12-2005

Spatiotemporal Variations in the Fire Regimes of Whitebark Pine (*Pinus albicaulis* Engelm.) Forests, Western Montana, USA, and Their Management Implications

Evan Reed Larson
University of Tennessee, Knoxville

Recommended Citation

Larson, Evan Reed, "Spatiotemporal Variations in the Fire Regimes of Whitebark Pine (*Pinus albicaulis* Engelm.) Forests, Western Montana, USA, and Their Management Implications. " Master's Thesis, University of Tennessee, 2005.
https://trace.tennessee.edu/utk_gradthes/4543

To the Graduate Council:

I am submitting herewith a thesis written by Evan Reed Larson entitled "Spatiotemporal Variations in the Fire Regimes of Whitebark Pine (*Pinus albicaulis* Engelm.) Forests, Western Montana, USA, and Their Management Implications." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Henri D. Grissino-Mayer, Major Professor

We have read this thesis and recommend its acceptance:

David L. Feldman, Sally P. Horn, Kenneth H. Orvis

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Evan Reed Larson entitled "Spatiotemporal Variations in the Fire Regimes of Whitebark Pine (*Pinus albicaulis* Engelm.) Forests, Western Montana, USA, and Their Management Implications" I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Henri D. Grissino-Mayer, Major Professor

We have read this thesis and
recommend its acceptance:

David L. Feldman

Sally P. Horn

Sally P. Horn

Kenneth H. Orvis

Acceptance for the Council:

Vice Chancellor and Dean of Graduate Studies

Spatiotemporal Variations in the Fire Regimes of Whitebark Pine (*Pinus albicaulis* Engelm.) Forests, Western Montana, USA, and Their Management Implications

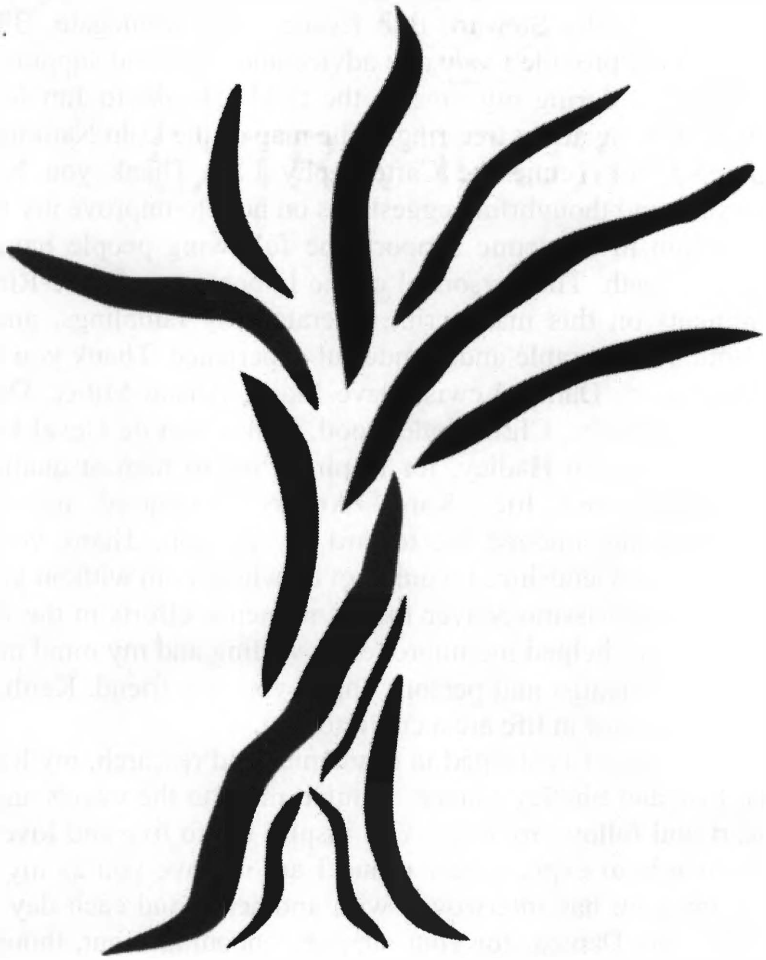
A Thesis Presented for the Master of Science Degree
The University of Tennessee, Knoxville

Evan Reed Larson
December 2005

Dedication

For their strength, beauty, resilience, and grace…

I dedicate this thesis to the Whitebark Pine.



Acknowledgments

This research could not have been conducted without the help and support of numerous people and organizations. Thank you Saskia van de Gevel-Edidin and David Mann for your assistance and company during the summer of 2004. That year will go down as one of the great field seasons of my career...MFF. I would like to thank my committee members Dave Feldman, Ken Orvis, and Sally Horn for their guidance and suggestions during the development of this thesis, as well as the knowledge and inspiration they passed on to me in and out of the classroom. This study was inspired from research that began during the 2004 North American Dendroecological Fieldweek (NADEF), and I am grateful for the opportunity to work on such an important topic in such a beautiful setting. Lori Daniels shared samples and data that she and others gathered during the 2004 NADEF that strengthened my age-structure analyses for Morrell Mountain. Cathy Stewart, Bob Keane, Vick Applegate, Bill Oelig, and Elaine Kennedy-Sutherland provided valuable advice and logistical support during the planning of this research and during my time in the field. Thanks to Jim for his shop time and patience while learning about tree-rings. The map of the Lolo National Forest was created by the University of Tennessee Cartography Lab. Thank you Kurt Kipfmueller for sharing your data and thoughtful suggestions on how to improve my thesis.

In addition to academic support, the following people have been mentors and friends along my path. The personnel of the Laboratory of Tree-Ring Science provided helpful comments on this manuscript, tolerated my ramblings, and made my time in Tennessee both a memorable and wonderful experience. Thank you Beth Atchley, Justin Hart, Joe Henderson, Daniel Lewis, Dave Mann, Alison Miller, Dana Miller, Whitney Nelson, Michelle Pfeffer, Chris Underwood, Saskia van de Gevel-Edidin, and Georgina Wight. Thank you Keith Hadley, for inspiring me to highest quality and ethics in my research, teaching, and life. Karen Arabas introduced me to the science of dendrochronology and nudged me toward my passion. Thank you so much for your support, advice, and friendship; I would not be where I am without you. Finally, I want to acknowledge Henri Grissino-Mayer for his immense efforts in the field, classroom, and laboratory. You have helped me improve my writing and my mind profoundly. You have made me a better scientist and person. Thank you, my friend. Keith, Karen, and Henri - know that my successes in life are a credit to you.

While my career is steeped in academics and research, my life is filled with love. My parents, Eric and Shelley Larson, brought me into the woods and taught me to think with my heart and follow my bliss. You inspire me to live and love with passion, and I have not the words to express how proud I am to have you as my parents. As I move through life, my path has interwoven with another's, and each day grows brighter than the last. Thank you Danica, for your support, encouragement, thoughtfulness, patience, and Love. I am a fortunate man to share this life with you.

Funding for this project was provided by the Biogeography Specialty Group of the Association of American Geographers, the Stewart K. McCroskey Memorial Fund of the Department of Geography, the University of Tennessee, and the Global Environmental Change Research Group at the University of Tennessee.

Abstract

Whitebark pine (*Pinus albicaulis*) is a long-lived tree species that exists throughout high elevation forest communities of western North America. It is the foundation of a diminishing ecosystem that supports Clark's nutcrackers, red squirrels, grizzly bears, and black bears. The decline of this species is directly related to mortality from widespread mountain pine beetle outbreaks and infestation by the invasive white pine blister rust, and may be exacerbated by fire suppression. Prescribed fire will be a primary management tool in efforts to preserve whitebark pine on the landscape. My research used dendrochronology to investigate the fire history of whitebark pine stands on three mountains in the Lolo National Forest, Montana, via fire-scar and age structure analyses. I then used these data to assess the USDA Fire Regime Condition Classification (FRCC) fire regime types for my sites. Additionally, I utilized traditional superposed epoch analysis techniques in a novel manner to develop a multi-decadal superposed epoch analysis for fire-climate and fire-tree establishment analyses. I sampled between 40 and 50 fire-scarred trees, snags, and remnants, and collected age structure data in two 0.5 ha plots at each site. Samples at all sites recorded a frost event in AD 1601 related to southern hemisphere volcanic activity. The fire-history and stand-structure data indicate all three sites were characterized by mixed-severity fire regimes and generally agreed with the FRCC classifications. However, fires occurred with greater frequency than previously found in whitebark pine forests and distinct differences existed between the fire regimes of each of the three sites that are likely related to topography, forest cover, and climate conditions. A period of widespread fire activity at all three sites occurred from the mid-1700s to the early 1800s and may be the expression of interactions between several climate variables. Fire suppression led to a decline in fire activity in the 1900s, but subalpine fir trees began establishing between 300 and 140 years ago at all three sites. This suggests fire suppression may not be responsible for the advanced succession found in these whitebark pine forests and management decisions based on that assumption are inappropriate for these sites. In addition, the spatial and temporal variability in fire activity between these sites requires a refinement in the Fire Regime Condition Classification methods if they are to be used for managing whitebark pine forests.

Keywords: Whitebark pine, *Pinus albicaulis*, fire history, dendrochronology, age structure, subalpine, MDSEA, mixed-severity, fire regime, FRCC, 1601, climate, Lolo National Forest, Montana, Northern Rocky Mountains.

Table of Contents

Chapter One 1

1. Fire, Ecosystems, and Land Management in the Western United States. 1
  1.1 Introduction 1
  1.2 Objectives of the Thesis 3
  1.3 Organization of the Thesis 4
  1.4 Forest Types and Fire Ecology of the Northern Rocky Mountains 5
  1.5 Fire Management in the Northern Rocky Mountains and Western United States.. 7
    1.5.1 Early History and the Fires of 1910 7
    1.5.2 The Era of Total Fire Suppression 8
    1.5.3 Wildland Fire Management Guidelines and Ecosystem Management 9
    1.5.4 The National Fire Plan: A Federal Fire Policy 10
    1.5.5 Proactive Fire Management 14
  1.6 Fire Regime Classification and the Historical Range of Variability 14
    1.6.1 Fire Regime Types 15
    1.6.2 Fire Regime Condition Class 16
  1.7 Whitebark pine (*Pinus albicaulis* Engelm.) 18
    1.7.1 Biogeography 18
    1.7.2 Fire Ecology 21
    1.7.3 Significance of the Species 21
    1.7.4 Status of the Species 23
    1.7.5 Management of Whitebark Pine 25
    1.7.6 Research Needs 26
  1.8 The Science of Dendrochronology 27

Chapter Two 29

2. Literature Review of Whitebark Pine 29
  2.1 Fire and Whitebark Pine 29
    2.1.1 Fire and Whitebark Pine in the Northern Rockies 29
    2.1.2 Fire and Whitebark Pine in the Greater Yellowstone Ecosystem 33
    2.1.3 Crossdated Fire History Research 35
  2.2 Dendrochronology of Whitebark Pine 36
    2.2.1 Dendroglaciology 36
    2.2.2 Dendroecology 37
    2.2.3 Dendroclimatology 40

Chapter Three 42

3. Study Site Descriptions 42
  3.1 General Setting of the Lolo National Forest, Western Montana 42
    3.1.1 Climate 42
    3.1.2 Geology 46
    3.1.3 Soils 46

3.1.4 Plant Communities 47
3.1.5 Land Use History 49
3.1.5.1 Pre-Euro-American Settlement 49
3.1.5.2 Mining History 50
3.1.5.3 Logging History 50
3.1.5.4 Agriculture 51
3.1.6 Forest Management 51
3.1.6.1 Timber Management 52
3.1.6.2 Pest Management 53
3.1.6.3 Fire Management 53
3.1.6.4 Whitebark Pine Management 54
3.2 Morrell Mountain 54
3.2.1 Environmental Setting 54
3.2.2 Land Use and Disturbance History 58
3.3 Mineral Peak 58
3.3.1 Environmental Setting 58
3.3.2 Land Use and Disturbance History 62
3.4 Point Six 62
3.4.1 Environmental Setting 62
3.4.2 Land Use and Disturbance History 66

