen 1993; McCullough et al. 1998). Further, research indicates WSB outbreaks promote significant understory mortality leading to an accumulation of dead, dry fuels facilitating fire activity and spread (Agee and Hummel 2003). Conversely, other research indicates that WSB outbreaks reduce the fire risk and minimize the severity of subsequent outbreaks (Lynch and Moorcroft 2008).

The purpose of this study was to document site- and region-level disturbance-climate relationships in west central B.C., and determine if grassland proximity influences the occurrence of fire or the initiation of WSB outbreaks. I also sought to

determine if fires and outbreaks of WSB occur synchronously, asynchronously or independently. The dry conifer forests and grasslands of interior B.C. are ecologically and economically important environments to First Nations, government agencies and industrial organizations. As only limited research was previously directed at understanding the influence of grasslands on disturbances in this setting, the findings of the research offer important insights for management strategies aimed at promoting resilience in these important ecosystems.

## 4.4 Methods

### *4.4.1 Study area and site selection*

Within the southern and central interior of B.C., Douglas-fir forests cover 16 000 km<sup>2</sup>, and are generally found at elevations between 800 and 1200 m above sea level (asl). Arid river valley bottoms are characterized by grasslands with high natural plant species diversity, dominate at elevations between 400-700 m asl, and support substantial agricultural and range activities (Tisdale 1947; Tisdale and McLean 1957; Nicholson et al. 1991). From 700-900 m asl the lower elevation grasslands transition to montane forests. Like forest-grassland ecotones elsewhere, this ecological transition is sustained by numerous factors including aspect, moisture availability, competition and disturbances (Hansen and di Castri 1992; Risser 1995). In this setting the grassland-forest ecotone was historically characterized as open and park-like with little understory vegetation (Strang and Parminter, 1980). This vegetation structure was maintained by high-frequency, low-severity fire activity typical of grassland ecosystems (Lepofsky et al. 2003, Bai et al. 2004). In the absence of 20<sup>th</sup> century fires, however, modern lower montane forests are denser and the encroachment of conifers has decreased the grassland area.

Fire and WSB outbreak histories were examined at eight sites in the Chilcotin and Fraser plateau region of west central B.C. (Table 4.1)(Figure 4.1). The physiography of the region is characterized by summit elevations ranging between 700 to 1500 m asl and arid valleys where the Chilcotin, Fraser and Nicola rivers incise the landscape (Church and Ryder 2010). A grassland-forest ecotone marks the transition between lower elevation grasslands and higher-elevation contiguous forests between 600-800 m asl.

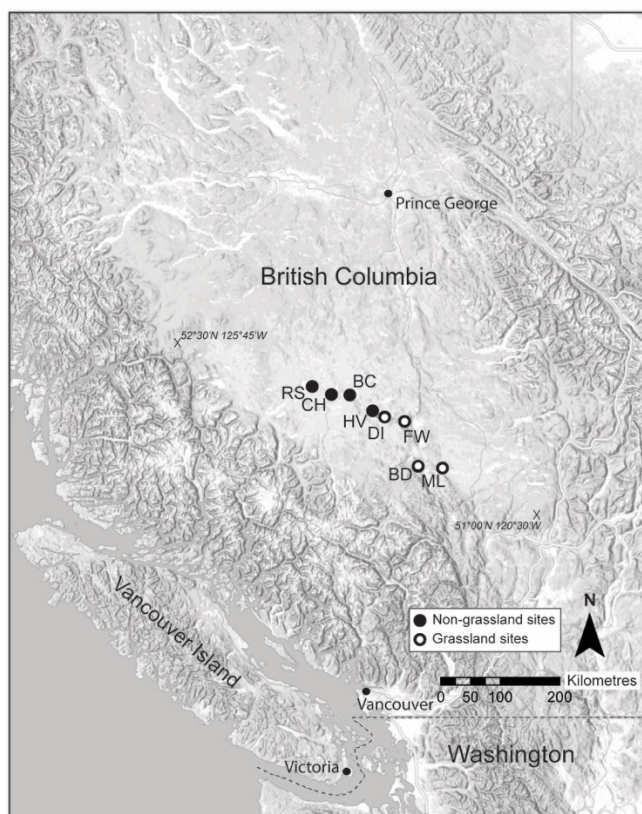


Figure 4.1. Location of eight study sites presented in this study.

The B.C. Coast Mountains lie to the west of the region and rise to over 4000 m asl generating an extensive rain shadow to the east. Warm, dry summers and cold, dry winters characterize the regional climate (Church and Ryder 2010). In the west portions of the study region at Tatlayoko Lake 436 mm of precipitation falls annually, with

summer and winter temperatures averaging 13.1 and -1.8°C, respectively (1980-2010 Climate Normals; Environment and Climate Change Canada 2016). In the eastern section of the study region at Williams Lake 451 mm of precipitation falls annually, and summer and winter temperatures average 14.5 and -1.3°C, respectively (1980-2010 Climate Normals; Environment and Climate Change Canada 2016).

Table 4.1. Site locations in the Cariboo Forest Region, British Columbia. Tree-ring chronologies are divided between those collected from non-grassland and grassland sites, and are arranged from east to west (Figure 4.1). The number of samples collected, number of fire years and mean return interval are presented by individual site.

Site	Latitude (N)	Longitude (W)	Elevation (m asl)	No. of samples collected	No. of fire years <sup>a</sup>	Mean return interval (years)
<i>Non-grassland sites</i>						
Redstone	52° 09.867'	123° 54.683'	1031	26	16	18
Chilko	52° 05.575'	123° 37.450'	897	22	6	31
Bull Canyon	52° 05.181'	123° 20.762'	788	19	11	30
Hanceville	51° 56.418'	122° 59.939'	1075	15	9	16
<i>Grassland sites</i>						
Dante's Inferno	51° 52.908'	122° 49.151'	1022	18	12	24
Farwell Canyon	51° 50.525'	122° 31.051'	915	20	14	16
Black Dome	51° 25.421'	122° 18.902'	1080	46	28	9
Meadow Lake	51° 24.234'	121° 56.761'	1125	24	17	16

<sup>a</sup> Fire years were identified when at least 2 trees were scarred by a fire

The sampling locations selected for study include four sites found within grassland-forest ecotones (within 200 m of expansive grasslands) at locations ranging in elevation from 915 to 1125 m asl, and are hereafter referred to as 'grassland sites' (Table 4.1). The forest cover at these sites is broken by grassy meadows dominated by bluebunch wheatgrass (*Elymus spicatus*), short-awned porcupine grass (*Hesperostipa spartea*), spreading needlegrass (*Acnatherum richardsonii*) and big sagebrush (*Artemisia tridentate* Nutt.).

Four additional sites were located in areas of contiguous forest cover with no nearby open grasslands at elevation ranging from 788 to 1075 m asl, and are hereafter referred to as ‘non-grassland sites’ (Table 4.1). At each of these sites Douglas-fir trees dominate, along with infrequent lodgepole pine and Rocky Mountain juniper (*Juniperus scopulorum*).

#### 4.4.2 Disturbance history reconstructions

##### 4.4.2.1 Fire

The thick bark of Douglas-fir trees protects the tree bole from the effects of low severity fires (Peterson and Arbaugh 1986). The same fires can, however, cause partial cambial scarring in younger trees (20-50 years old) with thin bark (< 2.5 cm in some *Pinus* spp.) (McBride 1983). Following this initial injury, surviving trees grow around the injury preserving the fire event as a scar in the annual growth rings (Fritts and Swetnam 1989). The exposed cambium is vulnerable to future fire activity and the tree may record multiple fire events while alive.

Dendrochronology uses crossdating techniques to assign dates to individual fire scars with annual and sometimes seasonal precision (Dieterich and Swetnam 1984). Site-level records of fire occurrence and return intervals are created by examining samples from multiple fire-scarred trees and identifying years when fires scarred two or more trees. Regional fire histories are developed by combining fire records from multiple sites to provide insights on the influence of climate on fire activity (Swetnam et al. 1999; Grissino-Mayer and Swetnam 2000; Swetnam and Baisan 2003).

In this study, fire-scarred trees were identified and sampled within 30-40 ha search areas to construct site-level fire histories. Trees with the greatest number of visible

scars were preferentially sampled. Partial stem cross-sections were collected using a chainsaw from living and standing dead trees, as well as from fallen logs, stumps and coarse woody debris. The samples were polished with progressively finer grit sandpaper until the ring boundaries were visible under magnification. The ring widths were measured to the nearest 0.01 mm and cross dated visually first and then quality checked using statistical methods (Grissino-Mayer 2001), against previously developed master tree-ring chronologies from nearby Farwell Canyon (AD 1490-2009) and Redstone (AD 1385-2009) (Axelson et al. 2015). Fire scars were dated based on their year of record in cross dated annual rings (Dieterich and Swetnam 1984).

Site-level fire histories were compiled for seven of the eight sites by selecting years when at least two fire scarred trees recorded fire events. At Black Dome the ‘grassland fire’ chronology reported in Harvey et al. (2017) was used that included fire years recorded by at least two trees within 400 m of grasslands. Regional fire histories were constructed for grassland sites and for non-grassland sites by pooling all the years when fires were recorded.

#### 4.4.2.2 *Western spruce budworm*

WSB is a widespread and destructive defoliating insect whose primary host in western North America are Douglas-fir trees (Fellin and Dewey 1982), as well as true firs (*Abies* spp.), western larch (*Larix occidentalis* Nutt.) and Engelmann spruce (*Picea engelmanni* Parry ex Engelm.) (Furniss and Carolin 1977; Fellin and Dewey, 1982). Defoliation by WSB results in reduced incremental growth during the outbreak and for several years following outbreak cessation (Swetnam and Lynch 1989; Alfaro and Maclauchlan 1992). The duration of WSB outbreaks in the study region ranges from 10-

20 years (Axelson et al. 2015), with a mean return interval of 33 years (Campbell et al. 2006; Alfaro et al. 2014).

The frequency and duration of WSB outbreaks in host trees is determined by removing the climate-related component of interannual radial growth. This procedure is accomplished by using a chronology from a cohabiting non-host tree species sensitive to the same climate limitations as the host species (Swetnam and Lynch 1989). Intervals of reduced incremental growth that remain in the ‘climate-corrected’ host chronology are inferred to result from WSB defoliation (Swetnam and Lynch 1989).

Multi-century WSB outbreak reconstructions were constructed at four sites: Chilko, Hanceville, Meadow Lake, and Black Dome (Figure 4.1). At each site a WSB host (Douglas-fir) chronology was constructed by preferentially sampling trees at breast height with 5.2 mm increment borers and collecting one core from a minimum of 20 trees. The cores were dried, mounted on slotted mounting boards, sanded, and the ring widths measured and cross dated using the methods described above.

Biological and geometric growth trends in the tree-ring series were removed with the program ARSTAN by first invoking a negative exponential curve followed by a 50-year 50% frequency response cubic smoothing spline (Cook and Peters 1981). A bi-weight robust mean was computed using a mean value function that minimized the effect of outliers to produce dimensionless stationary index time series with a mean of 1.0 and relatively constant variance (Cook and Kairiukstis, 1990). A non-host ponderosa pine (*Pinus ponderosa*) chronology compiled by Axelson et al. (2015) was used to remove the climate signal in the host chronologies and isolate the defoliation signal.

The tree-ring program OUTBREAK was used to reconstruct WSB outbreaks (Holmes and Swetnam 1996). The program applies a set of user-defined criteria to identify sustained periods of reduced radial growth associated with insect outbreak intervals (Holmes and Swetnam 1996). Following the approach previously taken in this region and in comparable environments (Swetnam and Lynch 1989, 1993; Alfaro et al. 2014; Axelson et al. 2015), the WSB outbreaks were identified where: 1) a minimum threshold of eight years of below average growth was detected; and, 2) there was a trend of reduced growth below -1.28 standard deviation. Stand-wide outbreaks were defined as occurring when at least 40% of host trees recorded defoliation. Some analyses required a single year to represent outbreak initiation. Similar to the thresholds employed by others (i.e. Flower et al. 2014a; Flower 2016), outbreak initiation was defined as the first of at least two consecutive years when an outbreak was recorded, preceded by two or more years without an outbreak.

#### *4.4.3 Disturbance-climate relationships*

The association between WSB outbreaks and climate was examined over the full duration of the disturbance and climate records at each site. To determine whether to include 20<sup>th</sup> century outbreaks in the analysis, the number of years recording at least 40% defoliation and the cumulative percent defoliation for 100-year intervals was compared at each site. The cumulative percent defoliation was calculated over the common interval AD 1700-2009 to see if there was any apparent difference based on site or temporal window. Based on these results (Figures 4.3 and 4.4), the relationship between WSB outbreaks and climate was analyzed over the full duration of the disturbance and climate records (see Results for more details).

To represent regional moisture availability, I relied upon gridded reconstructions of the Palmer Drought Severity Index (PDSI; Cook et al. 2008a; AD 1600-2005) and precipitation (Big Creek; Watson and Luckman 2004; AD 1600-1996). The PDSI is a measure of moisture stress calculated from temperature, precipitation and soil type (Cook et al. 2008a). Annual summer (June-August) PDSI values were used from the grid point located closest to the study region (Gridpoint 30; 52.5°N, -122.5°W), and the one showing the highest Pearson's correlation with the host ring-width indices. Considering the influence of precipitation may be greater than temperature on WSB defoliation (Williams and Liebhold 1995), a proxy precipitation reconstruction from Watson and Luckman (2004) was used. When detected, autocorrelation was removed from the climate time series using an ARMA model of an order determined based on Akaike's Information Criterion.

At each site the relationship between moisture availability and disturbance events was assessed using superposed epoch analysis (SEA) in the package `dplr` in R. SEA averages climate variables at multiple temporal lags relative to each disturbance event, creating a composite of climatic variable values before and after disturbance events (Grissino-Mayer and Swetnam 2000; Rother and Grissino-Mayer 2014). An 11-year window of analysis was used to assess climate in the year of the disturbance event and in the five years prior and following events. The analysis was conducted separately for fire and WSB outbreak event years. Statistical significance was assessed using 1,000 Monte Carlo simulations to estimate bootstrapped confidence intervals (95 and 99%).

To explore regional patterns in disturbance-climate relationships, four regional disturbance histories were created by compiling all years when: 1) fires affected non-

grassland sites; 2) fires affected grassland sites; 3) outbreaks initiated in non-grassland sites; and, 4) outbreaks initiated in grassland sites. SEA analysis was again used to compare these regional disturbance histories to the climate records. Additional motivation for utilizing regional disturbance histories in the analyses was to verify the site-level disturbance-climate relationships when the number of disturbance events over the interval of analysis was low, particularly for budworm outbreaks.