Chapter Four 67

4. Methods 67
4.1 Field Methods 67
4.1.1 Fire History 67
4.1.2 Age Structure 68
4.2 Laboratory Methods 69
4.2.1 Sample Preparation 69
4.2.2 Crossdating and Chronology Construction 69
4.2.3 Fire History 72
4.2.4 Age Structure 75
4.3 Graphical Analyses 76
4.3.1 Fire History Charts 76
4.3.2 Age Structure Charts 76
4.4 Statistical Analyses 77
4.4.1 Fire History Descriptive Statistics 77
4.4.1.1 Measures of Central Tendency 77
4.4.1.2 Measures of Range 79
4.4.1.3 Measures of Dispersion 79
4.4.1.4 Measures of Shape 80
4.4.2 Temporal Analyses 80
4.4.3 Spatial Analyses 81
4.4.4 Fire Seasonality Analyses 81
4.4.5 Fire-Tree Establishment Relationships 81
4.4.6 Fire-Tree Growth Relationships 83

4.5 Fire-Climate Relationships 84
4.6 Fire Regime Type Classification 85

Chapter Five 87

5. Results 87
5.1 Crossdating and Chronology Construction 87
5.2 Fire History 90
5.2.1 Morrell Mountain 90
5.2.2 Mineral Peak 93
5.2.3 Point Six 93
5.2.4 All Sites 96
5.3 Age Structure 97
5.3.1 Morrell Mountain 97
5.3.2 Mineral Peak 100
5.3.3 Point Six 100
5.3.4 All Sites 100
5.4 Statistical Analyses 101
5.4.1 Descriptive Statistics 101
5.4.2 Temporal Analyses 104
5.4.3 Spatial Analyses 104
5.4.4 Fire Seasonality Analyses 109
5.4.5 Fire-Tree Establishment Relationships 109
5.4.6 Fire-Tree Growth Relationships 114
5.5 Fire-Climate Relationships 116
5.6 Fire Regime Type Classification 122

Chapter Six 125

6. Discussion 125
6.1 Fire History and Age Structure of Whitebark Pine Forests 125
6.2 Spatiotemporal Variations in Fire Activity 135
6.3 Relationships Between Fire Activity, Tree Establishment, and Tree Growth 141
6.4 Fire-Climate Relationships 145
6.5 Management of Whitebark Pine 148

Chapter Seven 153

7. Conclusions and Future Research 153
7.1 Conclusions 153
7.2 Future Research 159

References 162
Appendices 194
Appendix A. Statistical descriptions for the 214 measurement series from fire-scarred cross-sections collected on three mountains in the Lolo National Forest. 195

Appendix B. Fire-scar data from 111 fire-scarred cross sections collected from three mountains in the Lolo National Forest. 201
Appendix C1. Fire-tree establishment MDSEA output for annual tree establishment... 219
Appendix C2. Fire-tree establishment MDSEA bootstrapped confidence intervals for annual tree establishment.......... 221
Appendix D1. Fire-tree establishment MDSEA for 5-yr mean tree establishment. 223
Appendix D2. Fire-tree establishment MDSEA bootstrapped confidence intervals for 5-yr mean tree establishment. 225

Vitae 227

List of Tables

Table 1.1 Fire Regime Condition Class Guidebook fire regime type definitions............ 16

Table 1.2 Fire Regime Condition Class categories. 17

Table 2.1 Fire intervals reported for whitebark pine forests and the methods used for the reconstruction. 30

Table 3.1 General setting of the study sites in whitebark pine forests on three mountains in the Lolo National Forest, Montana. 56

Table 4.1 Abbreviations and definitions of the descriptive statistics used to characterize the fire regimes and their historical range of variability on three mountains in the Lolo National Forest, Montana 78

Table 5.1 Statistics for tree-ring chronologies developed from fire-scarred whitebark pines on three mountains in the Lolo National Forest, Montana, and for all sites combined. 89

Table 5.2 Descriptive statistics for fire history chronologies developed from whitebark pines on three mountains in the Lolo National Forest, Montana.............................. 91

Table 5.3 Age-structure data from three stands in the Lolo National Forest, Montana... 98

Table 5.4 Results of the temporal analyses between the pre-settlement (POR–1850) and settlement (1851–1920) periods. 105

Table 5.5 Results of the temporal analyses between the pre-settlement (POR–1850) and fire suppression (1921–POR) periods. 106

Table 5.6 Results of the temporal analyses between the settlement (1851–1920) and fire suppression (1921–POR) periods. 107

Table 5.7 Results of the spatial analyses of fire chronologies developed from whitebark pine on three mountains in western Montana. 108

Table 5.8 Fire seasonality in whitebark pine forests on three mountains in the Lolo National Forest, Montana, and all sites combined... 110

Table 5.9 Fire regime classifications for study sites on three mountains in the Lolo National Forest.. 124

List of Figures

Figure 1.1 Wildland fire statistics for the United States. 11

Figure 1.2 Distribution of whitebark pine (*Pinus albicaulis* Engelm.). 20

Figure 3.1 Locations of the three study sites in the Lolo National Forest, Western Montana. 43

Figure 3.2 Forest types and forestland cover of the Lolo National Forest, Montana. 48

Figure 3.3 The study site on Morrell Mountain. 55

Figure 3.4 A south-facing alpine meadow in the transition between the lower and upper subalpine forest types on Morrell Mountain. 57

Figure 3.5 The study site on Mineral Peak. 59

Figure 3.6 An example of the forest structure on the talus slopes of the upper subalpine forest zone on Mineral Peak. 61

Figure 3.7 The results of the 10,000-hectare Mineral-Primm fire complex that burned throughout the Gold Creek drainage in 2003, as seen from the trail to the summit of Mineral Peak. 63

Figure 3.8 The study site on Point Six. 64

Figure 4.1 Illustration of recorder and non-recorder rings on a fire-scarred cross-section. 74

Figure 4.2 Graphical representation of the years included in the multi-decadal superposed epoch analyses examining the relationship between fire and tree establishment. 83

Figure 5.1 A frost event in 1601 damaged 17 of 22 samples from Morrell Mountain, 15 of 25 samples on Mineral Peak, and the only sample on Point Six alive that year. ... 88

Figure 5.2 A weathered stump near the summit of Morrell Mountain. 88

Figure 5.3 The fire history chart for Morrell Mountain in the Lolo National Forest, Montana. 92

Figure 5.4 The fire history chart for Mineral Peak, in the Rattlesnake National Recreation Area and Wilderness, Lolo National Forest, Montana. 94

Figure 5.5 The fire history chart for Point Six, in the Lolo National Forest, Montana. .. 95

Figure 5.6 The master fire charts of (A) all fires and (B) fires that scarred multiple trees on three mountains in the Lolo National Forest, Montana. 96

Figure 5.7 Age structure of trees on (A) Morrell Mountain, (B) Mineral Peak, (C) Point Six, and (D) all three sites combined. 99

Figure 5.8 Fire-free interval distributions for (A) Morrell Mountain, (B) Mineral Peak, (C) Point Six, and (D) all sites combined. 103

Figure 5.9 Fire seasonality in whitebark pine forests on three mountains in the Lolo National Forest, Montana, and all sites combined. 110

Figure 5.10 Results from four multi-decadal superposed epoch analyses examining the relationship between fire and annual tree establishment. 111

Figure 5.11 Results from four multi-decadal superposed epoch analyses examining the relationship between fire and the 5-yr moving average of tree establishments........ 112

Figure 5.12 Fire-tree establishment relationships over the 98 years following fire events in study sites on three mountains in the Lolo National Forest, Montana. 113

Figure 5.13 Results from multi-decadal superposed epoch analyses of the relationship between all fires and tree growth at (A) local and (B) regional scales................115

Figure 5.14 Results from superposed epoch analyses (SEA) of the relationship between widespread fires and tree growth at (A) local and (B) regional scales.................... 117

Figure 5.15 Visual representation of the relationships between: (A) temperature (annual and 5-yr moving average; Briffa *et al.* 1992); (B) Precipitation (annual and 5-yr moving average; Fritts 1991); (C) Palmer Drought Severity Index (annual and 5-yr moving average; Cook *et al.* 1999); and (D) fire activity, including a 20-yr moving average of the number of fire scars recorded at all sites. 118

Figure 5.16 Visual representation of the relationship between: (A) Nino3 (D'Arrigo *et al.* in press) and (B) Southern Oscillation Index (inverse z-scores; Stahle *et al.* 1998), with (C) fire activity, including a 20-yr moving average of the number of fire scars recorded at all sites. 120

Figure 5.17 Visual representation of the relationship between (A) Pacific Decadal Oscillation (annual and 20-yr moving average; D'Arrigo *et al.* 2001), and (B) the Atlantic Multidecadal Oscillation (Gray *et al.* 2004), with (C) fire activity, including a 20-yr moving average of the number of fire scars recorded at all sites................ 121

Figure 5.18 Fire regime types for three study sites in the Lolo National Forest, Montana. 123

Chapter One

1. Fire, Ecosystems, and Land Management in the Western United States

1.1 Introduction

Fire plays a major role in shaping nearly every forest ecosystem in North America. This includes the vast tracts of yellow pine that stretch from the American Southwest (Dieterich 1983, Baisan and Swetnam 1990, Grissino-Mayer *et al.* 2004) up through the Columbia Plateau (DeBano *et al.* 1998, Heyerdahl *et al.* 2002), the coastal rainforests of California and the Pacific Northwest (Morrison and Swanson 1990, Agee 1993, Brown and Swetnam 1994), the pine and oak forests of the East and Midwest (Clark and Royal 1996, Shumway *et al.* 2001, Welch and Waldrop 2001), the boreal forests of Alaska and Canada (Dansereau and Bergeron 1993, Lesieur *et al.* 2002), and the diverse forest systems of the Rocky Mountain cordillera (Arno 1980, Wright and Bailey 1982, Goldblum and Veblen 1992, Sherriff *et al.* 2001). The historical fire regimes of these ecosystems varied widely across the landscape, from frequent surface fires in the American Southwest that recurred on 2- to 15-yr intervals (Dieterich 1983, Grissino-Mayer 1995, Swetnam and Baisan 1996), to the infrequent, stand-replacing fires that burned across thousands of hectares in the northern boreal forests at intervals of 150 years or more (Viereck 1973, Johnson 1992).

Over the past century, many of these ecosystems that historically experienced a frequent fire regime have undergone extraordinary changes in species composition and forest structure. The current paradigm, born out of the American Southwest, is that 100 years of fire suppression have allowed forests to become increasingly dense while advancing successionally toward shade-tolerant, fire-intolerant species, decreasing forest health while increasing susceptibility to high-severity, stand-destroying fires (Cooper 1960, Gruell 1983, Covington and Moore 1994, Steele 1994). These ecological changes are documented in ponderosa pine (*Pinus ponderosa* Douglas ex. C. Lawson) forests of the Four Corners region (Cooper 1960, Covington and Moore 1994), the Colorado Front Range (Mast *et al.* 1998), and eastern Oregon and Washington (Weaver 1961, West 1969, McNeil and Zobel 1980, Bork 1984), and many believe that the severe fire seasons of the 1990s and 2000s were a result of these changes (Arno 1996, Keane *et al.* 2002).

As with many environmental processes, some uncertainty surrounds the relationship between anthropogenic activity (*i.e.* fire suppression) and fire regimes. Research in some forest systems suggests that the effects of fire suppression are not pervasive on the landscape and that some modern fire regimes are still operating within their historical range of variability (Baker and Ehle 2001, Johnson *et al.* 2001, Sherriff *et al.* 2001, Veblen 2003). Additionally, research is increasingly implicating regional- and hemispheric-scale climate variability as a significant driver that affects the timing and extent of fires throughout the West (Swetnam and Betancourt 1990, 1998, Grissino-Mayer and Swetnam 2000, Kitzberger *et al.* 2001, Heyerdahl *et al.* 2002, Veblen and Kitzberger 2002), including in modern fire regimes (Westerling and Swetnam 2004). The situation is further complicated by the relatively unknown impacts of extensive landscape level changes, such as forest fragmentation and the expansion of the urban-wildland interface (Reed *et al.* 1996, Tinker *et al.* 1998, Knight *et al.* 2000).

In this climate of uncertainty, land management agencies are being spurred by both public and private interests to implement management practices that restore the ecological health of these systems while protecting human life and property (Teensma

1996, Brown 2000). The response to these pressures has been a shift toward ecosystem management throughout the federal system (Brown 1994, Arno 1996, Brown 2001). The difficulties now faced by land managers stem from incomplete understandings of the ecosystems being managed, while a growing sense of urgency surrounds many forest communities at risk of severe and rapid decline.