Bivariate event analysis (BEA) was used to compare disturbance event years to extreme climate years. BEA is a modified one-dimensional bivariate Ripley's K-function used to determine whether disturbance events and extreme climate events occur closer together in time than expected by chance (Gavin et al. 2006; Schoennagel et al. 2007; Gavin 2010; Gartner et al. 2012). Using both the grassland and non-grassland regional disturbance histories, synchrony with climate was assessed for each regional disturbance history during the period common to both the disturbance and climate records. The climate records were ranked based on index value and extreme climate event years defined as either the 30, 40, or 50 most extreme (positive or negative) index values. In instances where the period of analysis was: 250 years, the 30 most extreme years were used; 300 years, the 40 extreme years were used; and, 400 years, the 50 extreme years were used. The bivariate Ripley's K-function was transformed to the  $L$  function to stabilize the mean and variance and improve result interpretation (Gavin et al. 2006; Gavin 2010). Forward selection was used in the K1D software, where fire and WSB event years were preceded by extreme climate years. Ninety-five percent confidence intervals were based on 1000 simulations. Values of the  $L$  function that exceed the upper confidence interval indicate a strong relationship of fire events  $t$  years after the extreme

climate years. Values of the  $L$  function that fall below the lower confidence interval indicate fire-climate asynchrony at  $t$  years after the extreme climate years.  $L$  function values between the confidence intervals indicate fires occur independently of extreme climate years.

#### 4.4.4 *Fire-insect disturbance interaction*

BEA was used to assess the temporal synchrony between fire and WSB outbreak initiation over the interval of AD 1700 to 1900. At each site, the years when fire activity was recorded were compared to the years when WSB outbreaks were initiated. To provide a regional perspective, existing ‘regional fire’ (Harvey et al. 2017) and ‘regional outbreak’ (Axelson et al. 2015) disturbance records were used. Forward selection was used in the K1D software, where fire event years were preceded by WSB initiation years.

## 4.5 Results

### 4.5.1 *Disturbance history reconstructions*

Between 6 and 28 fire years were identified at the study sites from AD 1600 to 1900 (Table 4.1; Figure 4.2). Fifty-eight years were identified when fire affected forests adjacent to grasslands, and 37 years were revealed when fire affected forests not adjacent to grasslands. The average return interval of fires at non-grassland sites was 24 years (range: 16-31 years) and 16 years (range: 9-24 years) at grassland sites (Table 4.1).

The WSB outbreak reconstructions for Hanceville, Dante’s Inferno, Black Dome and Chilko begin between AD 1600 and 1697 (with at least 4 trees recording defoliation) (Table 4.2; Figure 4.2). Incorporating site data from Axelson et al. (2015)(Table 4.2) at non-grassland sites, an average of eight outbreaks (range: 7-8 outbreaks) were identified. Average outbreak duration was 18 years but varied between 14 and 26 years and the

mean return interval was 49 years (site mean return interval range: 43-67 years). At all grassland sites, I identified an average of seven outbreaks (range: 5-8 outbreaks), average outbreak duration was 18 years and varied between 15 and 19 years and the mean return interval was 64 years (site mean return interval range: 55-76 years).

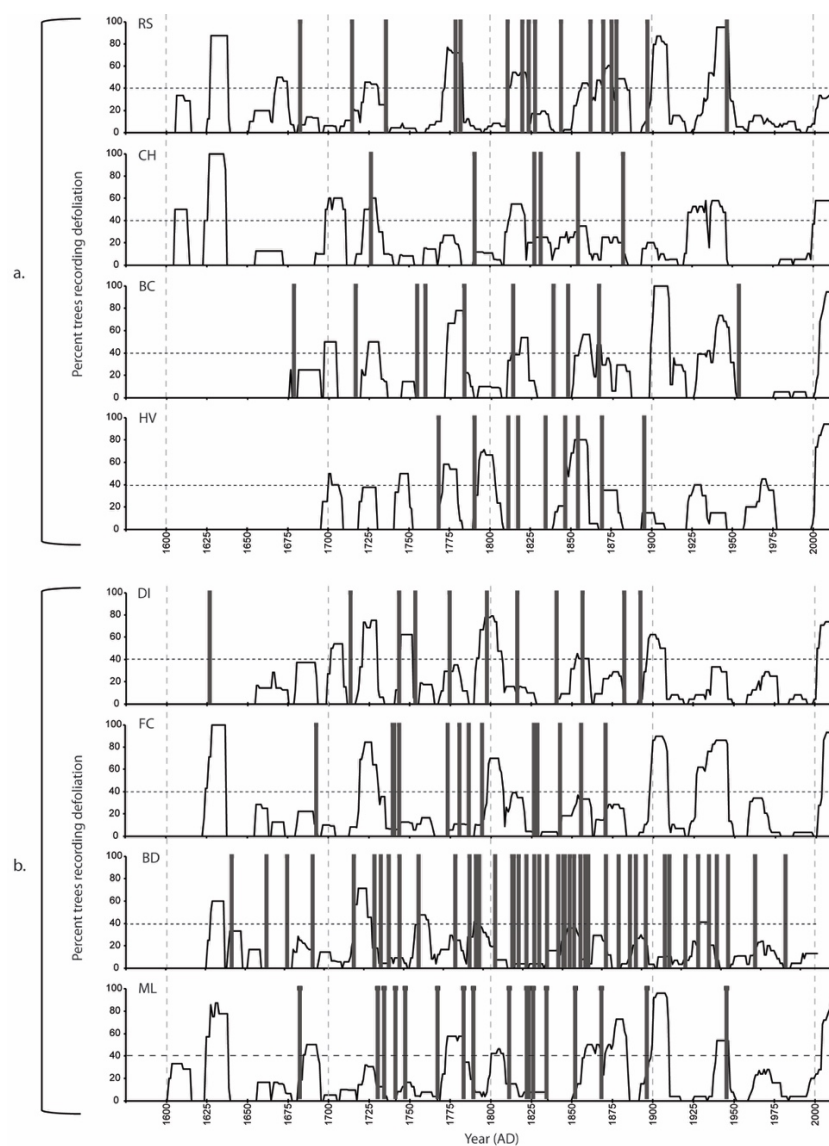


Figure 4.2. Tree-ring reconstructed chronologies of western spruce budworm outbreaks (black line) and fire (vertical grey bars) at non-grassland (a) and grassland (b) sites over the period AD 1600 to 2010. Horizontal dashed lines are the 40% threshold used to identify outbreak periods. Sites are arranged from west to east (top to bottom). Site name abbreviations: RS=Redstone, CH=Chilko, BC=Bull Canyon, HV=Hanceville, DI=Dante's Inferno, FC=Farwell Canyon, BD, Black Dome, ML=Meadow Lake.

Table 4.2. Properties of western spruce budworm host chronologies in the Cariboo Forest Region of British Columbia, Canada. Chronologies are divided into non-grassland and grassland sites and then arranged from east to west (See Figure 4.1). The reconstructed number, duration and return interval of outbreaks by individual sites.

Site	Series length (years AD)	No. of dated series	Inter-series $r$	Start of record <sup>a</sup>	No. of outbreaks <sup>b</sup>	Mean duration (years) <sup>c</sup>	Mean return interval (years) <sup>d</sup>	Source
<i>Non-grassland sites</i>								
Redstone	1385-2009	68	0.74	1576	8	26	43	Axelson et al. 2015
Chilko	1555-2013	20	0.80	1600	7	14	67	This study
Bull Canyon	1560-2009	38	0.75	1676	8	18	41	Axelson et al. 2015
Hanceville	1611-2013	20	0.85	1697	8	14	43	This study
<i>Grassland sites</i>								
Dante's Inferno	1606-2013	24	0.82	1650	7	15	50	This study
Farwell Canyon	1490-2009	57	0.77	1615	6	18	76	Axelson et al. 2015
Black Dome	1620-2013	37	0.83	1625	5	18	74	This study
Meadow Lake	1516-2010	50	0.76	1594	8	19	55	Axelson et al. 2015

<sup>a</sup> Start of record for each site truncated when there were fewer than four host trees in the sample.

<sup>b</sup> Outbreaks when at least 40% of trees were defoliated for one or more years

<sup>c</sup> Duration spanned the interval when at least two trees recorded defoliation

<sup>d</sup> Return intervals are number of years between initiation years of outbreaks

No coherent patterns were detected when the number of years with  $\geq 40\%$  defoliation and cumulative percent defoliation for non-grassland and grassland sites was compared (Figures 4.3 and 4.4).

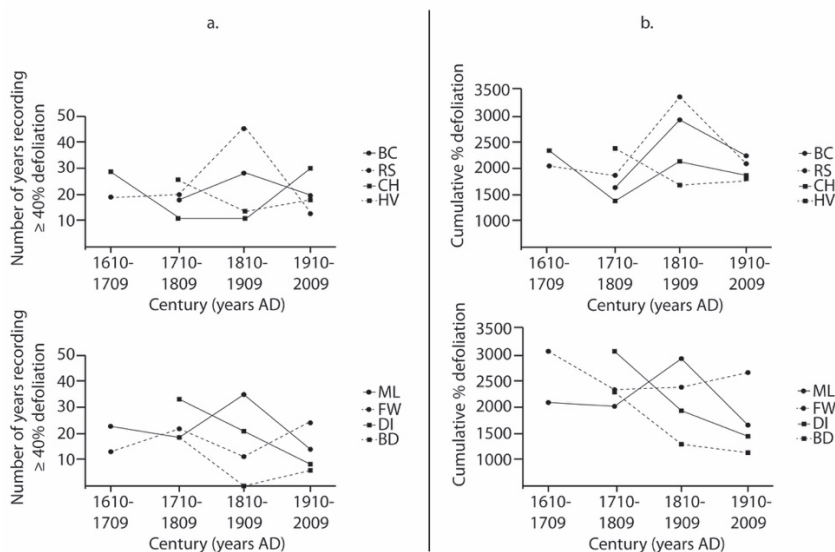


Figure 4.3. Comparison of the number number of years recording  $\geq 40\%$  defoliation (top plots) and cumulative percent defoliation (lower plots) within 100 year periods at non-grassland (a) and grassland (b) sites over the interval AD 1610 to 2009. See Figure 4.2 caption for site abbreviation descriptions.

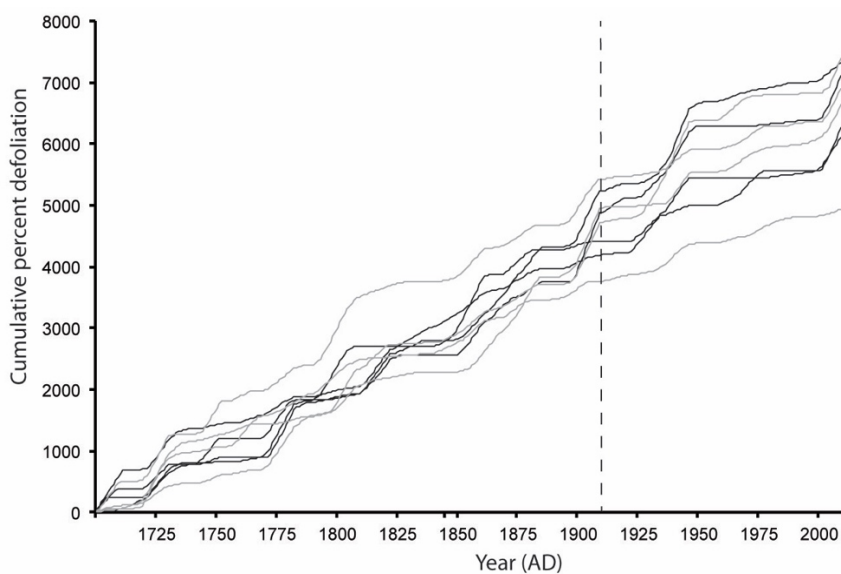


Figure 4.4. Cumulative percent defoliation from AD 1700 to 2010 at non-grassland (black line) and grassland (grey line) sites.

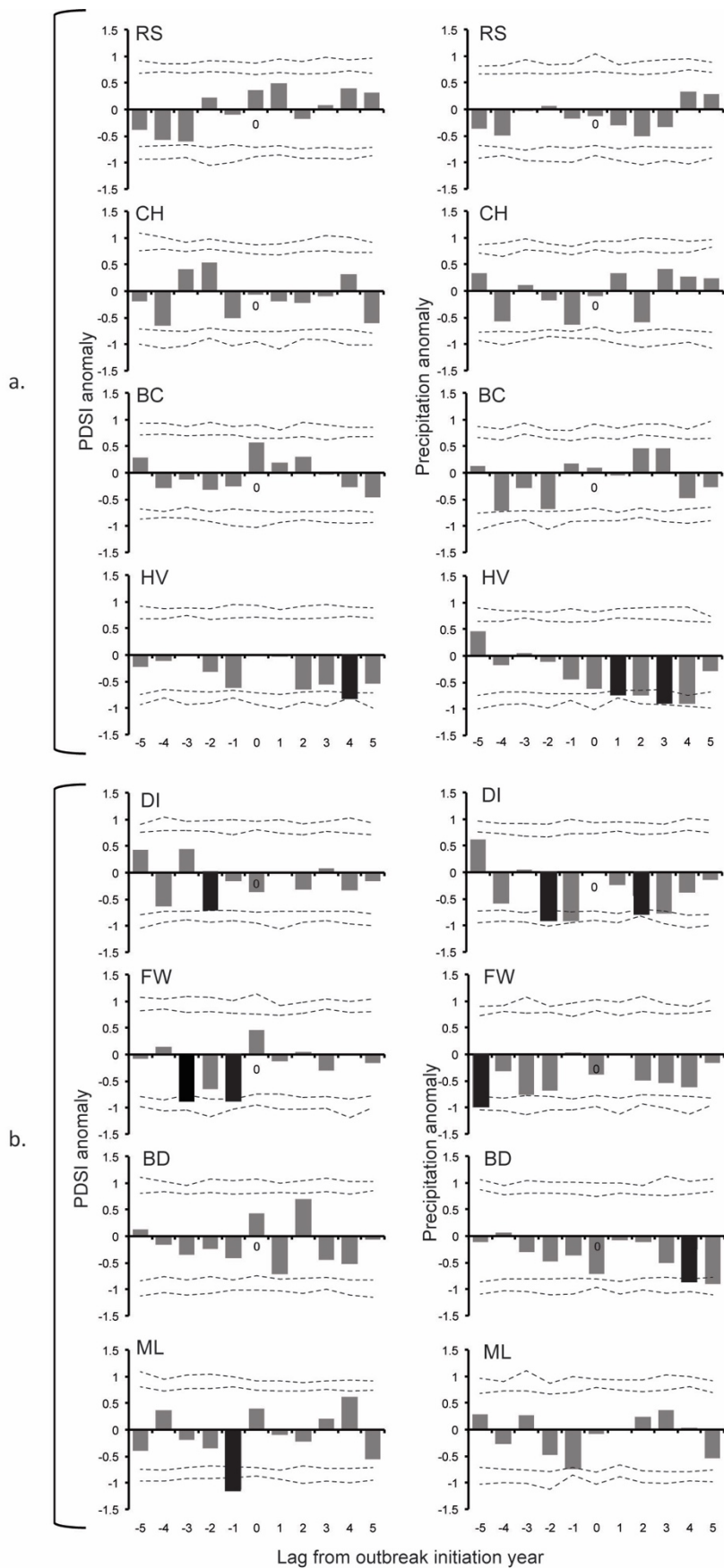
#### 4.5.2 *Disturbance-climate relationships*

##### 4.5.2.1 *WSB outbreak initiation*

At the site level, SEA identified statistically significant relationships between outbreak initiation years, PDSI and precipitation in the years prior to the outbreak at four sites (Figure 4.5). At these sites anomalously low PDSI and/or precipitation occurred during or preceded outbreak initiation by one to five years (Figure 4.5). A significant relationship was also found at Hanceville, where anomalously low PDSI and precipitation occurred 3-5 years following outbreak initiation. No significant relationships were found between outbreak initiation, PDSI and precipitation at Redstone, Bull Canyon or Chilko (Figure 4.5).