1.2 Objectives of the Thesis

My thesis research investigates the role of fire in whitebark pine forests on three mountains in the Lolo National Forest, western Montana. My objectives are to:

- Reconstruct the fire history and age structure of whitebark pine forests on three mountains in the Lolo National Forest, western Montana.
- Describe the historical fire regimes of these forests in terms of the frequency, severity, and seasonality of past fires.
- Determine whether distinct spatial and/or temporal patterns exist in the fire regimes of these forests locally, at the individual site level, and regionally, by comparing and contrasting the sites with each other.
- Describe the fire-tree establishment and fire-tree growth relationships that exist in these forests.
- Describe the fire-climate relationships for my sites.
- Use my results as a framework to examine the current management of whitebark pine in the Lolo National Forest.

1.3 Organization of the Thesis

This thesis consists of seven chapters written in response to a pressing need to understand the fire ecology of the whitebark pine (*Pinus albicaulis* Engelm.) ecosystem. In Chapter One, I introduce my thesis research with an overview of the ecology and management of fire in forest systems of western North America, focusing specifically on the Northern Rocky Mountains. I then describe the biogeography, fire ecology, and significance of whitebark pine and the community it supports, addressing the current management provisions for the species and the research needed to better understand this at-risk ecosystem. I introduce my primary method of investigation for my thesis research, dendrochronology, and then conclude Chapter One with a list of my research objectives.

Chapter Two provides a comprehensive review of the literature on the fire ecology of whitebark pine and the dendroecological research focused on this species. Chapter Three describes the general setting of my research in the Lolo National Forest, including the flora, climate, geology, and land-use history of the region. I briefly review the current Lolo National Forest Plan in terms of managing both fire and whitebark pine, and then describe my three study sites within the Lolo National Forest.

Chapter Four outlines the field and laboratory methods I used to collect and process my data, and the statistical methods I employed in my analyses. Chapter Five presents the results of my research. In Chapter Six, I discuss the significance of my research and its implications for the current paradigm of the role of fire in whitebark pine communities. I also use my results as a framework to analyze current management strategies relevant to whitebark pine forests. Chapter Seven contains my concluding remarks and suggestions for future research in the whitebark pine ecosystem.

1.4 Forest Types and Fire Ecology of the Northern Rocky Mountains

Fire is the dominant disturbance throughout the Northern Rocky Mountains (Arno 1980, Gruell 1983, Alexander 1988, Arno and Allison-Bunnell 2002), and while the role of fire among different forest types varies, its effects are evident across the landscape (Fischer and Bradley 1987). The historical fire regimes of this region were products of climate, topography, forest type, and disturbance history (Arno 1980, Ryan 2002, Bassman *et al.* 2003, Schoennagel *et al.* 2004), with Native American activity augmenting fire regimes and affecting vegetation patterns on a local to landscape scale (Barrett and Arno 1982, Arno 1985). Lightning storms are quite common during the mid- and late- summer months and provide the main ignition source for wildfires in the Northern Rockies (Barrows 1977, USFS 1986). The fire season in the Northern Rockies typically begins in July as precipitation decreases and convective thunderstorms become more common, and continues until precipitation increases in late September and early October (Brown *et al.* 1994).

Historically, surface fires occurred throughout the lower elevations of the region at intervals of 15–30 years (Habeck and Mutch 1973, Tande 1979). These fires maintained grass meadows and open stands of ponderosa pine in the valley bottoms and on the driest sites, shifting to mixed ponderosa pine-Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests on the surrounding slopes (Pfister *et al.* 1977, Arno 1980, Habeck 1987). Douglas-fir and western larch (*Larix occidentalis* Nutt.) make up a large component of stands on moister sites (Alexander 1988, Peet 1988) where mean fire-free intervals (MFI) ranged from 20–50 years (Arno 1980, Arno *et al.* 1997).

The forest communities of the middle elevations are dominated by nearly pure stands of Rocky Mountain lodgepole pine (*P. contorta* Douglas ex Loudon var. *latifolia* Engelm. in Watson) that blend with the ponderosa pine-Douglas-fir series at their lower limit and subalpine series at their upper limit (Alexander 1988, Peet 1988). These communities experienced a wide range of fire regimes, including relatively frequent (MFI of 25–50 years), mixed-severity fires on drier sites (Tande 1979), less frequent (MFI of approximately 150 years), higher-severity fire regimes on more moist sites (Barrett *et al.* 1991), and high-severity, stand-replacing fires at intervals of 250+ years on harsh, high-elevation sites (Romme 1982). Evidence of large-scale stand-replacing fire events exists throughout all of the lodgepole-pine-dominated forest types in the region (Arno 1980).

High-elevation forests that extend from the upper limits of the lodgepole pine zone to the treeline constitute the widest ranging forest types in much of the Northern Rockies (Pfister *et al.* 1977). These communities are composed of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and whitebark pine, with occasional seral communities of lodgepole pine, Douglas-fir, western larch, and alpine larch (*Larix lyallii* Parl.; Peet 1988). The fire regimes of these forest types are generally thought to be composed of high-severity, stand-replacing fires at MFI of 100–400+ years (Agee 1993). These fires are often spotty and erratic in behavior due to the role of weather in fire activity in this region (Bessie and Johnson 1995), and create mosaics of single-age stands on the landscape (Tande 1979, Bebi *et al.* 2003). One subalpine forest type that may be an exception to this dominant fire regime is the whitebark pine community. The fire regime of whitebark pine forests has recently been characterized as mixed-severity (Arno *et al.* 2000), and research shows fire may occur much more frequently in these forests than in other subalpine communities (Morgan and Bunting 1990).

1.5 Fire Management in the Northern Rocky Mountains and Western United States

1.5.1 Early History and the Fires of 1910

Fire management in the Northern Rocky Mountains began in the 1800s. Early Euro-American pioneers used fire extensively to clear and maintain pastures for cattle , and as mineral exploration spread across the region, fires were used to clear the land in preparation for mining activity (Smith 1992). As the pioneer era closed, large-scale logging operations spread across the region. In the economy of timber, fire was viewed as a destructive force, and by the late 1800s fire suppression was the dominant management strategy throughout the region (Kotok 1930). Initial fire suppression efforts were largely ineffective in the Northern Rocky Mountains. The complex terrain made vast tracts of land nearly inaccessible except by foot or by horse, and the number of ignitions during summer thunderstorms often overwhelmed the available fire fighting resources. Yet by the early 1900s, fire suppression techniques had matured to the point where a general sense of confidence was felt throughout the fledgling USDA Forest Service (Pyne 1982).

The defining moment for fire management in the Northern Rocky Mountains and the nation as a whole came during the fire season of 1910. The year 1910 was one of severe droughts across North America, and steady winds parched millions of hectares creating a virtual tinderbox throughout the West (Arno and Allison-Bunnell 2002). The fire season began in late summer, with lightning storms igniting hundreds of fires in

California, Oregon, Washington, Idaho, Montana, and Wyoming, overwhelming suppression efforts by the USDA Forest Service (Pyne 2002). The most severe of these fire complexes was labeled “The Big Blowup,” which, fanned by gale winds, burned nearly 1.2 million hectares across western Montana and Idaho over the course of two days, incinerating several communities and killing 85 people (Davis 1959). As the fall rains brought the fire season to a close, national reactions to the catastrophe initiated a massive restructuring of fire management in the United States (Pyne 2002).

1.5.2 The Era of Total Fire Suppression

In the post-1910 setting, the approach to fire suppression took on the air of warfare, with almost exclusive control given to the USDA Forest Service (Pyne 1982). An attitude of total fire suppression, coupled with the development of the automobile, improved the effectiveness of fire suppression efforts following World War I, but forest access was still limited, and significant improvements in the efficacy of fire suppression did not arise until the New Deal and Civilian Conservation Corps era of the 1930s (van Wagtendonk 1991). During this period, extensive road and trail projects increased access throughout the nation’s forests, allowing Forest Service personnel to rapidly attack and suppress wildfires. Following World War II, the use of aircraft for spotting and suppressing fires led to additional improvements in suppression effectiveness (van Wagtendonk 1991). The establishment of the Smoke Jumper program in 1940 in the Northern Rocky Mountain region (USFS 1968) facilitated the rapid attack of fires even in remote wilderness areas. The increasing success with which wildfires were controlled and extinguished led to a nearly annual decrease in the number of hectares burned and human lives lost, yet with this success a century of dramatic ecological change was set in motion.

1.5.3 Wildland Fire Management Guidelines and Ecosystem Management

Widespread fires in 1967 burned 36,000 hectares in the Northern Rocky Mountains and brought fire management under renewed scrutiny. Research was beginning to illustrate the ecological impacts of fire suppression (Weaver 1959, Cooper 1960), and with the social backdrop of the environmental movement, a growing number of land managers began to explore the use of fire in the management of ecosystems that seemed to be growing increasingly out of balance (van Wagtendonk 1991). In 1970, the Society of American Foresters created a task force to examine the role of fire in the Northern Rocky Mountains. The committee reported that fire could not be excluded from this region and suggested that fire could be used to advance and maintain productive and healthy forest conditions (Wellner 1970). Following this report, the use of prescribed fire gained increasing support across the nation, and especially in the Northern Rockies (Pyne 1982).

In 1986, the national government issued the Wildland Fire Management Guidelines, which explicitly outlined the importance of fires in forest ecology and management, and described the procedures and standards to follow when attempting to manage both prescribed and naturally occurring fires on public lands (NPS 1986). The changes outlined by this policy increased the ecological considerations of forest management plans, but changes in the field were slow to materialize and the inertia of past fire suppression would prove difficult to rein in. A lull in severe fire activity during the 1970s and 1980s was broken and the increasingly volatile condition of forests throughout western North America finally gained widespread public attention in the late 1980s. The conflagration that erupted in Yellowstone National Park in 1988 captured the nation's interest (Lauber 1991), and even though these fires likely functioned within what most researchers consider normal for this fire regime (Romme and Despain 1989), the event focused media attention on the state of the environment and gave leverage to proponents of a more proactive fire management plan for public lands. The Wildland Fire Management Guidelines were opened to scrutiny and rewritten, renewing pressure on the USDA Forest Service to expand the use of prescribed fire and mechanical thinning to mimic historical disturbances in the absence of wildfires (Attiwill 1994). Yet even as land managers attempted to address the ecological concerns of the nation's forests, it quickly became evident that the Yellowstone Fire of 1988 was simply a harbinger of what was to come.

1.5.4 The National Fire Plan: A Federal Fire Policy

The 1990s and early 2000s saw a dramatic increase in the scale and intensity of wildfire activity in the Northern Rockies and across the western states of North America. Large wildfires continued to grow more common and widespread over this period as six of the 10 most severe fire seasons in the nation's history occurred over a 10-year span (Figure 1.1; NIFC 2005). Economic losses skyrocketed over this time as suppression and firefighting costs reached record levels among federal agencies. Extensive media coverage brought attention to the situation, raising public concern and increasing pressure on politicians to act. As in 1988, the catalyst for action came in the flames of 1994,

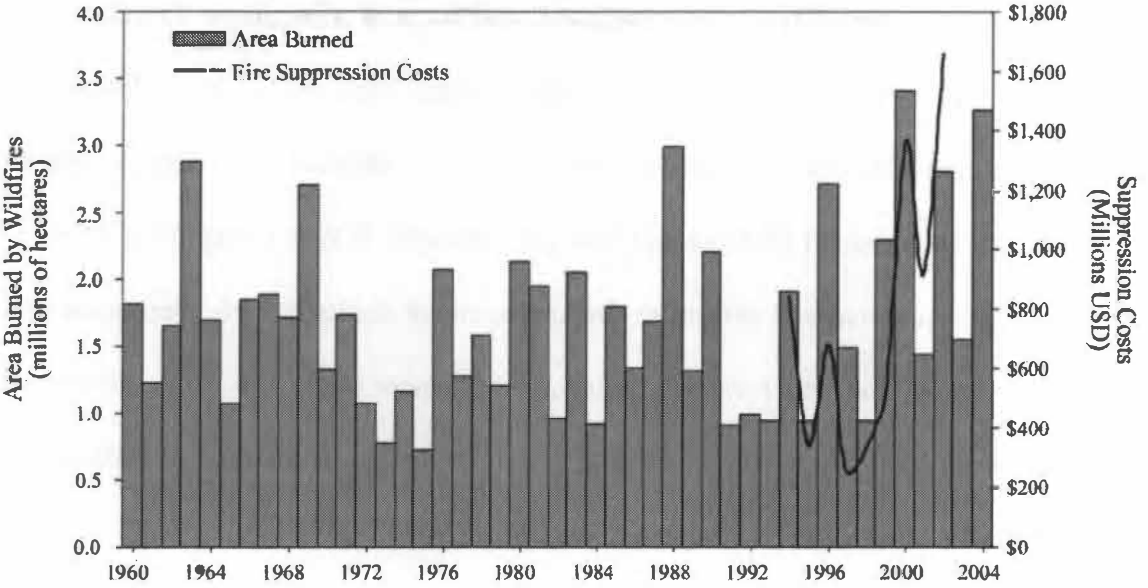


Figure 1.1 Wildland fire statistics for the United States. Data for the total area burned across the nation include the years 1960–2004, and total fire suppression costs (in constant dollars) are available for the years 1994–2002 (NIFC 2005).

during which over 1.9 million hectares burned, nearly $850 million were spent on fire fighting activities, and 36 wildland fire fighters lost their lives (NWCD 1995). The following year, the 1986 Wildland Fire Management Guidelines were replaced by the 1995 Federal Wildland Fire Management Policy (NWCD 1995).

The new wildfire policy was a comprehensive plan founded on greater ecological understanding of the role of fire in forest systems and produced by a collaborative effort between the Department of the Interior and the Department of Agriculture. The document stressed the need for a cohesive "umbrella" federal fire policy to enhance the effectiveness and efficiency of the numerous agencies affected by wildfires, and to encourage the involvement of tribal and state governments in fire management (NWCD 1995). The plan emphasized proactive fire management through fuels treatments and prescribed burning, and under the new policy, management plans were to be developed using the "best available science" for "all areas subject to wildland fire," with risk assessments preceding all fire management decisions (NWCD 1995).

The 1995 Federal Wildland Fire Management Policy was implemented in February of that year, and was followed by a relatively short and calm fire season. The following year, however, again brought wildfires to the forefront of the public eye as explosive fires burned 2.7 million hectares across the United States. While fewer total hectares burned in 1997 and 1998, wildland fires continued to become more severe and dangerous to fight (NWCD 2001). The decade of the 1990s ended with fires consuming over 2.3 million hectares in 1999, with over half a billion dollars spent on fire fighting. The year 2000 followed with the most severe fire season in over 50 years, burning more than 3.4 million hectares, costing billions of dollars in economic losses and insurance claims, a record $1.6 billion dollars spent on fire fighting, and over 30 lives lost (NIFC 2005).

The severe fire seasons of 1999 and 2000 kept the issue of wildland fire in the news, and dramatic stories and images flooded the media. One event in particular drew heavy public criticism. In May 2000, an escaped prescribed burn in New Mexico grew into the 19,500 hectare Cerro Grande Fire, destroying 405 homes and creating a potential breach in national security at the Los Alamos National Laboratory (GAO 2000). The event spurred a great amount of concern over the planning and implementation of fire management and fuels treatment under the 1995 Federal Wildland Fire Management Policy, and was a significant factor in prompting additional fire policy reforms (Brown 2001).

The first initiative on fire policy taken in the new millennium occurred at the tail end of the record fire year of 2000, when President Clinton called for a review of the 1995 fire plan to bring it up to date with the most recent science and technology. The review, conducted by the Department of the Interior and the Department of Agriculture, added language of ecosystem sustainability, restoration, and program evaluation to the 1995 document, but found that "the policy is generally sound and continues to provide a solid foundation for wildland fire and natural resources management activities of the federal government" (NWCD 2001). The updated fire policy was submitted to Congress as the National Fire Plan. After mandating the development of a 10-year Comprehensive Strategy to supplement the plan (WLFC 2002), Congress signed the new policy and supported it in the Fiscal Year 2001 Appropriations Act (United States Congress 2000).

1.5.5 Proactive Fire Management

The new era of fire management ushered in by the National Fire Plan integrated massive proactive fuels treatment efforts with existing prescribed fire and suppression policies (NWCD 2001). Over the course of 2001 and 2002, nearly 1.7 million hectares of fuels reduction projects were completed on federal lands, with another 1.1 million hectares treated in 2003 following the announcement of the Healthy Forests Initiative (United States Congress 2003). The Healthy Forests Initiative aimed to streamline the process of developing and implementing fuels treatment projects in high-risk areas, and several sites in the Northern Rocky Mountains qualified as suitable pilot projects (Healthy Forests 2005).

1.6 Fire Regime Classification and the Historical Range of Variability

Understanding the modern roles of fire on the landscape depends on our ability to understand the historic roles of fire on the landscape (Swetnam *et al.* 1999). In response to this need, great amounts of time and money have been invested in research on the fire history of forested landscapes throughout North America (Wright and Bailey 1982, Agee 1993, DeBano *et al.* 1998). The knowledge gained from this research led to the creation of several fire regime classification systems that facilitate the description, comprehension, and management of fire-dependent ecosystems (Fischer and Bradley 1987, Williams and Rothermal 1992, Brown 1994). The first classification system for fire regimes was based on fire intensity, fire size, and fire frequency, and described seven distinct fire regimes (Heinselman 1978, 1981). Fire regime classification has since included fire severity in place of fire intensity, and during the 1990s shifted toward using three general fire regime descriptions: low severity, frequent fires; mixed-severity, mixed-frequency fires; and high-severity, infrequent fires (Brown 1994, Agee 1996).

The classification of fire regimes has continued to evolve in response to recent increases in the sophistication of fire management and the growing importance of inter-agency communication spurred by the severe fire seasons of the late 1990s (Hann and Bunnell 2001). The current classification system used by federal agencies (Hann *et al.* 2004) includes five fire regime types coupled with a Fire Regime Condition Class (FRCC) rating that describes the departure of a forest system from its historic fire regime (Hardy *et al.* 2001, Schmidt *et al.* 2002). Incorporated in the FRCC methodology is the vital concept of the "historical range of variability" inherent to disturbance regimes (Morgan *et al.* 1994a). This concept emphasizes the dynamic nature of ecosystems and provides a framework to better understand ecosystem processes and ecological change over time. When used judiciously, it can guide management to achieve a range of desirable future conditions within the natural bounds of an ecosystem (Landres *et al.* 1999).

1.6.1 Fire Regime Types

The FRCC guidebook describes five historical fire regime types based on fire frequency and fire severity (Table 1.1). Fire regime types are assigned to specific sites according to the "natural" role of fire on a landscape in the absence of modern human intervention, and are meant to guide management practices within the historical context of the ecosystem (Hann *et al.* 2004).

Table 1.1 Fire Regime Condition Class Guidebook fire regime type definitions. Fire regime type is based on the frequency and severity of fire on a landscape in the absence of modern human intervention (Hann *et al.* 2004).

Fire Regime	Mean Fire-Free Interval	Description
Type I	0–35 yrs	Low to mixed severity fires replacing less than 75% of the dominant overstory vegetation
Type II	0–35 yrs	High severity fires replacing at least 75% of the dominant overstory vegetation
Type III	35–100+ yrs	Mixed severity fires replacing less than 75% of the dominant overstory vegetation
Type IV	35–100+ yrs	High severity fires replacing at least 75% of the dominant overstory vegetation
Type V	200+	High severity, stand replacing fires

1.6.2 Fire Regime Condition Class

The FRCC categories are defined by Schmidt *et al.* (2002) as:

> "…the degree of departure from historical fire regimes, possibly resulting in alterations of key ecosystem components such as species composition, structural stage, stand age, canopy closure, and fuel loadings. One or more of the following activities may have caused this departure: fire suppression, timber harvesting, livestock grazing, introduction and establishment of exotic plant species, introduced insects and disease, or other management activities."

All ecosystems can be classified into one of three FRCC (Table 1.2), based on the relative degree of departure from the central tendency of its historical fire regime, given the historical range of variability for that regime (Hann and Strohm 2003).

Table 1.2 Fire Regime Condition Class categories. Used to describe the relative degree of departure of an ecosystem from the central tendency of its historical fire regime (Hann and Strohm 2003).

Fire Regime Condition Class	Description	Potential Risks
Condition Class 1	Within the natural (historical) range of variability for vegetation characteristics, fuel composition, fire frequency, severity and pattern, and other associated disturbances	Fire behavior, effects, and other associated disturbances are similar to those that occurred prior to fire exclusion and other types of management that do not mimic the natural fire regime and associated vegetation and fuel characteristics. Composition and structure of vegetation and fuels are similar to the natural (historical) regime. Risk of losing key ecosystem components (e.g. native species, large trees, and soil) is low.
Condition Class 2	Moderate departure from the natural (historical) regime of vegetation characteristics, fuel composition, fire frequency, severity and pattern, and other associated disturbances	Fire behavior, effects, and other associated disturbances are moderately departed (more severe or less severe). Composition and structure of vegetation and fuel are moderately altered. Risk of losing key ecosystem components is moderate.
Condition Class 3	High departure from the natural (historical) regime of vegetation characteristics, fuel composition, fire frequency, severity and pattern, and other associated disturbances	Fire behavior, effects, and other associated disturbances are highly departed (more severe or less severe). Composition and structure of vegetation and fuel are highly altered. Risk of losing key ecosystem components is high.

1.7 Whitebark pine (*Pinus albicaulis* Engelm.)

1.7.1 Biogeography

Whitebark pine is a five-needle conifer found in many high-elevation forests of western North America (Arno and Hoff 1990). The species is one of five stone pines (section *Strobus*, subsection *Cembrae*) found among the mountainous regions of the northern hemisphere, and the only stone pine found in the western hemisphere (Jorgensen and Hamrick 1997). Genetic research shows that whitebark pine likely diverged from the Eurasian stone pines between 0.6 and 1.3 million years ago (Krutovskii *et al.* 1990). The origin of the species and the timing of its arrival on the North American continent are still debated (Lanner 1996, McCaughey and Schmidt 2001).

As is characteristic of other stone pines, whitebark pine seeds are large and wingless (Lanner 1990), and the species depends on a mutualistic relationship with the Clark's nutcracker (*Nucifraga columbiana* Wilson) for regeneration and dispersal (Tomback 1982). This relationship enabled relatively rapid adjustments in the range of whitebark pine during the periods of glacial advance and retreat throughout the Pleistocene (Tomback 2001), with macro- and micro-fossil evidence indicating the continuous presence of whitebark pine in the Yellowstone region for the past 100,000 years (Baker 1990). Following the retreat of the Pleistocene glaciers, whitebark pine expanded northward rapidly until *ca.* 10,000 to 8,000 years ago when warming conditions restricted it to high-elevation sites (MacDonald *et al.* 1989). Whitebark pine distribution stabilized *ca.* 4,000 years ago during a relatively cool period, and has changed little since (McCaughey and Schmidt 2001).

The modern range of whitebark pine extends from the northern Canadian Rockies (55° N) to the southern Sierra Nevada (37° N) and from the Coast Range of the Pacific Northwest (128° W) to the eastern Rocky Mountains of Montana and Wyoming (107° W) (Figure 1.2; Little 1971). Several disjunct populations exist in eastern Montana and northeastern Nevada (Weaver and Dale 1974). The elevational distribution of whitebark pine relates to latitude, with upper bounds ranging from 900 meters at the northern limits of the species in British Columbia to over 3,600 meters in the Sierra Nevada (Arno and Hoff 1990). The lower elevational limit of whitebark pine varies throughout its range and is determined by competition with other tree species (Weaver 2001).

Whitebark pine is associated with several community types determined by site conditions. On high-elevation sites that experience extreme temperatures, wind scouring, and drought, whitebark pine is commonly the only tree species able to withstand the environment and is considered a climax species (Pfister *et al.* 1977). These stands often develop into open forestland at the treeline and krummholz forests above treeline (Weaver and Dale 1974). On sites capable of supporting competing species in a limited number, whitebark pine can be found as a co-climax species growing alongside subalpine fir, Engelmann spruce, and lodgepole pine (Weaver and Dale 1974).