At the regional level for non-grassland sites, SEA identified statistically significant relationships between outbreak initiation and anomalously low PDSI in the year prior to outbreak initiation, and between outbreak initiation and anomalously low precipitation four years before outbreaks (Figure 4.6). At grassland sites, statistically significant relationships between outbreak initiation, and anomalously low PDSI and precipitation were found in the two years prior to outbreaks (Figure 4.6). BEA corroborated the results of the SEA at both non-grassland and grassland sites, identifying significant associations between outbreak initiation years and extreme negative PDSI and precipitation years during the outbreak year and multiple year preceding the outbreak (Figure 4.7).

Additionally, at grassland sites BEA reported a statistically significant asynchronous relationship between outbreak initiation years, extreme positive PDSI and precipitation years in the two years preceding outbreak initiation (Figure 4.7).



Lag from outbreak initiation year

Figure 4.5. (Previous page) Superposed epoch analysis indicating the direction of reconstructed climate anomalies (Palmer Drought Severity Index (Cook et al. 2008a) and precipitation (Watson and Luckman 2004)) for an 11-year window centered on outbreak initiation dates at the four non-grassland (a) and four grassland (b) sites. Descending bars indicate a negative association with the climate variable (i.e., droughty conditions), ascending bars indicate a positive association with the climate variable (i.e., wetter conditions). Dashed lines mark the 95% and 99% confidence intervals and dark grey shading highlights statistically significant (95% confidence intervals) anomalies. See Figure 4.2 caption for site abbreviation descriptions.

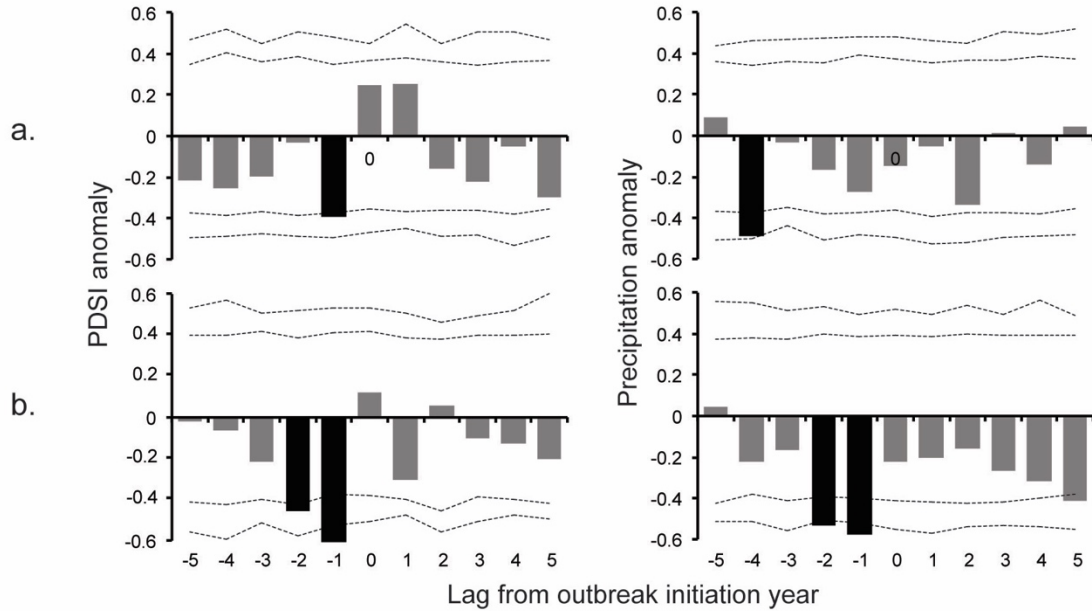


Figure 4.6. Superposed epoch analysis indicating the regionalized direction of reconstructed climate anomalies (Palmer Drought Severity Index (Cook et al. 2008a) and precipitation (Watson and Luckman 2004)) for an 11-year window centered on outbreak initiation dates from all non-grassland (a) and all grassland (b) sites. Descending bars indicate a negative association with the climate variable (i.e., droughty conditions), ascending bars indicate a positive association with the climate variable (i.e., wetter conditions). Dashed lines mark the 95% and 99% confidence intervals and dark grey shading highlights statistically significant (95% confidence intervals) anomalies.

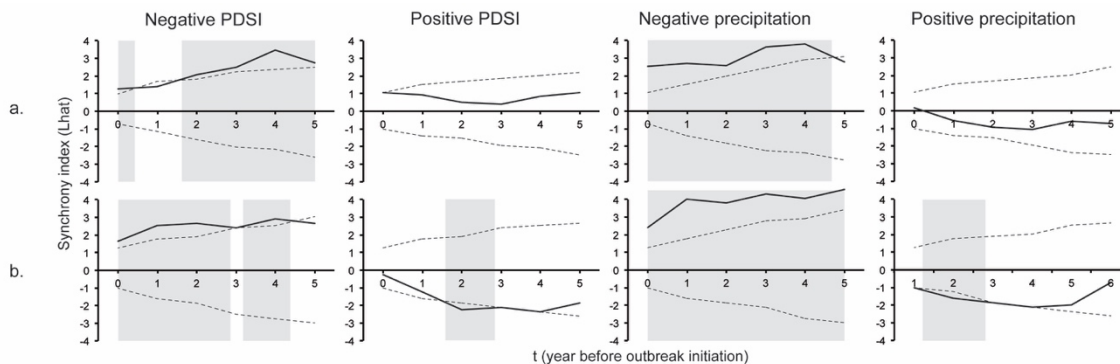


Figure 4.7. Bivariate event analysis of the temporal association of extreme negative and positive Palmer Drought Severity Index (Cook et al. 2008a) and precipitation (Watson and Luckman 2004) with the non-grassland (a) and grassland (b) regionalized histories of outbreak initiation. Black solid lines indicate  $Lhat$  values ( $L$  function with stabilized mean and variance) for  $t$  years before the fire events ( $t=0$ ). Dotted lines indicate the upper and lower confidence intervals (95%).  $Lhat$  values outside the confidence intervals indicate synchrony with fire, and values between the confidence intervals indicate a random relation of fire and climate events. Grey shaded bars highlight statistical significance ( $P < 0.05$ ).

#### 4.5.2.2 Fire

At the site level, SEA identified statistically significant relationships between years when fire was recorded, PDSI and precipitation at five sites (Figure 4.8). At Hanceville fire years were associated with above average PDSI values three years prior to the fire years. At Meadow Lake fires were significantly related to anomalously low PDSI in the year of the fire, high PDSI in the year prior to the fire and high precipitation three years prior to the fire. At Farwell Canyon below average PDSI five years prior to the fire was significantly associated to fire years. At Dante's Inferno a significant association was found between anomalously high PDSI three years prior to fire years and below average precipitation five years before fire years. Lastly, at Black Dome significant relationships between above average PDSI were found in the year prior to fire years, and between

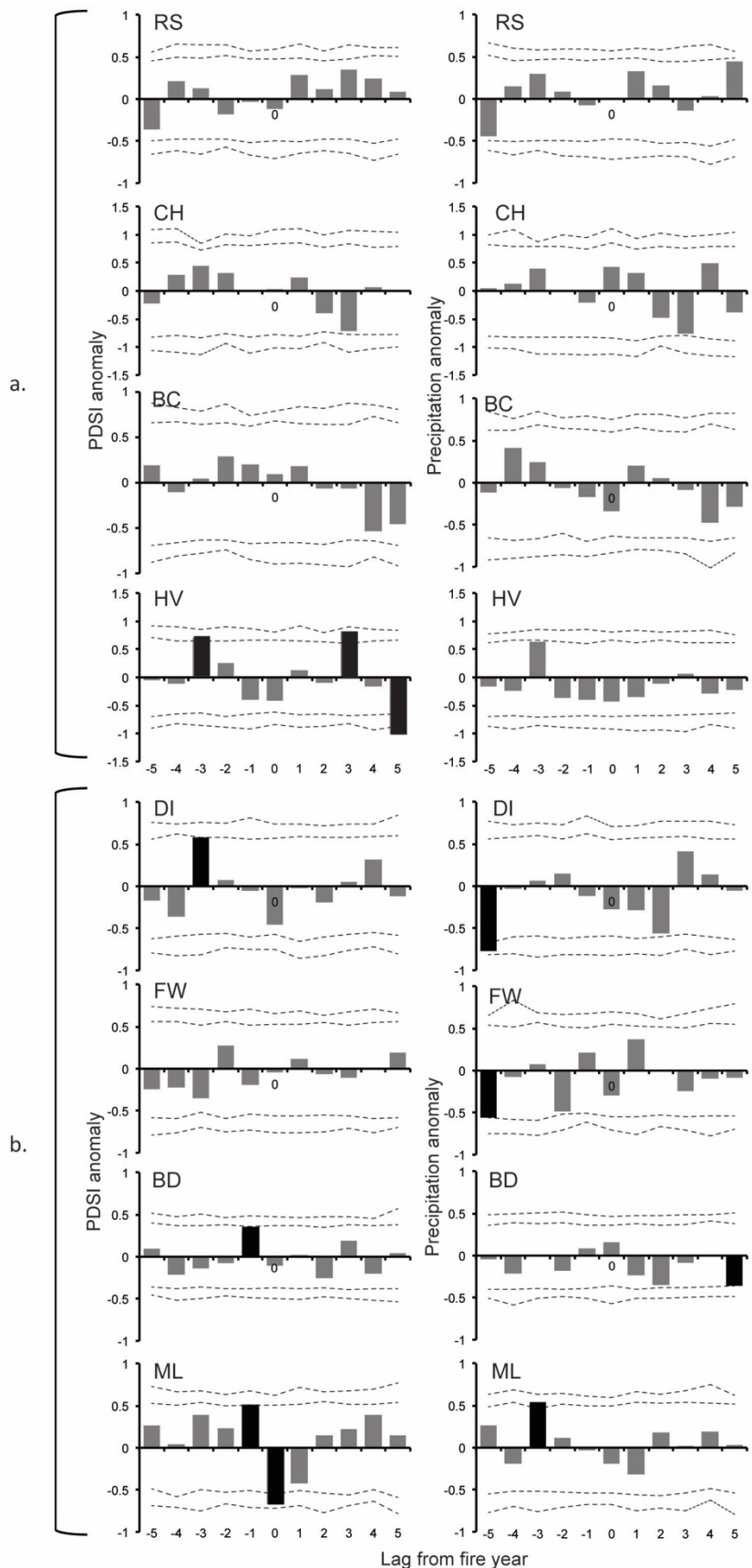


Figure 4.8. (Previous page) Superposed epoch analysis indicating the direction of reconstructed climate anomalies (Palmer Drought Severity Index (Cook et al. 2008a) and precipitation (Watson and Luckman 2004)) for an 11-year window centered on fire years at the four non-grassland (a) and four grassland (b) sites. Descending bars indicate a negative association with the climate variable (i.e., droughty conditions), ascending bars indicate a positive association with the climate variable (i.e., wetter conditions). Dashed lines mark the 95% and 99% confidence intervals and dark grey shading highlights statistically significant (95% confidence intervals) anomalies. See Figure 4.2 caption for site abbreviation descriptions.

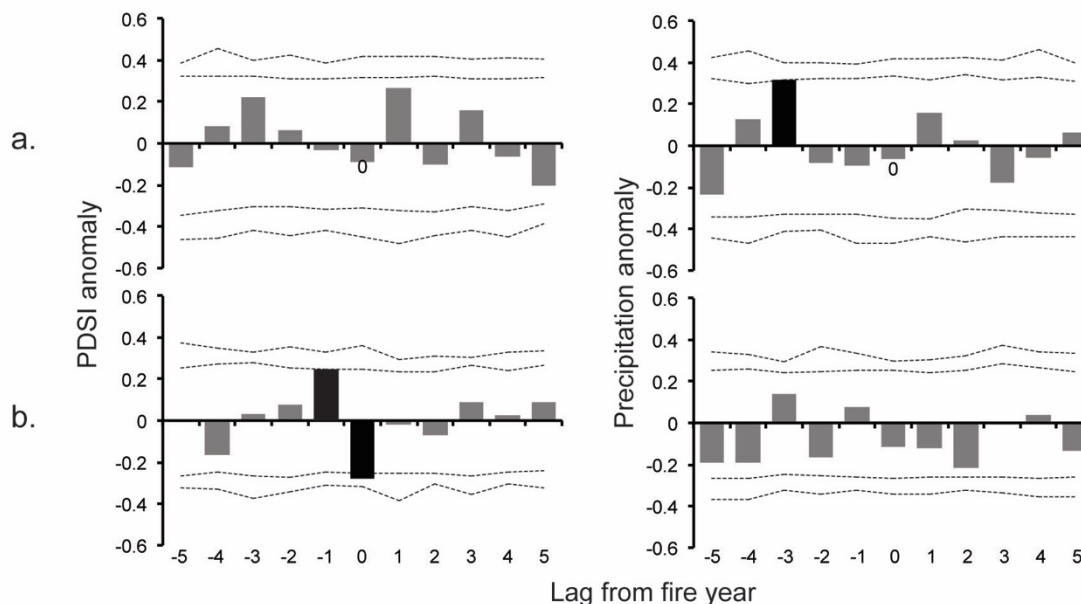


Figure 4.9. Superposed epoch analysis indicating the regionalized direction of reconstructed climate anomalies (Palmer Drought Severity Index (PDSI; Cook et al. 2008a) and precipitation (Watson and Luckman 2004)) for an 11-year window centered on fire years from all non-grassland (a) and all grassland (b) sites. Descending bars indicate a negative association with the climate variable (i.e., droughty conditions), ascending bars indicate a positive association with the climate variable (i.e., wetter conditions). Dashed lines mark the 95% and 99% confidence intervals and dark grey shading highlights statistically significant (95% confidence intervals) anomalies.

fire years and low precipitation values five years after the fire year. No significant relationships were found at the Bull Canyon, Redstone and Chilko sites.