As a seral species in the upper and lower subalpine habitat types (Pfister and Arno 1980), the partially shade-tolerant whitebark pine (Arno and Hoff 1990) depends on disturbances such as fire and windthrow to create forest openings suitable for regeneration. Clark's nutcrackers act as the main dispersal agent of whitebark pine by preferentially caching seeds in forest openings (Tomback 1982), giving whitebark pine seedlings a distinct advantage in these harsh environments over less hardy, wind-

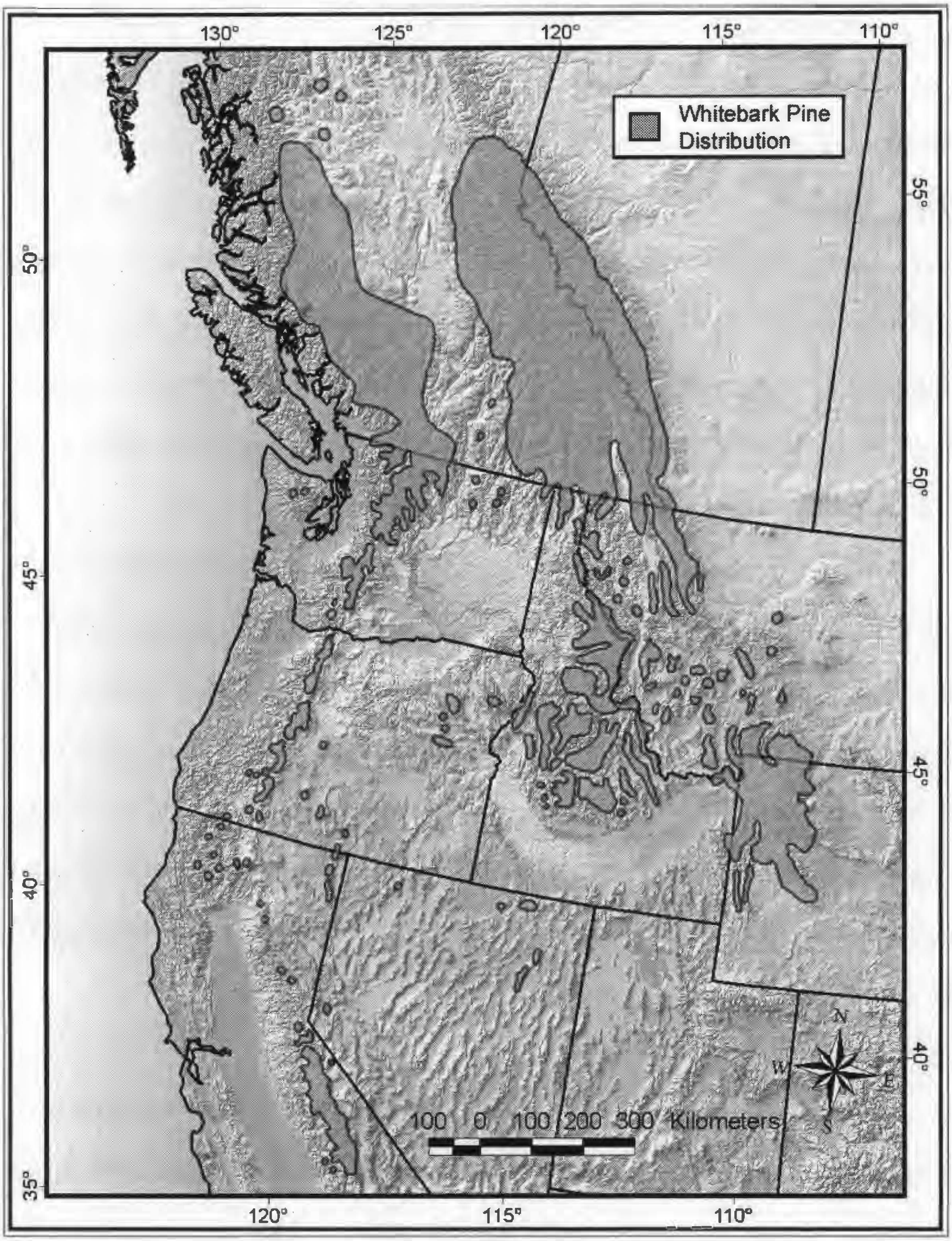


Figure 1.2 Distribution of whitebark pine (*Pinus albicaulis* Engelm.). Distribution data are from Little (1971).

dispersed tree species (Tomback *et al.* 1990, Tomback 1994b). The 1,000+ yr lifespan of whitebark pine (Perkins and Swetnam 1996, Luckman and Youngblut 1999) often maintains whitebark pine as a major seral species in the upper subalpine zone or a minor seral species in the lower subalpine zone long after a disturbance (Arno and Hoff 1990).

1.7.2 Fire Ecology

Whitebark pine is a fire-dependent species (Morgan *et al.* 1994b). On sites where whitebark pine is a seral species, fire plays a major role in creating the forest openings that are required for whitebark pine regeneration (Morgan and Bunting 1990). On drier sites, surface fires can slow succession by removing competing species and undergrowth, creating open stands dominated by whitebark pine (Morgan and Bunting 1990, Arno 2001). In the absence of fire, whitebark pine forests shift to later successional, shade tolerant species (Keane *et al.* 1990a), with whitebark pine losing canopy dominance after 150–400 years without disturbance, depending on site factors (Keane 2001b). Fire suppression may have altered the natural fire regime of forests dominated by whitebark pine, and is associated with the encroachment of fire-intolerant species throughout the range of whitebark pine (Arno 2001, Keane 2001a).

1.7.3 Significance of the Species

Whitebark pine was historically regarded as a species of negligible value in terms of lumber due to its slow growth, often twisted and stunted form, and the general inaccessibility of whitebark pine forests (Losensky 1990). More recently, it has become highly regarded for its aesthetic value on the landscape and its role as shelter and a resource base for wildlife (Tomback *et al.* 2001a). Ecologically, whitebark pine plays important roles in watershed dynamics and is regarded as a keystone species critical to the stability of subalpine ecosystems. The ability of whitebark pine to act as a pioneer on recently disturbed sites greatly reduces erosion, and by facilitating the recovery of other plant communities, maintains the integrity of the headwaters of many important watersheds (Arno and Hoff 1990) while increasing the biodiversity of subalpine communities (Weaver 2001). Whitebark pine-dominated forests at treeline and the krummholz forests above catch and retain snow (Arno and Hammerly 1984), and provide a major source of moisture for lower-elevation ecosystems in the form of meltoff during the late spring and summer months (Farnes 1990).

Whitebark pine is the foundation of an ecosystem involving Clark's nutcrackers, red squirrels (*Tamiasciurus hudsonicus* Trouessart), grizzly bears (*Ursus arctos* L.), and black bears (*Ursus americanus* Pallas) (Mattson and Jonkel 1990, Tomback 1994a, Mattson and Reinhart 1997). Whitebark pine seeds are significantly larger than the seeds of other high-mountain conifers of North America (Lanner 1996), and contain high levels of fats and nutrients, making them a valuable food source for wildlife (Arno 1986). The cones of whitebark pine that hold these seeds do not open on their own, and remain on the tree until the seeds are picked out by Clark's nutcrackers or when squirrels cut the entire cone from the tree (Lanner 1996).

Red squirrels store the cones in middens that are up to several square meters in area and are scattered throughout stands of whitebark pine (Mattson *et al.* 2001). The nutritious whitebark pine seeds that fill these middens provide a readily available food source and are frequently excavated by grizzly bears and black bears as they prepare for hibernation (Mattson *et al.* 1991, Mattson and Reinhart 1997). Nutcrackers, after picking anywhere from 15 to > 90 seeds, travel up to several kilometers before selecting a site to create a cache (Tomback 1982, 1994b). Nutcrackers preferentially cache seeds in forest openings, between 1–3 cm under the surface of the soil (Tomback 2001). These site conditions are ideal for the successful establishment of whitebark pine, and the seeds not recovered by birds or eaten by rodents are in turn the main source of regeneration for whitebark pine throughout its range (Lanner 1982, Tomback *et al.* 1990).

1.7.4 Status of the Species

The whitebark pine ecosystem has undergone extraordinary declines over the last 80 years. Mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreaks in the 1930s and 1980s caused extensive mortality of whitebark pine in the central and northern Rocky Mountains (Bartos and Gibson 1990, Kipfmueller *et al.* 2002). The outbreaks commonly began in mature lodgepole pine forests (Stuart 1984), and as beetle population increased, spread upslope into neighboring stands of whitebark pine (Bartos and Gibson 1990). Mortality is caused by girdling from the construction of egg galleries and the feeding of larvae on the inner phloem of infected trees (Cole and Amman 1980). The beetle also introduces the secondary pathogen blue stain fungus (*Ophiostoma* spp.) that reduces the transport of water and nutrients within a tree, which places additional stress on infected individuals (Solheim 1995). The beetles tend to selectively attack larger trees that have thicker phloem to sustain beetle and larvae populations (Amman 1972). This leads to smaller trees often surviving outbreaks and acting as seed sources for the recovery of the forest (Cole and Amman 1980). Bark beetles have been a disturbance agent in whitebark pine forests well into the past, as indicated by the J-shaped galleries engraved on sun-bleached snags of whitebark pine throughout the subalpine regions of western North America (Arno and Hammerly 1984). Research suggests, however, that the impacts of beetle outbreaks may be changing in response to shifts in forest structure and climate change, allowing beetles to affect larger areas, extend to higher elevations, and to potentially produce multiple generations per year (Logan *et al.* 1995, Logan and Powell 2001).

The introduction of the exotic white pine blister rust (*Cronartium ribicola* (A. Dietr.) J.C. Fisch.) in Vancouver, British Columbia, in the early 1900s brought an additional disturbance agent into whitebark pine forests (Hoff and Hagle 1990). Blister rust is a heteroecious fungus that alternates between five-needle pines and *Ribes* species (van der Plank 1963). The rust infects a tree through the needles, initially forming cankers on the outer branches, but eventually moving to the main trunk where it can girdle and kill the tree (Hoff and Hagle 1990). Over the past 90 years, blister rust has spread throughout the range of five needle pines along the west coast and Rocky Mountains (McDonald and Hoff 2001).

Blister rust first appeared on whitebark pine in the coastal range of British Columbia in 1926 and spread to northern Idaho by 1938 (Childs *et al.* 1938). Since then, the range of whitebark pine affected by white pine blister rust has expanded and infection levels have intensified (McDonald and Hoff 2001). Whitebark pine is highly susceptible to the rust, with fewer than 1 in 10,000 trees showing resistance (Kendall 1994), and rust-caused mortality is extensive throughout the northern portions of its range (Hoff 1992). In the Pacific Northwest, 40–100% of the whitebark pine are dead in most forest stands, with 50–100% of the live trees showing signs of infection (Campbell and Antos 2000, Goheen 2002). In the Columbia River Basin, 98% of the whitebark pine communities have disappeared since the turn of the century (Keane 1995). A project to reconstruct landscape patterns of whitebark pine in western Montana found that 14% of the stands were dominated by whitebark pine around 1900, but not one of these stands was dominated by whitebark pine in the 1990s (Keane and Arno 1993). Of the remaining live whitebark pine trees in these stands, 80% were infected with white pine blister rust, and the cone-bearing crowns of over one-third of them were dead. Whitebark pine populations have coexisted with mountain pine beetle for millennia, and if affected by blister rust alone would likely develop resistance over a relatively short evolutionary period. Faced with the synergistic impacts of both disturbances simultaneously, with potential complications from fire suppression (Arno 2001), whitebark pine is at serious risk of local and regional extinctions within the next 25 years (Tomback *et al.* 2001a).

1.7.5 Management of Whitebark Pine

The plight of whitebark pine and its significance on the landscape have inspired several management initiatives focused on preserving the species and the community it supports (Tomback *et al.* 2001b). Ongoing projects include the breeding of rust-resistant whitebark pine (Burr *et al.* 2001), the development of silvicultural techniques to slow blister rust infection (Hoff *et al.* 2001), and the development of mountain pine beetle protection programs (Vandygriff *et al.* 2000). Efforts have also focused on developing a broad prescribed fire program to enable land managers to apply fire as a tool to achieve management objectives at the local and landscape scale (Keane 2001a).

1.7.6 Research Needs

The status of our knowledge on whitebark pine is improving, but several important knowledge gaps remain. Two important patterns emerge from the existing fire history data for whitebark pine. First, while fire suppression is widely cited as a major factor in advancing succession throughout whitebark pine forests, the evidence of such an effect is ambiguous at best in several fire history studies. Second, fire history studies that used crossdating, the main principle behind the science of dendrochronology (Fritts 1976), reported more frequent fire activity than those studies that did not implement crossdating. Although the studies varied widely in area, both Morgan and Bunting (1990) and Kipfmueller (2003) reported fire-free intervals ranging well below the values reported in other studies. These two patterns indicate that, in some stands of whitebark pine, fire occurred more frequently than the current paradigm suggests, and at the same time fire suppression may not be solely responsible for the structural and compositional changes now occurring in whitebark pine forests.