At the regional level for non-grassland sites, SEA identified statistically relationships between fire years and above average precipitation three years prior to the fire year (Figure 4.9). At grassland sites, statistically significant relationships between fire years and anomalously low PDSI in the fire year and above average PDSI in the year prior to the fire year. At non-grassland sites, BEA indicated a significant association between fire years and extreme negative PDSI years in the year of the fire and multiple years preceding the fire (Figure 4.10). Extreme positive precipitation three years prior to fire years was also found to be significantly related at non-grassland sites. At grassland

sites, BEA suggested that both positive and negative extreme PDSI and precipitation years were related to fire years in the fire year and in years prior to the fire (Figure 4.10).

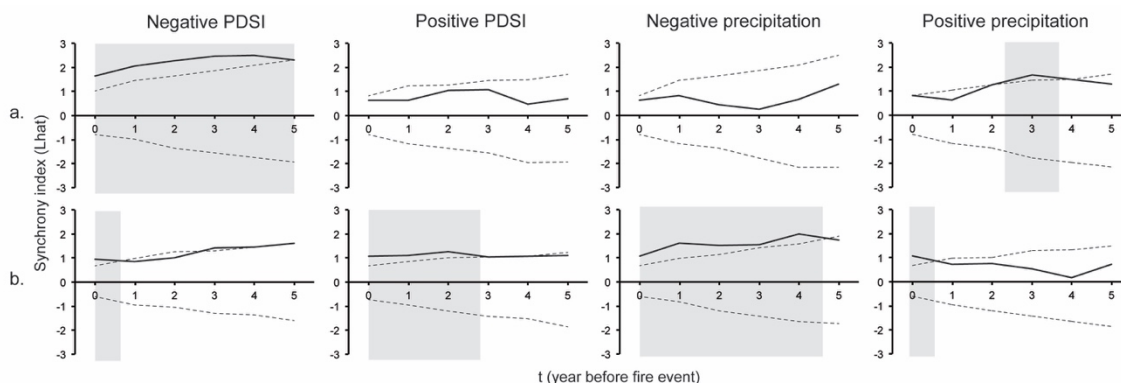


Figure 4.10. Bivariate event analysis of the temporal association of extreme negative and positive Palmer Drought Severity Index (Cook et al. 2008a) and precipitation (Watson and Luckman 2004) with the non-grassland (a) and grassland (b) regionalized fire histories. Black solid lines indicate  $L\hat{t}$  values ( $L$  function with stabilized mean and variance) for  $t$  years before the fire events ( $t=0$ ). Dotted lines indicate the upper and lower confidence intervals (95%).  $L\hat{t}$  values outside the confidence intervals indicate synchrony with fire, an values between the confidence intervals indicate a random relation of fire and climate events. Grey shaded bars highlight statistical significance ( $P < 0.05$ ).

#### 4.5.3 Fire-insect disturbance interaction

At the site level, no consistent relationships between fire years and outbreak initiation years were identified (Figure 4.11). At Redstone a significant relationship between fire years and outbreak initiation years suggests that outbreaks occurred around 20 years prior to fire years more often than expected by chance (Figure 4.11). While an asynchronous relationship at Meadow Lake between fire years and outbreak initiation was found (Figure 4.11), similar relationships were not detected elsewhere. At the regional level, no significant relationships between fire years and outbreak initiation years were documented (Figure 4.12).

## 4.6 Discussion

### 4.6.1 *Disturbance histories*

The mean fire return intervals determined for the study sites (non-grassland sites: 24 years; grassland sites: 17 years) are similar to those reported elsewhere in the CFR (Daniels and Watson 2003 [27 years; 1 ha plots]; and Harvey et al. 2017 [23 years; 7 km<sup>2</sup> study area]). In the Stein River Valley, ~150 km southeast of the study region, Heyerdahl et al. (2007) records historic fire activity every 14-24 years, with variability attributed mainly to aspect (mean plot size: 0.3 ha). Frequent historic fires in the study region and similar environments elsewhere, would have suppressed understory vegetation in areas of contiguous forests and maintained open parkland forests adjacent to grasslands (Agee 1996).

Visual assessment of the outbreak reconstructions shows that budworm populations have fluctuated since the 17<sup>th</sup> century in the CFR (Figure 4.2). Across all the study sites the mean outbreak duration (18 years) and the mean return interval (56 years) is similar to previously reported moderate to severe outbreaks from interior B.C. (Campbell et al. 2006; Axelson et al. 2015), the inland northwest U.S. (Flower et al. 2014a; Flower 2016), and the southwest U.S. (Swetnam and Lynch 1993). The mean outbreak duration, number of outbreaks, defoliation levels and return interval for non-grassland sites and grassland sites was similar (Table 4.2; Figures 4.3 and 4.4), suggesting the historic character of outbreaks was generally consistent across Douglas-fir forests in the study region.

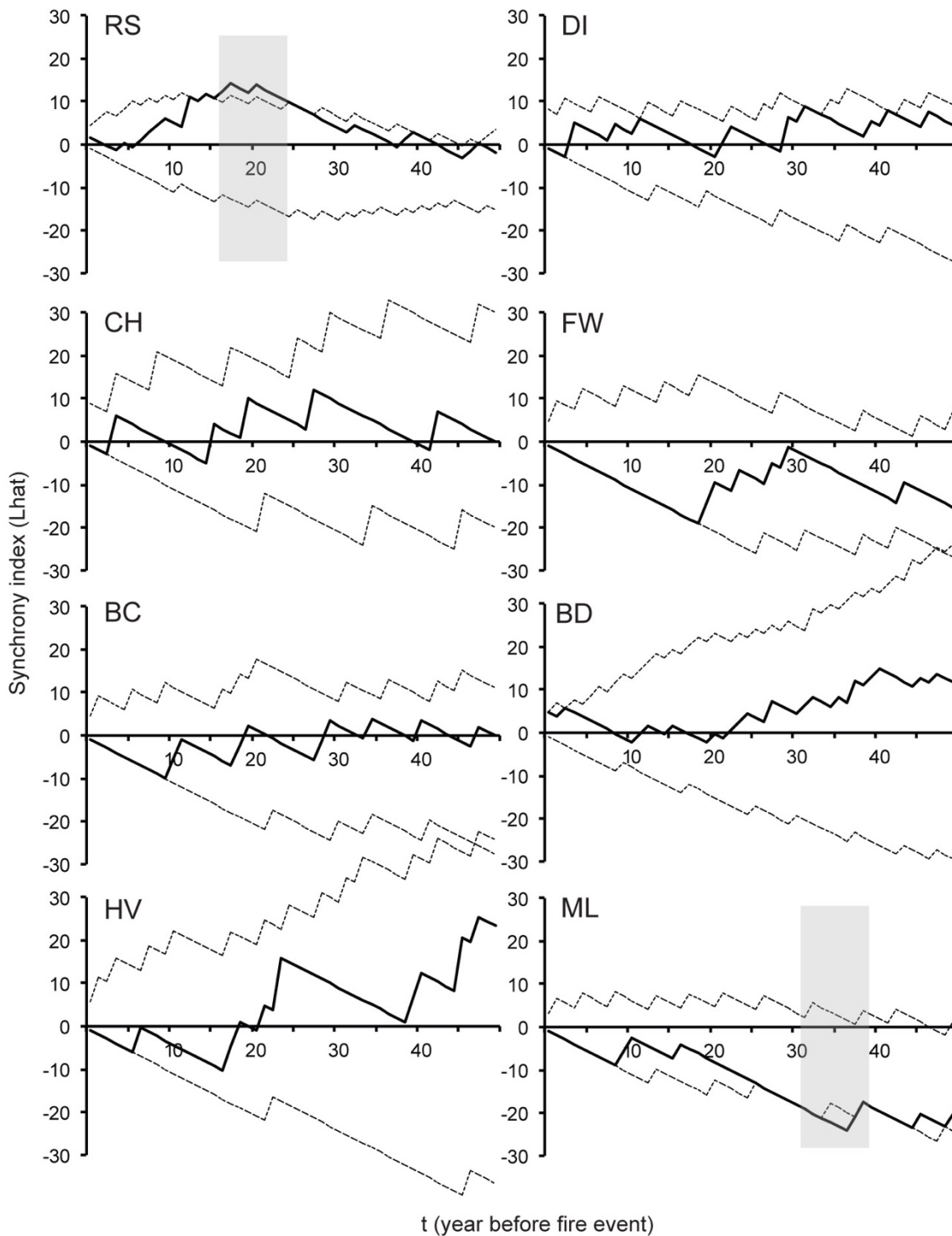


Figure 4.11. Synchrony of fire occurrence and the initiation years of western spruce budworm outbreaks, analyzed using bivariate event analysis at each of the eight sites. See the caption for Figure 4.7 for more details and Figure 4.2 caption for site abbreviation descriptions.

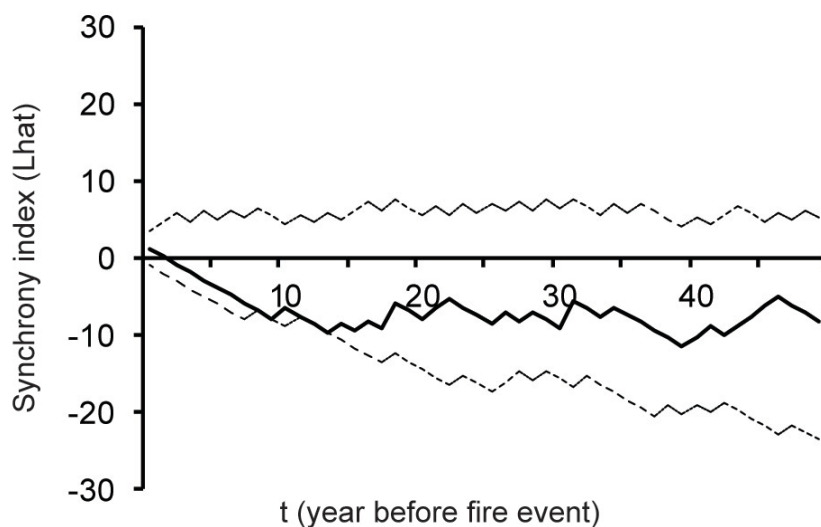


Figure 4.12. Synchrony of regional fire occurrence and regional initiation years of western spruce budworm outbreaks analyzed using bivariate event analysis. See the caption for Figure 4.7 for more details.

#### 4.6.2 Outbreaks of WSB triggered by drought, especially at grassland sites

These analyses suggest that anomalously warm, dry conditions associated with drought are an important prerequisite for initiation of WSB outbreaks (Figures 4.5-4.7). Research documenting the association of climate and bark beetle outbreaks in conifer-dominated forests (e.g. Hart et al. 2014) indicates that drought conditions reduce photosynthesis (Pallardy and Kozlowski 2008), leaf area (Mattson and Haack 1987) and terpene production (Bohmann 2012). These drought-triggered physiological process changes would likely have limited impact on defoliating insects such as the WSB.

The association between drought and outbreaks of defoliating insects likely stems from the drought-induced improvements in the nutritional quality of foliage, climate conditions that promote larval survival and forest structure characteristics. First, drought increases foliar nitrogen content, which promotes insect survival especially in the early stages of larval development (White, 1984). Second, warm and dry conditions

characteristic of drought create a physical environment that increases larval survival (Rhoades 1983; Mattson and Haack 1987), where larval survival, growth and reproductive rates are greater during periods of low precipitation, foliar moisture content and/or soil moisture (Cates et al. 1983; Mattson and Haack 1987; Clancy 1991; Campbell 1993). Third, it is postulated that in areas where available host trees are limited (e.g. open forests, grassland adjacent forests, mixed composition forests), improved forage and climate conditions caused by drought conditions may be of even greater importance to the initiation of outbreak levels of WSB.

Research conducted by Flower et al. (2014a) documents an association between warm, dry conditions and the initiation of WSB outbreaks in the inland northwest. Similarly, Senf et al. (2016) reports an association between recent WSB outbreaks and anomalously dry autumn conditions in B.C. from AD 1995 to 2013. Swetnam and Lynch (1993); Williams and Liebhold (1995); Ryerson et al. (2003); and Flower et al. (2014a) report on a relationship between cool, wet conditions and outbreaks. These findings suggest positive moisture conditions may increase the quantity of foliage available for larval feeding. In contrast to these reports, however, the analyses reported here did not identify a significant relationship between positive moisture conditions and outbreaks. These findings could suggest that the highly contiguous forests in this region provide sufficient foraging pathways during outbreaks to overcome any effects of moisture induced reductions in foliar growth.

To the best of my knowledge, this study is the first to explicitly recognize the influence of grassland proximity on WSB outbreaks. At the site and regional scales, the relationship between drought and outbreaks was stronger and more persistent at grassland

sites than at non-grassland sites (Figures 4.6 and 4.7). Forests near grasslands are generally less dense than forests further from grasslands, where the open structure of grassland adjacent forests was maintained historically by frequent fires (Gartner et al. 2012; Harvey et al. 2017). I postulate that the sensitivity of outbreak initiation to climate is greater at grassland sites and attribute this finding to the reduced density in host trees emphasizing the drought requirement for outbreak initiation. I recognize that the positive relationship identified between drought and WSB outbreaks may not be linear, and that future insect populations may be negatively affected by drought-induced changes to the prevalent forest structure.

#### *4.6.3 Enhanced fire-climate sensitivity at grassland sites*

Forests adjacent to grasslands were found to have experienced fires more frequently than non-grassland sites from AD 1600 to 1900. The data describe an average fire return interval of 24 years (range: 16-31 years) at the non-grassland sites and 18 years (range: 16-24 years) at grassland sites (Table 4.1). Results from the analyses indicate that positive antecedent moisture conditions are related to fire years at grassland sites at the site and regional level (Figures 4.8-4.10). This climatic association suggests that cool, wet spring and early summer conditions may promote the growth and productivity of the herbaceous layer, thereby increasing the availability of fine fuels that would assist the spread of fire in environments (i.e. Miller and Urban 2000). The results from BEA indicate that at grassland sites both positive antecedent moisture and drought conditions are related to fire activity, highlighting the complex fire-climate relationships at grassland proximal forests. High and low extremes of moisture conditions preceding fires could be related to pulses of fine fuel growth and then intense drying of the fuels.

The absence of significant fire-climate relationships at three of the non-grassland sites (Figure 4.8) may indicate that fires affecting these forests occurred independent of climate. In this region the summer climate is generally warm and dry, and in the event of ignition and conducive weather conditions (e.g. wind), localized fires would spread into forests regardless of the seasonal climate. When considering the regional fire history composites, it was shown that fire years at non-grassland sites were related to positive antecedent moisture three years prior to the fire using only the precipitation reconstruction. BEA corroborated this finding, and may indicate that at non-grassland sites fine fuels are also a significant component of the fuel environment.

#### *4.6.4 Fire and WSB outbreaks occur independently*

No consistent relationship was identified between fire and WSB outbreaks among the eight sites, nor to the regional fire and outbreak histories (Figures 4.11 and 4.12). Both fire and WSB outbreaks were associated with reduced moisture availability. However, the analyses suggest these disturbances occur randomly in time relative to each other, and are thus possibly responding to climate variability over different temporal scales (Flower et al. 2014b). WSB outbreaks are associated with the cumulative effects of persistent drought, while fire is associated with stochastic ignitions and the probability of fire spread. In this region, the latter is influenced by dry, hot conditions in the fire year and oftentimes preceded by positive moisture conditions promoting fine fuel growth especially at grassland adjacent forests.

Feedbacks and interactions between multiple disturbance types are dependent on the timing, intensity and severity of each disturbance. In the case of WSB and fire, studies suggest that understory mortality caused by WSB outbreaks, promotes

accumulations of dead, dry fuels facilitating fire activity and spread (Swetnam and Betacourt 1998; Agee and Hummel 2003). Others have reported decreased fire risk and intensity with WSB outbreaks citing reduced ladder fuel and canopy foliage following outbreaks (Lynch and Moorecroft 2008; Sturtevant et al. 2012; Cohn et al. 2014). These results support the findings of Flower et al. (2014b) and suggest that fire and WSB outbreaks occurred independently across the dry Douglas-fir dominated forests of the interior Pacific Northwest between AD 1600 and 2010.

#### *4.6.5 Management and implications*

Over the past century fire activity was infrequent in the study region (Figure 4.2). Fire suppression and other land management practices have altered the ecological structure and function of forests and grasslands through the infilling of montane forests and the encroachment of woody plants into grasslands (Strang and Parminter 1980; Bai et al. 2004). Forest infilling can increase fire risk and intensity contributing to more dangerous fire activity with deleterious ecological effects. The encroachment of conifers into grasslands alters species composition and decreases the quality and quantity of available forage for agricultural grazing (Bai et al. 2004).

In interior B.C. efforts to restore forests to their historical character include prescribed burning and thinning treatments (Klenner et al. 2008). Forest management prescriptions are oftentimes applied at the forest-grassland ecotone to mitigate the effects of 20<sup>th</sup> century management programs (e.g. fire suppression). Our understanding of disturbance histories that affected the forest-grassland ecotone is often based on data not directly collected at the ecotone. This approach may result in the application of management prescriptions inappropriate for this sensitive ecosystem. The findings of

these analyses suggest that fires burned more frequently in grassland adjacent, lower montane forests than in middle montane forests. In areas near grasslands it is suggested that restoration prescriptions aimed at mimicking historical fire activity be expanded, and that they be applied at a frequency of around 17 years. In middle and upper montane forests where fire risk is higher due to forest infilling, treatments such as thinning should be applied. Heterogeneous forest structure in montane forests, and in most natural systems, improves ecosystem resilience to disturbances and creates greater habitat and species diversity (Reich et al. 2001; Peterson and Reich 2008).

Synchronous WSB outbreaks have occurred over large areas of western North America (Flower 2016), and at finer spatial scales outbreaks of low, moderate and high severity have been identified occurring at variable temporal scales (e.g. Axelson et al. 2015). Outbreaks are associated with impacts such as timber losses, stem defects, understory mortality, and delayed regeneration caused by budworm feeding on developing cones (Alfaro et al. 1982; Fellin and Dewey 1982; Alfaro and Maclauchlan 1992; Hadley and Veblen 1993; Maclauchlan and Brooks 2009).

The B.C. government conducts an annual spray program to suppress WSB outbreaks in high value stands using *bacillicus thurigenensis* var. *kustaki* (*btk*). Considering the significant association identified between outbreak initiation and warm, dry climate conditions, I suggest prioritizing research and monitoring that identifies the early stages of WSB outbreaks in order to provide the opportunity to minimize their impact (applications of *btk*) in anomalously dry, warm years. Further, it is recommended that high-value Douglas-fir stands found adjacent to grasslands be targeted for spraying when conditions are hot and dry. These efforts may help reduce the economic losses associated

with the transition of endemic to epidemic insect populations. Lastly, areas identified as high risk to budworm defoliation could be thinned to promote stand and tree vigour.

It is worth noting that these results indicate WSB has been an active disturbance agent in forests since AD 1600 including the 20<sup>th</sup> century. Consequently, the occurrence of WSB outbreaks is not evidence of the impact of fire suppression, however, future research associating the spatial synchronicity of defoliator outbreaks to contemporary changes in forest structure warrants attention.

#### 4.7 Conclusion

Future warmer and drier climates are likely to predispose interior B.C. forests to more frequent disturbance from wildfires and insect outbreaks (Spittlehouse and Stewart 2004). The 20<sup>th</sup> century character of montane forests is dense and expanding into grasslands; frequent disturbances driven by climate change could lead to alternative ecosystem states such as lower montane forests becoming grasslands (Turner 2010). For example, forests recovering from disturbances have been found to be more susceptible to the negative effects of drought such as mortality (Jactel et al. 2012), which further highlights the importance in understanding disturbance dynamics and climate relationships.

Oftentimes management prescriptions are applied at grassland-forest ecotones based on disturbance histories collected in forests not adjacent to grasslands. These findings suggest that disturbances affecting grassland adjacent forests occurred at different frequencies and are more sensitive to climatic variability than forests not adjacent to grasslands. The finding emphasizes the importance of collecting ecosystem specific baseline data to correctly characterize historical disturbance regimes. The results

from this research support the restoration efforts ongoing in similar ecosystems in the U.S. (Ryan et al. 2013), and reinforce the need for expanding similar management prescriptions (prescribed burning and thinning) in the dry conifer forests of interior B.C. to reduce the risk of severe fire and WSB disturbances (Klenner et al. 2008).

## Chapter 5 Conclusion

### 5.1 Introduction

The forest and grassland ecosystems of the Cariboo Forest Region (CFR) contain economically and ecologically important forest resources. This research describes the climate and ecological factors that influenced past disturbance activity and provides important information for management activities aimed at promoting the health and resilience of these ecosystems in the face of changing climates.

### 5.2 Summary of main research results

1. I found that spatially variable fire-climate relationships and forest structure indicates a mixed-severity fire history at the forest-grassland ecotone in the Churn Creek Protected Area (CCPA). Fires that affected only forest-grassland ecotonal forests were associated with positive antecedent moisture conditions, while widespread fires affecting much of the entire study area were likely driven by persistent drought conditions. Plot-level descriptions of forest structure indicated that historically low, mixed and high severity fire activity occurred in the study area.
2. Climate-fire analyses at multiple sites across the CFR reveal that interannual climate variability, and not large-scale patterns of climate variability, drives fire activity from local to regional scales. Utilizing multiple reconstructions of PDO, ENSO and PNA, weak relationships were found between regional fire activity and large-scale patterns of climate variability between AD 1600 and 1900, and that regional fire events were strongly driven by interannual climate variability as expressed by reconstructed PDSI.

3. My findings suggest drought conditions are an important prerequisite for the initiation of WSB outbreaks, especially at sites adjacent to grasslands. Existing research documenting the relationships between outbreak initiation and climate in B.C. are limited, therefore this finding represents a significant contribution to understanding disturbance-climate relationships.
4. Fire activity at sites adjacent to grasslands was more frequent than at sites not close to grasslands, and was related to antecedent moisture conditions. This research outcome suggests that historically, fine fuel growth was a key determinant of fire activity in forest-grassland ecotones of the CFR.
5. I did not document a relationship or interaction between years of outbreaks of WSB and fire activity. Although no significant historical interaction was detected, the developing denser contemporary forest structure coupled with increased insect outbreaks may result in future novel disturbance interactions.

### 5.3 Management implications

Forest land managers of dry conifer ecosystems across much of western North America have long been frustrated by conflicting interpretations of fire history and appropriate restoration goals. The research findings presented in this dissertation provide several key recommendations to forest managers working to promote economic and ecological resilience in these forest ecosystems. First, at the tree and stand scale, the findings indicate that existing forest and grassland management activities (e.g. thinning and prescribed fire) should be expanded to include treatments to mimic patches created by high-severity fire. Increased stand-level heterogeneity improves tree vigour and stand

resilience to disturbances including both fire and WSB. Although the efficacy of forest restoration efforts in similar ecosystems is variable (Roccafert et al. 2010), in consideration of projected climate change, forest management activities should be increased to decrease fire risk in the province.

Second, this research is a novel contribution that explicitly recognizes the role of proximity to grasslands as a key determinant of fire history and WSB outbreak parameters. Additional research in this area is required, specifically management activities applied at the forest-grassland ecotone should be based on data collected in these environments, and not inferred from relationships found in middle and upper montane forest ecosystem. Continuing to do so, could result in inappropriate management prescriptions applied to this sensitive ecosystem.

Third, in consideration of the significant association that was identified between WSB outbreak initiation and warm, dry climate conditions, I suggest prioritizing future research and monitoring that identifies the early stages of outbreaks, and that management activities aimed at minimizing the effects of outbreaks, such as applying *btk*, be intensified in anomalously dry, warm years.

Lastly, the application of hierarchical forest management plans that holistically consider multiple disturbance agents and climate change, could incorporate prescriptions at the tree, stand and landscape scales to improve multi-scale heterogeneity and resilience in forest ecosystems (Hessburg et al. 2015). For example, building landscape-level heterogeneity by decreasing host connectivity and density across the CFR, may decrease the risk of epidemic outbreaks of WSB and Douglas-fir beetle and also dangerous fire activity.

## 5.4 Future research

After completing the research presented in this dissertation, I identified four areas with significant potential for future research efforts.

1. Spatially explicit fire history reconstructions are limited in B.C., especially in areas of the western and northern Cariboo-Chilcotin region not covered in this dissertation. Improving the spatial resolution of historical fire datasets will improve past characterizations of fire-climate relationships and, in turn, better inform our knowledge about future fire-climate associations and how best to restore and promote resilience in dry conifer forests.
2. In this dissertation, superposed epoch and bivariate event analyses were used to detect relationships between historical fire and climate datasets. Future research should explore other statistical techniques intended to link continuous climate-time series data, climate extreme datasets and discrete fire event years. Additionally, different climate datasets could be utilized to describe fire-climate relationships including proxy reconstructions of sea surface temperature and the site-specific, moisture-limited Douglas-fir chronologies.
3. The research presented in Chapter 4 focused on characterizing the historical relationships between fire, WSB and climate. Characterizing the twentieth century recovery of Douglas-fir cohorts after single and multiple disturbances would increase our understanding of long-term impacts on these forest ecosystems. Impacts could include growth recovery rates and the initiation of compensatory growth mechanisms following disturbances of different severities and the influence of canopy position on recovery.
4. The expansion of existing forest management programs, and the implementation of new programs in B.C., that include silvicultural treatments such as overstory and/or understory thinning, prescribed burning and mixed species planting, require long-term research programs

to evaluate how management prescriptions can alter the effects of disturbances of various intensities. These efforts would enhance management activities aimed at promoting resilience and reducing the dangerous effects of fire and the susceptibility of Douglas-fir dominated forests to WSB outbreaks.

## References

- Abatzoglou, J.T., and A.P Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* 113:11770-11775.
- Agee, J. K. 1996. *Fire Ecology of Pacific Northwest Forests*. Island Press. Washington, DC.
- Agee, J.K., and S. Hummel. 2003. Western spruce budworm defoliation effects on forest structure and potential fire behavior. *Northwest Science* 77:159-169.
- Agee, J.K., and C.N. Skinner. 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211:83-96.
- Alfaro, R.I., G.V. Sickle, A.J. Thomson, and E. Wegwitz. 1982. Tree mortality and radial growth losses caused by the western spruce budworm in a Douglas-fir stand in British Columbia. *Canadian Journal of Forest Research* 12:780-787.
- Alfaro, R., and L.E. Maclauchlan. 1992. A method to calculate the losses caused by western spruce budworm in uneven-aged Douglas fir forests of British Columbia. *Forest Ecology and Management* 55:295-313.
- Alfaro, R.I., J. Berg, and J. Axelson. 2014. Periodicity of western spruce budworm in Southern British Columbia, Canada. *Forest Ecology and Management* 315:72-79.
- Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E.H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.-H. Lim, G. Allard, S.W. Running, A. Semerci, and N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259:660-684.
- Amoroso, M.M., L.D. Daniels, M. Bataineh, and D.W. Andison. 2011. Evidence of mixed-severity fires in the foothills of the Rocky Mountains of west-central Alberta, Canada. *Forest Ecology and Management* 262:2240-2249.
- Anderson, L., C.E. Carlson, and R.H. Wakimoto. 1987. Forest fire frequency and western spruce budworm outbreaks in western Montana. *Forest Ecology and Management* 22:251-260.
- Arno, S.F., and K.M. Sneek. 1977. A method for determining fire history in coniferous forests of the mountain west. USDA Forest Service General Technical Report INT-42. Intermountain Forest and Range Experiment Station, Ogden, Utah.