The uncertainties surrounding the role and occurrence of fire in whitebark pine forests may prove to be significant as prescribed fire programs advance with incomplete knowledge of the fire regimes of the species. The broad geographic and environmental distribution of whitebark pine must create regional variations in historical fire regimes, and a need exists for precise and accurate descriptions of whitebark pine fire regimes to develop ecologically sound management practices. Additional uncertainty is introduced by the relatively unknown relationships between fire activity in the mixed-severity fire regimes of whitebark pine forests and inter-annual to multi-decadal shifts in climate (but see Kipfmueller 2003). Research is needed to describe the fire regimes and fire-climate relationships in whitebark pine forests throughout the range of the species to enable land managers to develop prescriptions for the use of fire in managing whitebark pine forests within the historical context of the species.

1.8 The Science of Dendrochronology

Dendrochronology is a science based on the annual formation of rings in woody plant species and the analysis of information they hold (Douglass 1920). Seven principles provide the scientific foundation for dendrochronology (Fritts 1976), and while all of these principles are crucial to dendrochronological research, one is of particular importance to my research, the principle of crossdating. Crossdating is accomplished by matching patterns of wide and narrow rings among the radii of one tree, and from that tree to other trees in the same stand, forest, or region (Fritts 1976). The variability in tree-ring widths required to crossdate is caused by climate-related annual fluctuations in the factors limiting to plant growth, such as moisture availability in the Southwest (Fritts 1974) or temperature in high-elevation ecosystems (LaMarche and Stockton 1974). First applied in archeological research in the American Southwest (Douglass 1921), crossdating is now used in tree-ring studies around the world to ensure the precise and accurate dating of individual growth rings within a tree. Crossdating between living and dead material also enables dendrochronologists to construct tree-ring chronologies beyond the lifespan of individual trees, with some chronologies extending up to several thousand years in length (Ferguson 1969, Pilcher *et al.* 1984, Feng and Epstein 1994).

The accuracy, resolution, and temporal scale attainable by crossdating are essential for environmental research that examines processes that vary at inter-annual to seasonal scales, such as fire-climate relationships (Brown and Swetnam 1994, Grau and Veblen 2000, Heyerdahl *et al.* 2002), and those that vary on decadal to millennial scales, such as extended periods of fire activity and global climate (Briffa *et al.* 1990, Campbell and McAndrews 1993, Grissino-Mayer 1995, Grissino-Mayer and Swetnam 2000, Westerling and Swetnam 2004). Additionally, crossdating allows the investigation of processes that lead to the demise of trees, such as fire (Ehle and Baker 2003), beetle outbreaks (Veblen *et al.* 1991), and pathogens (*e.g.* blister rust) (Daniels *et al.* in press). The need to accurately describe the historical disturbance regimes and the fire-climate relationships of whitebark pine forests can only be addressed through crossdated, dendrochronological research.

Chapter Two

2. Literature Review of Whitebark Pine

2.1 Fire and Whitebark Pine

Several studies have examined the fire history of whitebark pine forests, and although a wide range in the frequency and severity of fire events has been reported for sites across the central and northern Rocky Mountains, the majority of these can be classified as Fire Regime Type III or Type IV (Table 2.1).

2.1.1 Fire and Whitebark Pine in the Northern Rockies

Arno (1976) developed tree ring-based fire histories for three study areas in the Bitterroot National Forest in west central Montana. The study areas covered a wide range of elevations and forest types, and Arno used non-crossdated fire-scarred samples collected from living trees and age-structure data to describe the frequency and severity of fires in the Bitterroot Mountains before the era of fire suppression. Data were collected from five upper-subalpine stands that included the *Abies lasiocarpa/Luzula hitchcockii* habitat type, the *Abies lasiocarpa-Pinus albicaulis/Vaccinium scoparium* habitat type, and the *Pinus albicaulis-Abies lasiocarpa* habitat type from Pfister *et al.* (1977); however, the numbers of each habitat type sampled were not reported. Fire scarred samples were collected from thirty-one trees in the five upper-subalpine stands, and MFI from AD 1600–1910 of 41 years, 30 years, and 33 years were reported for the three habitat types, respectively. Arno mentioned that numerous whitebark pine trees in the study area contained multiple fire scars. Age structure data were relatively mixed-age, but still indicated several likely post-fire cohorts. Arno emphasized the spatial variability in

Table 2.1 Fire intervals reported for whitebark pine forests and the methods used for the reconstruction. Fire regime type is based on the Fire Regime Condition Class guidebook (Hann *et al.* 2004). Adapted from Arno 2001. See Table 1.1 for definitions of fire regime types.

Fire-free interval (yrs)	Fire regime type	Methods	Geographic area	Source
13–46	Type I	Fire-scar and age-structure analyses	Russell Peak, Wyoming	Morgan and Bunting 1990
20–173	Type III	Fire-scar and age-structure analyses	Selway-Bitterroot Wilderness, Montana/Idaho	Kipfmueller 2003
57–94	Type III	Fire-scar and age-structure analyses	Bitterroot Valley, West Montana	Arno and Petersen 1983*
51–119	Type III	Fire-scar and age-structure analyses	Big Hole Basin, SW Montana	Murray *et al.* 1998*
55–304	Type IV	Fire-scar and age-structure analyses	Bob Marshall Wilderness, NW Montana	Keane *et al.* 1994*
80–300	Type IV	Age-structure analysis	Yellowstone National Park, Wyoming	Mattson and Reinhardt 1990*
66–>350	Type IV	Fire-scar and age-structure analyses	Yellowstone National Park, Wyoming	Barrett 1994*
300–400	Type V	Fire-scar and age-structure analyses	Yellowstone National Park, Wyoming	Romme 1982*

* indicates crossdating was not used and fire intervals are estimates.

the fire regimes of the study areas, and suggested mixed-severity fires played a more important role in the Northern Rockies than was recognized at the time. The effects of fire suppression were evident in the fire histories of lower elevation forests. Visual comparisons between fire activity and instrumental meteorological data showed a correlation between drought conditions and years of widespread fires. The potential impact of Native Americans on these fire regimes was tentatively broached. Arno concluded that fire has and will continue to be a major ecological component of forests in the Bitterroot National Forest and suggested several management techniques for reducing fuel loads and maintaining forest health.

Arno and Petersen (1983) reexamined the fire history data collected by Arno (1976) to illustrate the effects of different spatial scales on the reported fire frequencies. The original data that described MFI of 30–41 years were reanalyzed by Arno and Petersen and resulted in MFI of 106 years for single trees, 94 years for tree clusters of about 0.4 hectares, 61 years for small stands of 20–40 hectares, and 57 years for large stands of 80–320 hectares. Arno and Petersen used these results to emphasize the importance of using the appropriate scale when reporting results of fire history research.

Keane *et al.* (1994) conducted a landscape assessment of the effects of blister rust and fire suppression on whitebark pine forests in the Bob Marshall Wilderness Complex, Montana. The study combined satellite imagery with field reconnaissance and plot data to evaluate the disturbance history and recent shifts in whitebark pine populations. The fire history was determined using non-crossdated, fire-scarred samples and age-structure data. A MFI of 144 years was found for the entire study area, with individual site MFIs ranging from 55–304 years. Blister rust infections were identified on 83% of the inventoried whitebark pine, and high mortality rates due to blister rust were reported for 22% of the landscape containing whitebark pine. The study documented little to no whitebark pine regeneration. Subalpine fir dominated 14% of the total subalpine landscape, approximately 7% more than its historical composition. Regeneration throughout the study area was almost exclusively fir. Due to fire suppression and the blister rust-induced mortality of cone-producing whitebark pine, succession was accelerating from whitebark pine to subalpine fir throughout the Bob Marshall Wilderness Complex.

Murray *et al.* (1998) reconstructed the fire history of subalpine forests of the relatively small, biogeographically isolated West Big Hole mountain range to test the hypothesis that their study area would be more affected by fire suppression than larger mountain ranges. The study area straddles the Continental Divide along the southwestern border of Montana and Idaho and includes six watersheds, three to the east and three to the west of the divide. Fire-scar and age-structure data were collected in plots centered on a transect from the base to the head of each watershed. Crossdating was not used, and fire dates were estimated to be accurate within 10 years. Maps for large fires were delimited from stand structure, but the indistinct boundaries of small surface fires restricted the effectiveness of mapping all fires. Fire history data extended back to AD 1754 for all sites. West side historical fire regimes were classified as mixed-severity and smaller relative to the more widespread, non-stand-replacing fires that characterized east side fire regimes. A dramatic shift toward smaller fires occurred on both sides of the divide in 1874, with west side fires shifting toward non-stand replacing and east side fires becoming more variable and of mixed-severity. The authors suggested that fire suppression was not likely the cause of these landscape level changes, but that the widespread introduction of cattle and sheep may have reduced fuels sufficiently to affect the fire regimes of the area. Compared to larger mountain ranges, fires in the West Big Hole area were generally smaller and more frequent, perhaps due to a concentration of lightning strikes and the proximity of the range to steppe communities.

2.1.2 Fire and Whitebark Pine in the Greater Yellowstone Ecosystem

Romme (1982) examined the diversity and evenness of species throughout a 7,300-ha subalpine watershed in Yellowstone National Park in relation to its fire history. Whitebark pine made up a small component of the forest, but commonly displayed scars as evidence of past surface fires. Stand boundaries within the watershed were delimited using aerial photographs, and age-structure and fire-scar data were gathered for each stand. Fifteen fires were recorded in the watershed since AD 1600, seven of which burned over four hectares and were considered ecologically significant. The MFI of individual stands within the study area ranged from 300–400 years; however, if fires that only burned over small areas were included, the MFI would be 32–183 years. Romme suggested that the landscape is a non-steady-state system characterized by long-term, cyclic changes in diversity and composition that are driven by the development of a landscape scale fuel complex, and experiences a different fire regime than that of the Northern Rockies. It is unlikely that fire suppression affected the landscape processes of this area.

Mattson and Reinhardt (1990) also examined the fire history of subalpine forests in the Greater Yellowstone Ecosystem. To evaluate the status of whitebark pine on the

Mount Washburn Massif, stands were first delineated from aerial photographs, then the age-structure, stand composition, and site characteristics were documented in 5–26 variable radius forest inventory plots spaced evenly throughout each stand. The fire history was derived from stand age-structure and indicated a MFI of 80–300 years. The distribution of whitebark pine was closely related to a site warmth index, as opposed to subalpine fir and Engelmann spruce that were more sensitive to wind exposure. Whitebark pine and lodgepole pine were highly competitive where they coexisted, gained early dominance of most stands, and eventually lost stand dominance to shade tolerant fir and spruce. Extremely cold and exposed sites were dominated by whitebark pine.

Barrett (1994a) investigated the fire history of three forest types on the Absaroka Mountains in the northeast corner of Yellowstone National Park. Fire-scar and age-structure data were gathered in low-elevation Douglas-fir forests, mid-elevation lodgepole pine forests, and high-elevation whitebark pine forests, and composite fire chronologies were constructed for all sites. The MFI reported for the Douglas-fir forest type was approximately 30 years, increased with elevation to about 200 years in lodgepole pine forests, and was > 350 years in most whitebark pine forests. Barrett noted, however, that several whitebark pines contained multiple fire scars, and that tree age was highly variable in whitebark pine stands, indicating a mixed-severity fire regime. Four stands of whitebark pine at treeline experienced MFIs of 66–204 years, and indicated a very patchy fire regime. Barrett concluded that fire suppression, while affecting low-elevation fire regimes, has not influenced high-elevation ecosystems.

2.1.3 Crossdated Fire History Research

While these studies provided valuable information on the fire ecology of whitebark pine, a distinct pattern emerged between the reported MFI and the methods applied for each study. While non-crossdated fire histories conducted in stands of whitebark pine described relatively longer MFIs, two studies that developed crossdated fire histories for whitebark pine found lower MFIs. This suggests that fire was either more common at the sites of the crossdated studies, indicating spatial variability in the fire regimes of whitebark pine, or that non-crossdated fire history methods are not precise enough to accurately describe mixed-severity fire regimes.