- Arsenault, A., and W. Klenner. 2005. Fire regime in dry-belt forests of British Columbia: perspectives on historic disturbances and implications for management. In: *Mixed Severity Fire Regimes: Ecology and Management Symposium Proceedings*. Taylor, L., J. Zelnik, S. Cadwal-Lander, and B. Hughes (Eds.). November, 17-19, Spokane, WA. Association of Fire Ecology. Pgs. 105-121.
- Axelson, J.N., R.I. Alfaro, and B.C. Hawkes. 2009. Influence of fire and mountain pine beetle on the dynamics of lodgepole pine stands in British Columbia, Canada. *Forest Ecology and Management* 257:1874-1882.
- Axelson, J.N., R.I. Alfaro, and B.C. Hawkes. 2010. Changes in stand structure in uneven-aged lodgepole pine stands impacted by mountain pine beetle epidemics and fires in central British Columbia. *Forestry Chronicle* 86:87-99.
- Axelson, J.N., D.J. Smith, L.D. Daniels, and R.I. Alfaro. 2015. Multicentury reconstruction of western spruce budworm outbreaks in central British Columbia, Canada. *Forest Ecology and Management* 335:235-248.
- Bai, Y., K. Broersma, D. Thompson, and T.J. Ross. 2004. Landscape-level dynamics of forest-grassland transitions in British Columbia. *Rangeland Ecology and Management* 57:66-75.
- Baisan, C.H., and T.W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, U.S.A. *Canadian Journal of Forest Research* 20:1559-1569.
- Barlow, M., S. Nigam, and E.H. Berbery. 2001. ENSO, Pacific decadal variability, and US summertime precipitation, drought, and stream flow. *Journal of Climate* 14:2105-2128.
- Barnston, A.G., and R.E. Livezey. 1987. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Monthly Weather Review* 115:1083-1126.
- Bekker, M.F., and A.H. Taylor. 2001. Gradient analysis of fire regimes in montane forests of the southern Cascade Range, Thousand Lakes Wilderness, California, USA. *Plant Ecology* 155:15-28.
- Bentz, B.J., J. Régnière, C.J. Fettig, E.M. Hansen, J.L. Hayes, J.A. Hicke, R.G. Kelsey, J.F. Negrón, and S.J. Seybold. 2010. Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. *BioScience* 60:602-613.
- Bertram, D.F., A. Harfenist, and B.D. Smith. 2005. Ocean climate and El Niño impacts on survival of Cassin's Auklets from upwelling and downwelling domains of British Columbia. *Canadian Journal of Fisheries Aquatic Sciences* 62:2841-2853.

- B.C. Parks, 2000. Management Plan for Churn Creek Protected Area. B.C. Ministry of Environment, Lands and Parks.  
[http://www.env.gov.B.C..ca/B.C.parks/explore/parkpgs/churn\\_crk/#Management](http://www.env.gov.B.C..ca/B.C.parks/explore/parkpgs/churn_crk/#Management).
- Blackwell, B.A., F. Steele, R.W. Gray, K. Iverson, and K. MacKenzie. 2001. Fire management plan Churn Creek Protected Area. Cariboo District, British Columbia Parks.
- Blackstock, M.D., and R. McAllister. 2004. First Nations perspectives on the grasslands of the Interior of British Columbia. *Journal of Ecological Anthropology* 8:24-46.
- Bohlmann, J. 2012. Pine terpenoid defences in the mountain pine beetle epidemic and in other conifer pest interactions: specialized enemies are eating holes into a diverse, dynamic and durable defence system. *Tree Physiology* 32:943-945.
- Bonsal, B.R., A. Shabbar, and K. Higuchi. 2001. Impacts of low frequency variability modes on Canadian winter temperature. *International Journal of Climatology* 21:95-108.
- Box, G., and G.C. Tiao. 1975. Intervention analysis with applications to economic and environmental problems. *Journal of American Statistical Association* 70:70-79.
- Briffa, K.R., P.D. Jones, and F.H. Schweingruber. 1992. Tree-ring density reconstructions of summer temperature patterns across western North America since 1600. *Journal of Climate* 5:735-754.
- Brown, P.M., and R. Wu. 2005. Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. *Ecology* 86:3030-3038.
- Brown, P.M., C.L. Wienk, and A.J. Symstad. 2008. Fire and forest history at Mount Rushmore. *Ecological Applications* 18:1984-1999.
- Burgan, R.E. 1979. Estimating live fuel moisture for the 1978 National Fire Danger Rating System. USDA Forest Service Research Paper INT-226. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah.
- Campbell, E.M., S.C. Saunders, K.D. Coates, D.V. Meidinger, A. Mackinnon, G.A. O'Neill, D.J. Mackillop, S.C. Delong, and D.G. Morgan. 2009. Ecological resilience and complexity: A theoretical framework for understanding and managing British Columbia's forest ecosystems in a changing climate. Technical Report 055. British Columbia Ministry of Forests and Range, Victoria, British Columbia.
- Campbell, R.W. 1993. Population Dynamics of the Major North American Needle-Eating Budworms. Research Paper PNW-RP-463. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station.

- Campbell, R., D.J. Smith, and A. Arsenault. 2006. Multicentury history of western spruce budworm outbreaks in interior Douglas-fir forests near Kamloops, British Columbia. *Canadian Journal of Forest Research* 36:1758-1769.
- Caprio, A.C., and T.W. Swetnam. 1995. Historic fire regimes along an elevational gradient on the west slope of the Sierra Nevada, California. United States Department of Agriculture Forest Service General Technical Report INT. 173-179. In: *Proceedings: Symposium on Fire in Wilderness and Park Management*, Missoula, MT, March 30–April 1, 1993 Brown, J. K., R. W. Mutch, C. W. Spoon CW, and R. H. Wakimoto, (Tech. co-ords.). Ogden (UT): US Department of Agriculture, Forest Service, Intermountain Research Station. General Technical Report INT-GTR-320.
- Cates, R.G., R.A. Redak, and B. Colin. 1983. Patterns in defensive natural product chemistry: Douglas fir and western spruce budworm interactions. In: *American Chemical Society Symposium Series 208 Plant Resistance to Insects*. Hedin, P.A. (Ed.). Las Vegas, Nevada. Pgs. 3-19.
- Chavardès, R.D., and L.D. Daniels. 2016. Altered mixed-severity fire regime has homogenized montane forests of Jasper National Park. *International Journal of Wildland Fire* 25:433-444.
- Church, M., and J.M. Ryder. 2010. Physiography of British Columbia. *Compendium of Forest Hydrology and Geomorphology in British Columbia*. Pike, R.G., T.E. Redding, R.D. Moore, R.D. Winker, and K.D. Bladon (Eds.), *Land Management Handbook* 66:17-46.
- Churchill, D.J., A.J. Larson, M.C. Dahlgreen, J.F. Franklin, P.F. Hessburg, and J.A. Lutz. 2013. Restoring forest resilience: from reference spatial patterns to silvicultural prescriptions and monitoring. *Forest Ecology and Management* 291:442-457.
- Clancy, K.M. 1991. Western spruce budworm response to different moisture levels in artificial diets. *Forest Ecology and Management* 39:223-235.
- Cohn, G.M., R.A. Parsons, E.K. Heyerdahl, D.G. Gavin, and A. Flower. 2014. Simulated western spruce budworm defoliation reduces torching and crowning potential: a sensitivity analysis using a physics-based fire model. *International Journal of Wildland Fire* 23:709-720.
- Collins, B.M., P.N. Omi, and P.L. Chapman. 2006. Regional relationships between climate and wildfire-burned area in the Interior West, USA. *Canadian Journal of Forest Research* 36:699-709.
- Cook, E.R. 2009. North Pacific climate variability over the past millennium from long tree-ring records. *Eos Trans. AGU*, 90(52), Fall Meeting Supplement, Abstract PP12C-01.

- Cook, E.R., and L. Kairiukstis. 1990. (Eds.), *Methods of Dendrochronology: Applications in the Environmental Sciences*, Kluwer Academic Publishers, Dordrecht, Netherlands.
- Cook, E.R., and K. Peters. 1981. The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin* 41:45-53.
- Cook, E.R., R.D. D'Arrigo, and K.J. Anchukaitis. 2008b. 700 Year Tree Ring ENSO Index Reconstructions. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Ser. 2009–105, NOAA/NGDC Paleoclimatology Program, Boulder, Colorado.
- Cook, B.I., J.E. Smerdon, R. Seager, and E.R. Cook. 2014. Pan-continental droughts in North America over the last millennium. *Journal of Climate* 27:383-397.
- Cook, E.R., C.A. Woodhouse, C.M. Eakin, D.M. Meko, and D.W. Stahle. 2004. Long-Term Aridity Changes in the Western United States. *Science* 306:1015-1018.
- Cook, E.R., C.A. Woodhouse, C.M. Eakin, D.M. Meko, and D.W. Stahle. 2008a. North American Summer PDSI Reconstructions, Version 2a. [http://www.ncdc.noaa.gov/paleo/pdsi08\\_ts.html](http://www.ncdc.noaa.gov/paleo/pdsi08_ts.html).
- Covington, W.W., and M.M. Moore. 1994. Postsettlement changes in natural fire regimes and forest structure: ecological restoration of old-growth ponderosa pine forests. *Journal of Sustainable Forestry* 2:153-181.
- Cybulski, J.S., A.D. McMillan, R.S. Malhi, B.M. Kemp, H. Harry, and S. Cousins. 2007. The Big Bar Lake burial: Middle Period human remains from the Canadian Plateau. *Canadian Journal of Archaeology* 31:55-78.
- Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, and D. Simberloff. 2001. Climate change and forest disturbances: climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. *BioScience* 51:723-734.
- Daniels, L.D., and E. Watson. 2003. Climate–fire–vegetation interactions in Cariboo forests: a dendrochronological analysis. Report to Forest Innovation and Investment, Forest Research Program, Vancouver, British Columbia.
- Daniels, L.D., Z. Gedalof, M.F. Pisaric, C.J. Mustaphi, E. Da Silva, H. Marcoux, V. Mather, J. Nesbitt, E. Paul-Limoges, J. Perrault, and C. Steele. 2011. Historic climate-fire-vegetation interactions of the west versus east Kootenays: Implications

of climate change and fire suppression. Unpublished report: <http://trencher.com/public/library/files/kootenay-fire-report.pdf>.

- D'Arrigo, R., R. Villalba, and G. Wiles. 2001. Tree-ring estimates of Pacific decadal climate variability. *Climate Dynamics* 18:219-224.
- D'Arrigo, R., and R. Wilson. 2006. On the Asian expression of the PDO. *International Journal of Climatology* 26:1607-1617.
- D'Arrigo, R., E.R. Cook, R.J. Wilson, R. Allan, and M.E. Mann. 2005. On the variability of ENSO over the past six centuries. *Geophysical Research Letters* 32: L03711.
- Dawson, R.J., A.T. Werner, T.Q. Murdock, and T. Vold. 2008. Preliminary analysis of climate change in the Cariboo-Chilcotin area of British Columbia. Pacific Climate Impacts Consortium, University of Victoria, Victoria, British Columbia, Canada.
- Dieterich, J., and T.W. Swetnam. 1984. Dendrochronology of a fire-scarred ponderosa pine. *Forest Ecology and Management* 30:238-247.
- Duncan, R.P. 1989. An evaluation of errors in tree age estimates based on increment cores in kahikatea (*Dacrycarpus dacrydioides*). *New Zealand Natural Sciences* 16:31-37.
- Environment and Climate Change Canada, 2016. 1981-2010 Climate Normals. [http://climate.weather.gc.ca/climate\\_normals/index\\_e.html](http://climate.weather.gc.ca/climate_normals/index_e.html).
- Everett, R.L., R. Schellhaas, D. Keenum, D. Spurbeck, and P. Ohlson. 2000. Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. *Forest Ecology and Management* 129:207-225.
- Falk, D.A., E.K. Heyerdahl, P.M. Brown, C. Farris, P.Z. Fulé, D. McKenzie, T.W. Swetnam, A.H. Taylor, and M.L. Van Horne. 2011. Multi-scale controls of historical forest-fire regimes: new insights from fire-scar networks. *Frontiers in Ecology and the Environment* 9:446-454.
- Fauria, M., and E.A. Johnson. 2009. Large-scale climatic patterns and area affected by mountain pine beetle in British Columbia, Canada. *Journal of Geophysical Research* 114:G01012.
- Fellin D., and J. Dewey. 1982. Western spruce budworm. USDA Forest Service Report - Forest Insect and Disease Leaflet 53, Missoula, Montana.
- Fleming, S.W., and P.H. Whitfield. 2010. Spatiotemporal mapping of ENSO and PDO surface meteorological signals in British Columbia, Yukon, and southeast Alaska. *Atmosphere and Ocean* 48:122-131.

- Flower, A. 2016. Three Centuries of synchronous forest defoliator outbreaks in western North America. *PlosOne* 11:p.e0164737
- Flower, A., D.G. Gavin, E.K. Heyerdahl, R.A. Parsons, and G.M. Cohn. 2014a. Western spruce budworm outbreaks did not increase fire risk over the last three centuries: A dendrochronological analysis of inter-disturbance synergism. *PlosOne* 9:p.e114282.
- Flower, A., D.G. Gavin, E.K. Heyerdahl, R.A. Parsons, and G.M. Cohn. 2014b. Drought-triggered western spruce budworm outbreaks in the interior Pacific Northwest: a multi-century dendrochronological record. *Forest Ecology and Management* 324:16-27.
- Fritts, H.C., and T.W. Swetnam. 1989. Dendroecology: a tool for evaluating variations in past and present forest environments. *Advances in Ecological Research* 19:111-188.
- Furniss, R.L., and V.M. Carolin. 1977. Western forest insects. Miscellaneous Publication No. 1339. US Department of Agriculture, Forest Service.
- Gartner, M.H., T.T. Veblen, R.L. Sherriff, and T.L. Schoennagel. 2012. Proximity to grasslands influences fire frequency and sensitivity to climate variability in ponderosa pine forests of the Colorado Front Range. *International Journal of Wildland Fire* 21:562–571.
- Gavin, D.G. 2010. K1D: Multivariate Ripley's K-function for one-dimensional data. [http://geog.uoregon.edu/envchange/software/K1D\\_1.pdf](http://geog.uoregon.edu/envchange/software/K1D_1.pdf).
- Gavin, D.G., F.S. Hu, K.P. Lertzman, and P. Corbett. 2006. Weak climatic control of stand-scale fire history during the late Holocene. *Ecology* 87:1722–1732.
- Gayton, D. 2013. Documenting fire history in a British Columbia ecological reserve. *Journal of Ecosystems Management* 14:1-10.
- Gedalof, Z., and D.J. Smith. 2001. Interdecadal climate variability and regime-scale shifts in Pacific North America. *Geophysical Research Letters* 28:1515-1518.
- Gedalof, Z., D.L. Peterson, and N.J. Mantua. 2005. Atmospheric, climatic, and ecological controls on extreme wildfire years in the northwestern United States. *Ecological Applications* 15:154-174.
- Gershunov A., T.P. Barnett, and D.R. Cayan. 1999. North Pacific interdecadal oscillation seen as factor in ENSO-related North American climate anomalies. *Eos Trans. AGU* 80: 25–30.
- Google Earth. 2016. Churn Creek Protected Area. Centre of image: 51°25'43.63"N, 122°18'15.44"W. Image date: 12/31/2004. Accessed 08/2016.

- Grassland Strategy Working Group. 2001. Cariboo-Chilcotin grasslands strategy: Forest Encroachment onto grasslands and establishment of a grassland benchmark area. Williams Lake, B.C.
- Grissino-Mayer, H.D. 2001. Evaluating crossdating accuracy: A manual and tutorial for the computer program COFECHA. *Tree-Ring Research* 57:205–221.
- Grissino-Mayer, H.D., and T.W. Swetnam. 2000. Century scale climate forcing of fire regimes in the American Southwest. *The Holocene* 10:213-220.
- Hadley, K.S., and T.T. Veblen. 1993. Stand response to western spruce budworm and Douglas-fir bark beetle outbreaks, Colorado Front Range. *Canadian Journal of Forest Research* 23:479-491.
- Halpern, C.B., J.A. Antos, D. McKenzie, and A.M. Olson. 2016. Past tree influence and prescribed fire mediate biotic interactions and community reassembly in a grassland-restoration experiment. *Journal of Applied Ecology* 53:264-273.
- Halpern, C.B., R.D. Haugo, J.A. Antos, S.S. Kaas, and A.L. Kilanowski. 2012. Grassland restoration with and without fire: evidence from a tree-removal experiment. *Ecological Applications* 22:425-441.
- Hansen, A.J., and F. DiCasteri. 2012. *Landscape Boundaries: Consequences for Biotic Diversity and Ecological Flows*. Springer-Verlag, New York.
- Hart, S.J., D.J. Smith, and J.J. Clague. 2010. A multi-species dendroclimatic reconstruction of Chilko River streamflow, British Columbia, Canada. *Hydrological Processes* 24:2752-2761.
- Hart, S.J., T.T. Veblen, K.S. Eisenhart, D. Jarvis, and D. Kulakowski. 2014. Drought induces spruce beetle (*Dendroctonus rufipennis*) outbreaks across northwestern Colorado. *Ecology* 95:930-939.
- Harvey, J.E., D.J. Smith, and T.T. Veblen. 2017. Mixed-severity fire history at a forest-grassland ecotone in west central British Columbia, Canada. *Ecological Applications*. DOI: 10.1002/eap.1563.
- Haughian, S.R., P.J. Burton, S.W. Taylor, and C. Curry. 2012. Expected effects of climate change on forest disturbance regimes in British Columbia, Canada. *Journal of Ecosystems and Management* 13:1-24.
- Hemstrom, M.A., and J.F. Franklin. 1982. Fire and other disturbances of the forests in Mount Rainier National Park. *Quaternary Research* 18:32-51.

- Hessburg, P.F., J.K. Agee, and J.F. Franklin. 2005. Dry forests and wildland fires of the inland northwest USA: contrasting the landscape ecology of the pre-settlement and modern eras. *Forest Ecology and Management* 211:117-139.
- Hessburg, P.F., R.B. Salter, and K.M. James. 2007. Re-examining fire severity relations in pre-management era mixed conifer forests: inferences from landscape patterns of forest structure. *Landscape Ecology* 22:5-24.
- Hessburg, P.F., D.J. Churchill, A.J. Larson, R.D. Haugo, C. Miller, T.A. Spies, M.P. North, N.A. Povak, R.T. Belote, P.H. Singleton, and W.L. Gaines. 2015. Restoring fire-prone Inland Pacific landscapes: seven core principles. *Landscape Ecology* 30:1805-1835.
- Hessburg, P.F., T.A. Spies, D.A. Perry, C.N. Skinner, A.H. Taylor, P.M. Brown, S.L. Stephens, A.J. Larson, D.J. Churchill, N.A. Povak, and P.H. Singleton. 2016. Tamm Review: Management of mixed-severity fire regime forests in Oregon, Washington, and northern California. *Forest Ecology and Management* 366:221-250.
- Hessl, A.E., D. McKenzie, and R. Schellhaas. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. *Ecological Applications* 14:425-442.
- Heyerdahl, E.K., L.B. Brubaker, and J.K. Agee. 2002. Annual and decadal climate forcing of historical fire regimes in the interior Pacific Northwest, USA. *The Holocene* 12:597-604.
- Heyerdahl, E.K., K.P. Lertzman, and S. Karpuk. 2007. Local-scale controls of a low-severity fire regime (1750–1950), southern British Columbia, Canada. *Ecoscience* 14:40-47.
- Heyerdahl, E.K., K.P. Lertzman, and C.M. Wong. 2012. Mixed-severity fire regimes in dry forests of southern interior British Columbia, Canada. *Canadian Journal of Forest Research* 42:88-98.
- Heyerdahl, E.K., R.F. Miller, and R.A. Parsons. 2006. History of fire and Douglas-fir establishment in a savanna and sagebrush–grassland mosaic, southwestern Montana, USA. *Forest Ecology and Management* 230:107-118.
- Heyerdahl, E.K., D. McKenzie, L.D. Daniels, A.E. Hessl, J.S. Littell, and N.J. Mantua. 2008. Climate drivers of regionally synchronous fires in the inland Northwest (1651–1900). *International Journal of Wildland Fire* 17:40-49.
- Holmes, R.L., and T.W. Swetnam. 1996. Dendroecology program library: program OUTBREAK user's manual. Laboratory of Tree-Ring Research, University of Arizona, Tucson.

- Hsieh, W.W., and B. Tang. 2001. Interannual variability of accumulated snow in the Columbia Basin, British Columbia. *Water Resource Research* 37:1753–1759.
- IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
- Iverson, K.E., R.W. Gray, B.A. Blackwell, C. Wong, and K.L. MacKenzie. 2002. Past fire regimes in the Interior Douglas-fir, dry cool subzone, Fraser variant (IDFdk3). Report to the Innovative Forest Practices Agreement, Lignum Ltd., Williams Lake, B.C.
- Jactel, H., J. Petit, M.L. Desprez-Loustau, S. Delzon, D. Piou, A. Battisti, and J. Koricheva. 2012. Drought effects on damage by forest insects and pathogens: a meta-analysis. *Global Change Biology* 18:267-276.
- Keane, R.E., P.F. Hessburg, P.B. Landres, and F.J. Swanson. 2009. The use of historical range and variability (HRV) in landscape management. *Forest Ecology and Management* 258:1025-1037.
- Keeley, J.E. 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire* 18:116-126.
- Kilduff, D.P., E. Di Lorenzo, L.W. Botsford, and S.L. Teo. 2015. Changing central Pacific El Niños reduce stability of North American salmon survival rates. *Proceedings of the National Academy of Sciences* 112:10962-10966.
- Kipfmüller, K.F., E.R. Larson, and S. St. George. 2012. Does proxy uncertainty affect the relations inferred between the Pacific Decadal Oscillation and wildfire activity in the western United States? *Geophysical Research Letters* 39:L04703.
- Kitzberger, T., P.M. Brown, E.K. Heyerdahl, T.W. Swetnam, and T.T. Veblen. 2007. Contingent Pacific–Atlantic Ocean influence on multicentury wildfire synchrony over western North America. *Proceedings of the National Academy of Sciences*, 104:543-548.
- Klenner, W., R. Walton, A. Arsenault, and L. Kremsater. 2008. Dry forests in the southern interior of British Columbia: Historic disturbances and implications for restoration and management. *Forest Ecology and Management* 256:1711-1722.
- Krawchuk, M.A., and M. Moritz. 2011. Constraints on global fire activity vary across a resource gradient. *Ecology* 92:121-132.

- Kurz, W.A., C.C. Dymond, G. Stinson, G.J. Rampley, E.T. Neilson, A.L. Carroll, T. Ebata, and L. Safranyik. 2008. Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452:987-990.
- Landres, P.B., P. Morgan, and F.J. Swanson. 1999. Overview of the use of natural variability concepts in managing ecological systems. *Ecological Applications* 9:1179-1188.
- Leathers, D.J., and M.A. Palecki. 1992. The Pacific/North American teleconnection pattern and United States climate. Part II: temporal characteristics and index specification. *Journal of Climate* 5:707-716.
- Leathers, D.J., B. Yarnal, and M.A. Palecki. 1991. The Pacific/North American teleconnection pattern and United States climate. Part I: Regional temperature and precipitation associations. *Journal of Climate* 4:517-528.
- Lessard, V.C., T.D. Drummer, and D.D. Reed. 2002. Precision of density estimates from fixed-radius plots compared to N-tree distance sampling. *Canadian Journal of Forest Research* 48:1-5.
- Lepofsky, D., E.K. Heyerdahl, K.P. Lertzman, D. Schaepe, and B. Mierendorf. 2003. Historical meadow dynamics in southwest British Columbia: a multidisciplinary analysis. *Conservation Ecology* 7:5.
- Li, J., S.P. Xie, E.R. Cook, G. Huang, R. D'Arrigo, F. Liu, J. Ma, and X.T. Zheng. 2011. Interdecadal modulation of El Niño amplitude during the past millennium. *Nature Climate Change* 1:114-118.
- Littell, J.S., D.L. Peterson, K.L. Riley, Y. Liu, and C.H. Luce. 2016. A review of the relationships between drought and forest fire in the United States. *Global Change Biology* 22:2353-2369.
- Logan, J.A., J. Regniere, and J.A. Powell. 2003. Assessing the impacts of global warming on forest pest dynamics. *Frontiers in Ecology and the Environment* 1:130-137.
- Lynch, H.J., and P.R. Moorcroft. 2008. A spatiotemporal Ripley's K-function to analyze interactions between spruce budworm and fire in British Columbia, Canada. *Canadian Journal of Forest Research* 38:3112-3119.
- MacDonald, G.M., and R.A. Case. 2005. Variations in the Pacific Decadal Oscillation over the past millennium. *Geophysical Research Letters* 32:L08793.
- Maclauchlan, L.E., and J.E. Brooks. 2009. Influence of past forestry practices on western spruce budworm defoliation and associated impacts in southern British Columbia. *Journal of Ecosystems and Management* 10:37-49.

- Maclauchlan, L.E., and K. Buxton. 2015. 2015 Overview of Forest Health Conditions in southern British Columbia. British Columbia Ministry of Forests Lands and Natural Resource Operations. Kamloops, British Columbia.
- Maclauchlan, L.E., J.E. Brooks, and J.C. Hodge. 2006. Analysis of historic western spruce budworm defoliation in south central British Columbia. *Forest Ecology and Management* 226:351-356.
- Mantua, N.J. 2002. La Niña impacts on the Pacific Northwest. *La Niña and its Impacts: Facts and Speculation*. United Nations University Press. Glantz, M. H. (Ed.). Tokyo, Japan. Pgs. 102–114.
- Mantua, N.J., and S.R. Hare. 2002. The Pacific Decadal Oscillation. *Journal of Oceanography* 58:35-44.
- Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of American Meteorological Society* 78:1069-1079.
- Marcoux, H.M., L.D. Daniels, S.E. Gergel, E. Da Silva, Z. Gedalof, and P.F. Hessburg. 2015. Differentiating mixed-and high-severity fire regimes in mixed-conifer forests of the Canadian Cordillera. *Forest Ecology and Management* 341:45-58.
- Mattson, W.J., and R.A. Haack. 1987. The role of drought stress in provoking outbreaks of phytophagous insects. In: *Insect Outbreaks*, Barbosa, P., and J.C. Schultz (Eds.). Academic Press, San Diego, California. Pgs. 365-407.
- McAfee, S.A. 2014. Consistency and the lack thereof in Pacific decadal oscillation impacts on North American winter climate. *Journal of Climate* 27:7410-7431.
- McBride, J.R. 1983. Analysis of tree rings and fire scars to establish fire history. *Tree-Ring Bulletin* 43:51-67.
- McCabe, G.J., and M.D. Dettinger. 1999. Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States. *International Journal of Climatology* 19:1399-1410.
- McCabe, G.J., M.A. Palecki, and J.L. Betancourt. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *Proceedings of the National Academy of Sciences* 101:4136-4141.
- McCullough, D.G., R.A. Werner, and D. Neumann. 1998. Fire and insects in northern and boreal forest ecosystems of North America. *Annual Review of Entomology* 43:107-127.

- McKenzie, D., Z. Gedalof, D.L. Peterson, and P. Mote. 2004. Climatic change, wildfire, and conservation. *Conservation Biology* 18:890-902.
- Meyn, A., S.W. Taylor, M.D. Flannigan, K. Thonicke, and W. Cramer. 2010. Relationship between fire, climate oscillations, and drought in British Columbia, Canada, 1920–2000. *Global Change Biology* 16:977-989.
- Miller, C., and D. Urban. 2000. Connectivity of forest fuels and surface fire regimes. *Landscape Ecology* 15:145-154.
- Moore, R.D., D.L. Spittlehouse, P.H. Whitfield, and K. Stahl. 2010. Weather and Climate. *Compendium of Forest Hydrology and Geomorphology in British Columbia*. Pike, R.G., T.E. Redding, R.D. Moore, R.D. Winker, and K.D. Bladon (Eds.), Ministry of Forests, Range and Natural Resource Operations, Victoria, B.C. Pgs. 47-84.
- Morgan, P., E.K. Heyerdahl, and C. E. Gibson. 2008. Multi-season climate synchronized forest fires throughout the 20th century, Northern Rockies, USA. *Ecology* 89:717-728.
- Nicholson, A., E. Hamilton, W. Harper, and B. Wikeem. 1991. Chapter 8: Bunchgrass Zone. *Ecosystems of British Columbia*. Meidinger, D., and J. Pojar (Eds.). British Columbia Ministry of Forests. Pgs. 125-137.
- Odion, D.C., C.T. Hanson, A. Arsenault, W.L. Baker, D.A. DellaSala, R.L. Hutto, W. Klenner, M. Moritz, R. L. Sherriff, T.T. Veblen, and M.A. Williams. 2014. Examining historical and current mixed-severity fire regimes in ponderosa pine and mixed-conifer forests of western North America. *PlosOne* 9:p.e87852.
- Oliver, C.D. and B.C. Larson. 1990. *Forest Stand Dynamics*. McGraw-Hill, New York.
- Oliver, C. D., and B.C. Larson. 1996. *Forest Stand Dynamics: Updated Edition*. John Wiley and Sons.
- Pallardy, S.G., and T.T. Koslowski. 2008. Photosynthesis. *Physiology of Woody Plants*. Kramer, P.J., and T.T. Koslowski (Eds). Academic Press, New York. Pgs. 87-133.
- Parminter, J.V. 1978. An historical review of forest fire management in British Columbia. Masters thesis. University of British Columbia, Vancouver, British Columbia.
- Peltonen, M., A.M. Liebhold, O.N. Bjørnstad, and D.W. Williams. 2002. Spatial synchrony in forest insect outbreaks: roles of regional stochasticity and dispersal. *Ecology* 83:3120-3129.