Morgan and Bunting (1990) found MFIs of 13--46 years for whitebark pine forests on Russell Peak, Wyoming, based on 14 crossdated, fire-scarred samples. Coupled with age-structure data, the fire history illustrated a period of frequent fire activity from AD 1700–1850 that aligned with the establishment of a large cohort of whitebark pine. Fire activity began to decrease after 1850, and the last fire occurred in 1894, after which the abundance of subalpine fir continually increased until the time of the study. Morgan and Bunting hypothesized that whitebark pine forests burn often when young with abundant fine fuels under an open canopy, go through a period of relatively infrequent fires as the canopy closes, and then burn in old age as fuel loads develop due to senescence, encroachment of fire intolerant species, and insect-caused mortality.

Kipfmueller (2003) conducted the only other crossdated fire history of subalpine forests that contained whitebark pine, and examined the fire-climate relationships in four watersheds in the Selway Bitterroot Wilderness Area, on the border between Montana and Idaho. Fire dates were obtained from 96 crossdated fire-scarred samples collected from lodgepole pine, whitebark pine, and Douglas fir, and fire extent was estimated using stand boundaries coupled with stand age-structure data. The fire history data illustrated mixed-severity fire regimes in all four watersheds, with numerous small fires and seventeen widespread fire years identified over the past 800 years. MFI values ranged from 20–170 years at the watershed scale to 139–341 years for individual stands. A reduction in fire activity occurred across all four sites *ca.* AD 1935, and was likely the result of fire suppression. Superposed epoch analyses (SEA) were used to assess the influence of climate prior to the fire events, and revealed a significant relationship between two consecutive dry years and widespread fire events. The relationship between El Niño-Southern Oscillation (ENSO) and fire activity was less distinct, and may have been masked by the occurrence of widespread fires related to non-ENSO conditions. Kipfmueller compared the fire history data to spatial patterns of drought across the United States, and suggested the existence of a relationship between ENSO and widespread fires, as well as the potential presence of other synoptic regimes related to fire activity.

2.2 Dendrochronology of Whitebark Pine

2.2.1 Dendroglaciology

The longevity and environmental tolerance of whitebark pine make it a strong candidate for several lines of dendrochronological research, but relatively little work has taken advantage of this. The dendrochronological potential of whitebark pine gained recognition when Luckman *et al.* (1984) documented several whitebark pines with ages in excess of 700 years in the Canadian Rockies. Luckman followed his preliminary assessment with several projects that used evidence obtained from subalpine tree species to describe periods of glacial advance in the Canadian Rockies (Luckman 1994, 1995, 2000). Two dendrochronological methods were employed in these studies. First, the establishment dates of tree stands on moraines were used to estimate the age of the surface, from which the date of glacial advance and retreat could be inferred. Second, remnant and sub-fossil trees and stumps in glacier fore-fields were crossdated to construct death-date charts, thereby giving an estimate of both the timing and rate of glacial advance. These data were synthesized, compared to reconstructions of temperature and precipitation, and provided evidence of region-wide glacial advances during AD 1200–1300 and 1400–1600, and abundant evidence of regionally synchronous advances in the early 1700s and early 1800s (Luckman and Villalba 2001). Summer temperature was the primary driver of these fluctuations, but precipitation also played a strong role in some areas. Luckman also directed research on extending chronologies throughout the Canadian Rockies, and eventually found two whitebark pine trees that were at least 1,013 and 1,049 years of age (Luckman and Youngblut 1999).

2.2.2 Dendroecology

Dunwiddie (1977) investigated tree invasion of a subalpine meadow in the Wind River Mountains of western Montana, and was the first dendroecologist to study whitebark pine. The study was conducted by cutting 347 trees and saplings of whitebark pine, lodgepole pine, and Engelmann spruce in a 13×8 m plot that extended along a clear edge of mature forest, and determining the age and growth trends within these samples. Tree invasion was slow and relatively steady from AD 1889 to 1940, after which a significant acceleration in tree establishment rates occurred until a sudden cessation of establishment after 1962. Growth rates of trees within the meadow were higher than growth rates of trees in the forests, indicating that factors other than climate may restrict tree regeneration within the meadow. When compared to the grazing records, meadow invasion increased slightly when the area was heavily grazed, and the shift to rapid invasion occurred when grazing pressure was reduced, but still present on the landscape. Cattle were removed from the landscape in the early 1960s. Dunwiddie hypothesized that heavy grazing during the early 1900s decreased competition from meadow vegetation, but also led to increased seedling mortality. Fewer cattle in the area during the 1940s–1950s reduced competition from meadow vegetation but did not lead to high seedling mortality and instead facilitated the establishment of young trees and subsequent encroachment into the meadow. With the complete removal of cattle from the area, seedlings could no longer out-compete the meadow grasses and shrubs, and the meadow invasion ceased.

Peterson *et al.* (1990) conducted a dendroecological assessment of long-term growth trends in the subalpine forests of the central Sierra Nevada. They focused on high-elevation lodgepole pine and whitebark pine because these trees, growing at their ecological limit, were likely sensitive to small changes in the environmental factors that dictate their growth. The study examined changes in basal area of each species, calculated from ring widths, for the late AD 1700s up to the 1980s. Principle components analyses found climate explained between 22–40% of the variance in basal area for whitebark pine, depending on age class. Climate-response analyses found tree growth was significantly affected by spring temperature and annual precipitation. A trend of increasing basal area at an increasing rate and unrelated to climate was found in the chronologies of whitebark pine, similar to patterns of increased growth found in Great Basin bristlecone pine (*Pinus longaeva* D.K. Bailey) in the nearby White Mountains (Graybill and Idso 1993), suggesting the possible effects of atmospheric CO_2 fertilization on growth in upper-elevation trees.

Garfin (1998) used whitebark pine tree-ring data to examine the relationship of anomalous weather conditions and tree growth in the Sierra Nevada of California. He found winters that preceded years of high growth in whitebark pine were warm and wet, caused by anomalously low pressure in the northern Pacific Ocean, anomalously high pressure over northwestern Canada, and anomalously low pressure across the southern United States, all of which leads to a southwesterly flow of warm maritime air into California. Extreme low growth in whitebark pines was associated with a shift in the Westerlies north of their mean position and enhanced ridging in the northeast Pacific, which advects cool dry air into the Sierra Nevada. Garfin concluded that synoptic dendroclimatological studies such as his may provide insight about atmospheric circulation that will increase understanding of past climate variability derived from tree-ring studies.

Murray *et al.* (2000) examined the historical trends and successional status of whitebark pine over 240 years in six subalpine forests of the West Big Hole mountain range, where the fire history had previously been examined (Murray *et al.* 1998). Size-class and species composition data were collected along a transect from the base to the head of each watershed, and species dominance was calculated at 20-yr intervals using ring-width-derived basal areas for distinct size classes. Mid-seral forests dominated all six watersheds until 1950, when late seral stands became more dominant on the landscape. Overall, an 85% increase in basal area was found among all species since the 1870s, while whitebark pine dominance had decreased steadily over the same period. The authors suggested fire suppression and grazing may be the cause of advancing succession, and proposed active management may be required to maintain the historical structure and composition of this landscape.

2.2.3 Dendroclimatology

Perkins and Swetnam (1996) evaluated the potential of whitebark pine in central Idaho for reconstructing long-term climate and ecological processes. They constructed tree-ring chronologies from four sites in central Idaho that all extended at least 700 years, and included the oldest known living whitebark pine at the time (> 1270 years old). Crossdating with other tree-ring chronologies from the region was problematic due to relatively low inter-annual ring-width variability (chronology mean sensitivity ranged from 0.12–0.17), but the investigators succeeded by using several distinct marker rings. Correlation coefficients within and between sites ranged from 0.5–0.6, indicating strong statistical crossdating for high-elevation trees. Sites with similar aspects crossdated more strongly than sites in closer proximity. The peak mortality caused by a mountain pine beetle outbreak was determined by the outer ring of sampled snags to be 1930, and was synchronous at all four sites. Climate-response analyses revealed a similar signal among the four sites, with a positive correlation between ring-width and winter/spring precipitation, and a negative correlation between ring-width and May and July temperatures, indicating tree growth at these sites is both moisture and temperature limited. The study concluded that whitebark pine has excellent potential for dendroclimatological and dendroecological research.

Kipfmueller (2003) used whitebark pine to reconstruct climate and examine the fire-climate relationships of the Selway-Bitterroot Wilderness Area on the border between Idaho and Montana. He first examined the climate-tree growth relationships of whitebark pine and alpine larch within the study area, and then used these findings to reconstruct summer temperatures over the past 748 years. These analyses were conducted on six tree-ring chronologies, with individual chronologies of whitebark pine extending as far back as AD 721. Whitebark pine growth was significantly related to warm July temperatures, but a potential climate threshold was identified in the mid 1900s, when the response of whitebark pine to warmer summer temperatures diminished and was superseded by a negative relationship to spring temperatures. Kipfmueller hypothesized that this shift may be related to changing snow pack conditions and resulting moisture stress, and is potentially an expression of shifting ocean-atmospheric linkages. Despite the shifting climate-tree growth relationship, the climate reconstruction based on two alpine larch chronologies and one whitebark pine chronology explained 36% of the variance in summer temperature over the calibration period. Several distinct warm and cool periods were evident over the reconstruction, but no evidence of the Medieval Warm Period and limited evidence of cooling during the Little Ice Age were found.

Chapter Three

3. Study Site Descriptions

3.1 General Setting of the Lolo National Forest, Western Montana

The Lolo National Forest was established as the Lolo Forest Reserve in 1906, and has since grown to over 810,000 hectares of mountainous forestland in western Montana (Figure 3.1; USFS 1998). The forest is divided into five ranger districts: the central Missoula and Ninemile Ranger Districts, the Plains/Thompson Falls Ranger District in the Northwest area of the forest, the Seeley Lake Ranger District in the eastern portion of the forest, and the Superior Ranger District just to the west of Ninemile. The forest headquarters are based in Missoula, and over 300 personnel are employed full time for day-to-day operations. The entire forest is on the western slope of the Continental Divide, which runs along the eastern edge of the forest.

3.1.1 Climate

The Lolo National Forest is affected by both North Pacific maritime and continental air masses, creating a diverse climate over the region (Arno and Hammerly 1984). The forest lies within the National Oceanic and Atmospheric Administration's Montana Climate Division 1 (Western). Average annual temperature is 6° C, with summer and winter temperatures averaging 13° C and –2° C, respectively. Annual precipitation averages 480 mm, with the majority falling over the winter and late spring months (NCDC 2005). A rain shadow from the Bitterroot Range creates a gradient of decreasing moisture from west to east, with some peaks on the Idaho-Montana border receiving