- Perry, D.A., P.F. Hessburg, C. Skinner, T. Spies, S.L. Stephens, A.H. Taylor, J.F. Franklin, B. McComb, and G. Riegel. 2011. The ecology of mixed severity fire regimes in Washington, Oregon, and Northern California. *Forest Ecology and Management* 262:703-717.
- Peterson, D.L., and M.J. Arbaugh. 1986. Postfire survival in Douglas-fir and lodgepole pine: comparing the effects of crown and bole damage. *Canadian Journal of Forest Research* 16:1175-1179.
- Peterson, D.W., and P.B. Reich. 2008. Fire frequency and tree canopy structure influence plant species diversity in a forest-grassland ecotone. *Plant Ecology* 194:5-16.
- Plummer, F.G. 1900. Mount Rainier Forest Reserve, Washington. US Geological Survey 21<sup>st</sup> Annual Report to the Secretary of the Interior, 1899-1900. Part V: Forest Reserves. Pgs. 81-143.
- Raffa, K.F., B. Aukema, B.J. Bentz, A.L. Carroll, J. Hicke, M.G. Turner, and W.H. Romme. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *Bioscience* 58:501-517.
- Reich, P.B., D.W. Peterson, D.A. Wedin, and K. Wrage. 2001. Fire and vegetation effects on productivity and nitrogen cycling across a forest-grassland continuum. *Ecology* 82:1703-1719.
- Reid, J. 2008. The Grasslands debates: Conservationists, ranchers, First Nations, and the landscape of the middle Fraser. *B.C. Studies* 160:93-118.
- Reid, J. 2010. Grassland debates: conservation and social change in the Cariboo-Chilcotin, British Columbia. PhD dissertation. University of British Columbia, Vancouver, British Columbia.
- Rhoades, D.F. 1983. Herbivore population dynamics and plant chemistry. In: *Variable plants and herbivores in natural systems*. Denno, R., and M. McClure (Eds.). Academic Press. New York, New York.
- Risser, P.G. 1995. The status of the science examining ecotones. *BioScience* 45:318-325.
- Roccaforte, J.P., P.Z. Fule, and W.W. Covington. 2010. Monitoring landscape-scale ponderosa pine restoration treatment implementation and effectiveness. *Restoration Ecology* 18:820-833.
- Rodionov, S.N. 2004. A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters* 31:L09204.

- Rother, M.T., and H.D. Grissino-Mayer. 2014. Climatic influences on fire regimes in ponderosa pine forests of the Zuni Mountains, NM, USA. *Forest Ecology and Management* 32:69–77.
- Ryan, K.C., E.E. Knapp, and J.M. Varner. 2013. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. *Frontiers in Ecology and the Environment* 11:e15-e24.
- Ryerson, D.E., T.W. Swetnam, and A.M. Lynch. 2003. A tree-ring reconstruction of western spruce budworm outbreaks in the San Juan Mountains, Colorado, USA. *Canadian Journal of Forest Research* 33:1010-1028.
- Schoennagel, T., T.T. Veblen, and W.H. Romme. 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. *BioScience* 54:661-676.
- Schoennagel, T., T.T. Veblen, D. Kulakowski, and A. Holz. 2007. Multidecadal climate variability and climate interactions affect subalpine fire occurrence, western Colorado (USA). *Ecology* 88:2891-2902.
- Schoennagel, T., T.T. Veblen, W.H. Romme, J. Sibold, and E.R. Cook. 2005. ENSO and PDO variability affect drought-induced fire occurrence in Rocky Mountain subalpine forests. *Ecological Applications* 15:2000-2014.
- Senf, C., E.M. Campbell, P. Pflugmacher, M.A. Wulder, and P. Hostert. 2016. A multi-scale analysis of western spruce budworm outbreak dynamics. *Landscape Ecology* 32:501-514.
- Shabbar, A., and W. Skinner. 2004. Summer drought patterns in Canada and the relationship to global sea surface temperatures. *Journal of Climate* 17:2866-2880.
- Sheridan, S.C. 2003. North American weather-type frequency and teleconnection indices. *International Journal of Climatology* 23:27-45.
- Sherriff, R.L., and T.T. Veblen. 2007. A spatially-explicit reconstruction of historical fire occurrence in the ponderosa pine zone of the Colorado Front Range. *Ecosystems* 10:311-323.
- Sherriff, R.L., and T.T. Veblen. 2008. Variability in fire–climate relationships in ponderosa pine forests in the Colorado Front Range. *International Journal of Wildland Fire* 17:50-59.
- Sherriff, R.L., E.E. Berg, and A.E. Miller. 2011. Climate variability and spruce beetle (*Dendroctonus rufipennis*) outbreaks in south-central and southwest Alaska. *Ecology* 92:1459-1470.

- Sherriff, R.L., R.V. Platt, T.T. Veblen, T.L. Schoennagel, and M.H. Gartner. 2014. Historical, observed, and modeled wildfire severity in montane forests of the Colorado Front Range. *PlosOne* 9:p.e106971.
- Sigafoos, R.H., and E.L. Hendricks. 1969. The time interval between stabilization of alpine glacial deposits and establishment of tree seedlings. US Geological Survey Professional Paper 650B: B89–B93.
- Soulé, P.T., and P.A. Knapp. 2000. *Juniperus occidentalis* (western juniper) establishment history on two minimally disturbed research natural areas in central Oregon. *Western North American Naturalist* 60:26-33.
- Spittlehouse, D.L., and R.B. Stewart. 2004. Adaptation to climate change in forest management. *Journal of Ecosystems and Management* 4:1-11.
- Stahl, K., R.D. Moore, and I.G. McKendry. 2006. Climatology of winter cold spells in relation to mountain pine beetle mortality in British Columbia, Canada. *Climate Research* 32:13-23.
- Starheim, C.C., D.J. Smith, and T.D. Prowse. 2012a. Multi-century reconstructions of Pacific salmon abundance from climate-sensitive tree rings in west central British Columbia, Canada. *Ecohydrology* 6:228-240.
- Starheim, C.C., D.J. Smith, and T.D. Prowse. 2012b. Dendrohydroclimate reconstructions of July–August runoff for two nival-regime rivers in west central British Columbia. *Hydrological Processes* 27:405-420.
- Staver, A.C., S. Archibald, and S.A. Levin. 2011. The global extent and determinants of savanna and forest as alternative biome states. *Science* 3346053:230-232.
- Steen, O.A., and R. Coupé. 1997. A field guide to forest site identification and interpretation for the Cariboo Forest Region. B.C. Ministry Forests, Land Management Handbook No. 39, Victoria, B.C., Canada.
- St. George, S. 2014. An overview of tree-ring width records across the Northern Hemisphere. *Quaternary Science Reviews* 95:132-150.
- Strang, R.M., and J.V. Parminter. 1980. Conifer encroachment on the Chilcotin grasslands of British Columbia. *Forestry Chronicle* 56:13-18.
- Sturtevant, B.R. and B.R. Miranda, D. Shinneman, E.J. Gustafson, and P.T. Wolter. 2012. Comparing modern and presettlement forest dynamics of a subboreal wilderness: Does spruce budworm enhance fire risk? *Ecological Applications* 22:1278-1296.

- Swetnam, T.W., and C.H. Baisan. 1996. Historical fire regime patterns in the southwestern United States since AD 1700. *Fire Effects in Southwestern Forest: Proceedings of the 2nd La Mesa Fire Symposium*. Edited by: C. D. Allen. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RM-GTR-286. 11-32.
- Swetnam, T.W., and C.H. Baisan. 2003. Tree-ring reconstructions of fire and climate history in the Sierra Nevada and southwestern United States. In: *Fire and Climatic Change in Temperate Ecosystems of the Western Americas*. Veblen, T.T., W.L. Baker, G. Monenegro and T.W. Swetnam (Eds.). Springer New York. Pgs. 158-195.
- Swetnam, T.W., and J.L. Betancourt. 1990. Fire-southern oscillation relations in the southwestern United States. *Science* 249:1017-1020.
- Swetnam, T.W., and J.L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate* 11:3128-3147.
- Swetnam, T.W., and A.M. Lynch. 1989. A tree-ring reconstruction of western spruce budworm history in the southern Rocky Mountains. *Forest Science* 35:962-986.
- Swetnam, T.W., and A.M. Lynch. 1993. Multicentury, regional-scale patterns of western spruce budworm outbreaks. *Ecological Monographs* 63:399-424.
- Swetnam, T.W., C.D. Allen, J.L. Betancourt. 1999. Applied historical ecology: using the past to manage for the future. *Ecological Applications* 9:1189-1206.
- Taylor, S.W. 1998. Prescribed fire in Canada – A time of transition. *Wildfire* 7:34-37.
- Thistle, J. 2015. *Resettling the range: animals, ecologies, and human communities*. British Columbia. D. Kerr. (Ed.) U.B.C. Press, Vancouver, British Columbia, Canada. 244 pgs.
- Thomson, A.J., R.F. Shepherd, J.W. Harris, and R.H. Silversides. 1984. Relating weather to outbreaks of western spruce budworm, *Choristoneura occidentalis* (Lepidoptera: Tortricidae), in British Columbia. *The Canadian Entomologist* 116:375-381.
- Tisdale, E.W. 1947. The grasslands of the southern interior of British Columbia. *Ecology* 28:346-82.
- Tisdale, E.W., and A. McLean. 1957. The Douglas-fir zone of southern interior British Columbia. *Ecological Monographs* 27:247-266.
- Trouet, V., and A.H. Taylor. 2010. Multi-century variability in the Pacific North American circulation pattern reconstructed from tree rings. *Climate Dynamics* 35:953-963.

- Trouet, V., A.H. Taylor, A.M. Carleton, and C.N. Skinner. 2006. Fire-climate interactions in forests of the American Pacific coast. *Geophysical Research Letters* 33:L18704.
- Trouet, V., A.H. Taylor, A.M. Carleton, and C.N. Skinner. 2009. Interannual variations in fire weather, fire extent, and synoptic-scale circulation patterns in northern California and Oregon. *Theoretical Applied Climatology* 95:349-360.
- Trouet, V., A.H. Taylor, E.R. Wahl, C.N. Skinner, S.L. Stephens. 2010. Fire-climate interactions in the American West since 1400 CE. *Geophysical Research Letters* 37:L04702.
- Turner, M.G. 2010. Disturbance and landscape dynamics in a changing world. *Ecology* 91:2833–2849.
- Turner, N.J. 1999. Time to burn: traditional use of fire to enhance resource production by aboriginal peoples in British Columbia. In: *Indians, Fire and the Land in the Pacific Northwest*. Boyd, R. (Ed.). Oregon State University Press, Corvallis, Oregon Pgs.185-218.
- Turner, J.S., and P.G. Krannitz. 2000. Tree encroachment in the south Okanagan and lower Similkameen valleys of British Columbia. *Proceedings: From Science to Management and Back: a Science Forum for Southern Interior Ecosystems of British Columbia*. Hollstedt, C., K. Sutherland, K., and T. Innes (Eds.). Southern Interior Forest Extension and Research Partnership, Kamloops, British Columbia. Pgs. 81-83.
- Turner, J.S., and P.G. Krannitz. 2001. Conifer density increases in semi-desert habitats of British Columbia in the absence of fire. *Northwest Science* 75:176-182.
- Veblen, T.T., T. Kitzberger, and J. Donnegan. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. *Ecological Applications* 10:1178-1195.
- Wang, Y., M. Flannigan, and K. Anderson. 2010. Correlations between forest fires in British Columbia, Canada, and sea surface temperature of the Pacific Ocean. *Ecological Modeling* 221:122-129.
- Watson, E., and B. H. Luckman. 2004. Tree-ring based reconstructions of precipitation for the southern Canadian Cordillera. *Climatic Change* 65:209–241.
- Westerling, A.L., H.G. Hidalgo, D R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. *Science* 313:940-943.
- Westerling, A.L., A. Gershunov, T.J. Brown, D.R. Cayan, and M.D. Dettinger. 2003. Climate and wildfire in the western United States. *Bulletin of American Meterological Society* 84:595-604.

- White, T.C. 1984. The abundance of invertebrate herbivores in relation to the availability of nitrogen in stressed food plants. *Oecologia* 63:90-105.
- White, P.S., and S.T. Pickett. 1985. Natural disturbance and patch dynamics. In: *The Ecology of Natural Disturbance and Patch Dynamics*. Pickett, S.T., and P.S. White, P.S. (Eds). Academic Press, New York. Pgs. 3-13.
- Whitfield, P.H., R.D. Moore, S.W. Fleming, and A. Zawadzki. 2010. Pacific Decadal Oscillation and the hydroclimatology of western Canada—Review and prospects. *Canadian Water Resource Journal* 35:1-28.
- Williams, A.P., C.D. Allen, A. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T. W. Swetnam, S.A. Rauscher, R. Seager, H.D. Grissino-Mayer, J.S. Dean, E.R. Cook, C. Gangodagamage, M. Cai, and N.G. McDowell. 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change* 3:292-297.
- Williams, D.W., and A.M. Liebhold. 1995. Forest defoliators and climatic change: potential changes in spatial distribution of outbreaks of western spruce budworm (*Lepidoptera: Tortricidae*) and gypsy moth (*Lepidoptera: Lymantriidae*). *Environmental Entomology* 24:1-9.
- Wilson, I. R. 1998. Archaeological Overview assessment northern Secwepemc Traditional Territory. Report Prepared for First Nations of Canim Lake, Canoe Creek, Soda Creek, Williams Lake.
- Wise, E.K. 2015. Tropical Pacific and Northern Hemisphere influences on the coherence of Pacific Decadal Oscillation reconstructions. *International Journal of Climatology* 35:154-160.
- Wong, C.M., and K.P. Lertzman. 2001. Errors in estimating tree age: implications for studies of stand dynamics. *Canadian Journal of Forest Research* 31:1262-1271.
- Yarnal, B., and D.J. Leathers. 1988. Relationships between interdecadal and interannual climatic variations and their effect on Pennsylvania climate. *Annals of the Association of American Geographers* 78:624-641.
- Yu, B., and F.W. Zwiers. 2007. The impact of combined ENSO and PDO on the PNA climate: a 1,000-year climate modeling study. *Climate Dynamics* 29:837-851.
- Zanchettin, D., O. Bothe, F. Lehner, P. Ortega, C.C. Raible, and D. Swingedouw. 2015. Reconciling reconstructed and simulated features of the winter Pacific/North American pattern in the early 19th century. *Climate of the Past* 11:939-958.

## Appendices

Appendix 1. The location of trees (circular marker) recording the 14 widespread fire events in the Churn Creek Protected Area described in Chapter 2. Each fire year map uses the base map presented in Figure 1 and the fire year is presented in the white inset box. Widespread fire years were identified when fire was recorded by at least 25% of recording samples over the entire research area.