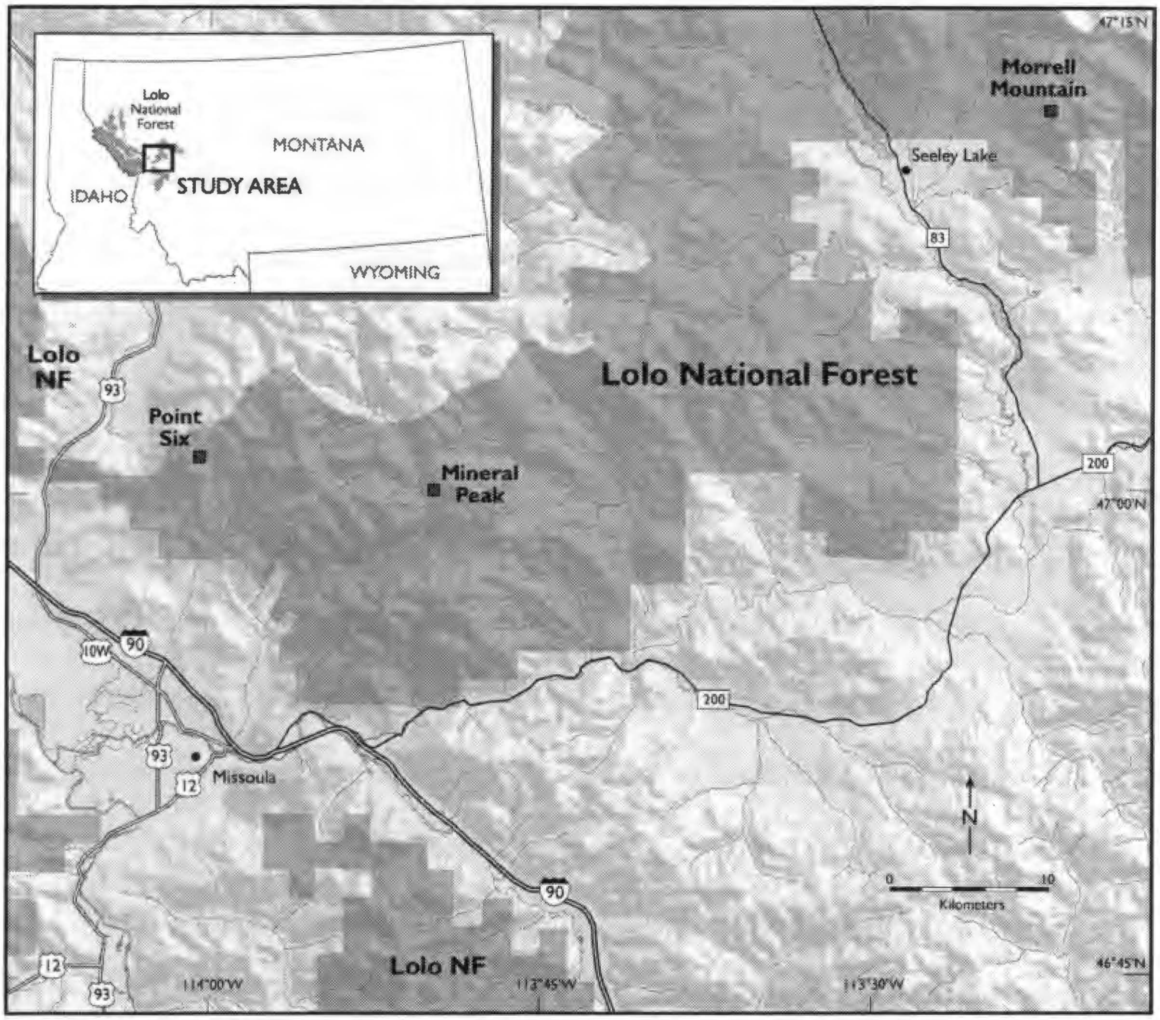


Figure 3.1 Locations of the three study sites in the Lolo National Forest, Western Montana.

nearly 760 mm of precipitation a year, compared to 250–430 mm for much of the eastern portion of the national forest (Owenby *et al.* 1991).

Ocean-atmospheric teleconnections that source from the Pacific Ocean affect the region in several ways. The ENSO phenomenon occurs about every 3–7 years, and is caused by a shift in the pressure systems of the tropical Pacific. This shift weakens the Peru high, diminishing the east-west pressure gradient that drives the tradewinds, and in turn reduces the Peru current and coldwater upwelling along the western coast of South America (Allan 2000). The development of El Niño conditions, the intrusion of a large body of warm water into the ocean along the equator adjacent to South America, modifies seasonal weather across western North America (Swetnam and Betancourt 1990, D'Arrigo and Jacoby 1991, Haston and Michaelsen 1994, Dettinger *et al.* 2001, Kitzberger *et al.* 2001, Pohl *et al.* 2003). In the Northern Rockies, El Niño events bring relatively drier summers and warmer winters (Allan 2000). Widespread fire years may be linked to ENSO activity (Kipfmueller 2003), but this relationship is somewhat ambiguous as several factors affect fire behavior in the region (Bessie and Johnson 1995).

ENSO activity is directly related to the Pacific/North American pattern (PNA), which is defined by the degree to which circulation patterns over North America are zonal or meridional (Keables 1992, Bell and Janowiak 1995). The PNA shifts on inter-seasonal, inter-annual, and inter-decadal scales. The positive phase is indicated by a deepening of the Aleutian low that forms ridges over Canada, leading to strong meridional flow and enhanced anticyclonic circulation over western North America (Leathers *et al.* 1991). Periods of positive phase PNA lead to the deflection of Pacific storms to the north of the Northern Rockies, causing drier winters throughout the region (Cayan 1996).

The Pacific Decadal Oscillation (PDO) is an ENSO-like phenomenon that involves the movement of warm and cold ocean water in the North Pacific on a multi-decadal scale (20–30-yr cycles), and creates regional to hemispheric influences on climate (Mantua and Hare 2002). The PDO affects the intensity of the Aleutian low. The positive (warm) phase indicates a strengthened low, which creates a blocking mechanism for the movement of Pacific storms into the interior of North America, much like the effects associated with a positive phase PNA (Bond and Harrison 2000). This results in relatively warmer, drier winters in the Lolo National Forest region of the Northern Rockies (Mantua *et al.* 1997). The persistence of the PDO creates a modulating effect on the climate variability induced by ENSO and the PNA, accentuating or muting the expression of these phenomena when in or out of phase, respectively (Kipfmueller 2003).

The recently described Atlantic Multidecadal Oscillation (AMO) is based on temperature variations in the Atlantic Basin on a scale of 60–100 years, and is linked to fluctuations in the intensity of the thermohaline circulation (Gray *et al.* 2003). Although the mechanisms are not fully understood, the AMO may have a modulating effect on ENSO activity and precipitation in the Rocky Mountains (Gray *et al.* 2004), and has been linked with increased fire activity in the Colorado Front Range during the positive phase of the AMO and decreased fire activity during the negative phase (Sibold and Veblen 2005).

3.1.2 Geology

The modern landscape of the Northern Rocky Mountains and the Lolo National Forest was sculpted by the weathering, erosion, and glaciations that have occurred since the original formation of the region approximately 40–70 mya during the Laramide orogeny (Peterson 1986). The bedrock of the region is composed of Proterozoic igneous rock, overlain in places with Devonian and Cambrian sedimentary rock (Alt and Hyndman 1972) and Quaternary sediments from glacial activity and glacial Lake Missoula (Alt 2001). Elevations of the Lolo National Forest range from 730 m below Thompson Falls on the Clark Fork River, up to 2,805 m on the summit of Scapegoat Mountain. The majority of the mountain ranges within the forest are between 2,000–2,500 m in elevation.

3.1.3 Soils

The soils of the Lolo National Forest are relatively young and rocky, reflecting their mountainous setting (Pfister *et al*. 1977). Soil mantles are better developed on the windward slopes due to wind-deposited loess and volcanic ash from the west (Daubenmire and Daubenmire 1968). The USDA soil taxonomy divides the soils of Montana into five subgroups, including Cryoborolls on the lower elevation slopes, Cryoboralfs on mid-elevation slopes, Cryandepts on mid-elevation slopes with volcanic ash deposits, Cryochrepts on higher elevation and steep slopes, and Torriorthents on the steepest slopes (USDA Soil Conservation Service 1975).

3.1.4 Plant Communities

Forestland covers over 95% of the total area of the Lolo National Forest (DeBlander 2000). The complex geologic structure of the region creates a diverse array of site conditions, and fourteen coniferous forest types are identified throughout the forest, including 17 conifer species and five hardwood species (Figure 3.2). Plant communities of the Lolo National Forest are modeled after Pfister *et al.* (1977), and include over 1,500 plant species grouped into a mosaic of communities, including non-forest (rock, meadow, and grassland), dry-warm and dry-cool Douglas-fir types, moist spruce-fir types, and cool and cold alpine fir types. Sagebrush and bunchgrass communities occupy the driest valley bottoms, with sparse grasses and undergrowth beneath the continuous canopies of the mid-elevation forests (Arno and Hammerly 1984).

Near treeline, the forests open up, creating a park-like setting of whitebark pine, subalpine fir, Engelmann spruce, and alpine larch growing over a heath of grouse whortleberry (*Vaccinium scoparium* Leib. ex Coville), red mountain-heath (*Phyllodoce empetriformis* (Sm.) D. Don), and smooth woodrush (*Luzula hitchcockii* Hamet-Ahti), interspersed with meadows of bear grass (*Xerophyllum tenax* (Pursh) Nutt.). Numerous shrubs and herbs compose the upper subalpine plant communities of the Lolo National Forest, including elk sedge (*Carex geyeri* Boott), pinegrass (*Calamagrostis rubescens* Buckl.), twin flower (*Linnaea borealis* spp. *borealis* L.), shooting star (*Dodecatheon pulchellum* (Raf.) Merr.), mountain blue-eyed grass (*Sisyrinchium montanum* var. *montanum* Greene), alpine fireweed (*Epilobium latifolium* L.), yellow avalanche-lily (*Erythronium grandiflorum* Pursh), mountain arnica (*Arnica montana* L.), arrowleaf ragwort (*Senecio triangularis* Hook.), and several other less common species.

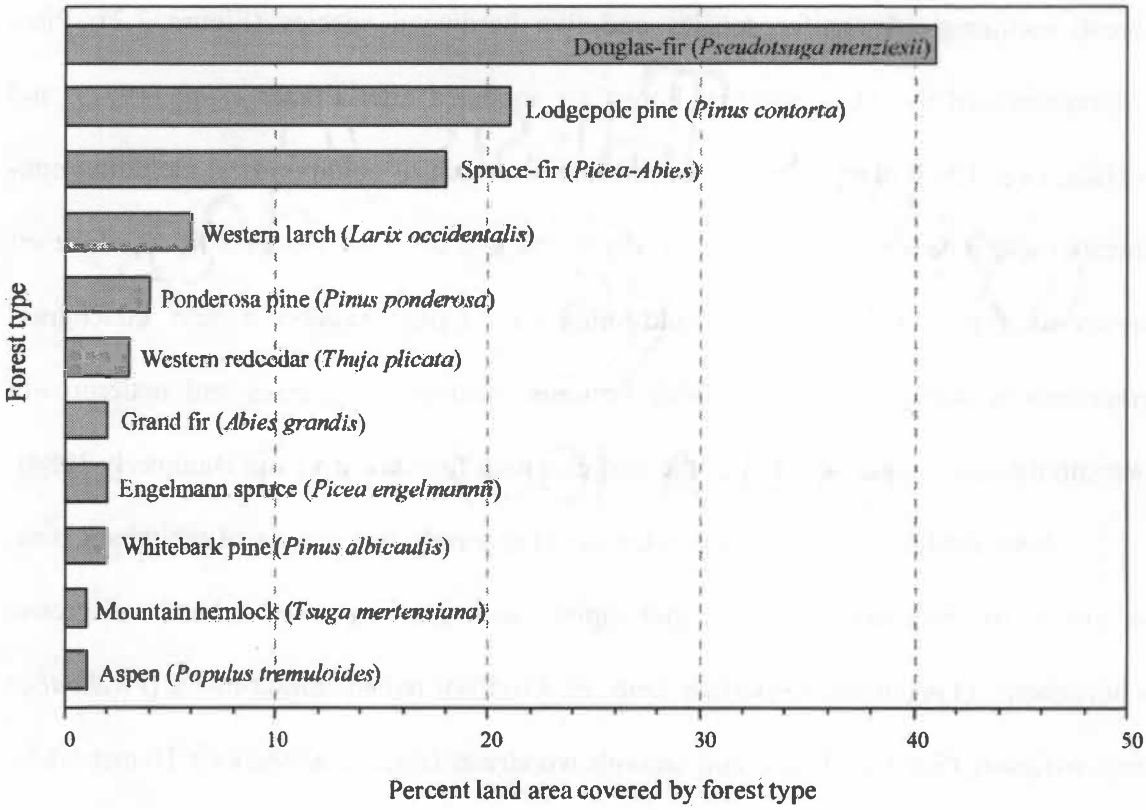


Figure 3.2 Forest types and forestland cover of the Lolo National Forest, Montana. Adapted from DeBlander 2000.

3.1.5 Land Use History

3.1.5.1 Pre-Euro-American Settlement

Several Native American groups used the region of the Northern Rockies currently included in the Lolo National Forest, including the Blackfoot, the Kootenai, the Nez Perce, and the Salish tribes (Hughes 1983, Sutton 2000). Native American impacts on the land included several permanent settlements, hunting, gathering, and maintaining an extensive trail system (Sutton 2000). One famous Native American trail network in the Lolo National Forest is the Lolo Trail mentioned throughout the oral histories of the Nez Perce and Salish. In 1805, Lewis and Clark were guided along 250 km of this trail as they traveled across the Rocky Mountains, through what is now the Lolo National Forest (Space 2001). Seventy years later the trail again served history as the Nez Perce followed it when fleeing from General Oliver Otis Howard's army during the Nez Perce War of 1877 (McWhorter 1984). This trail was often maintained with intentionally set fires (Lewis and Ferguson 1999, Barrett 2000), and is one example of the impacts on the landscape due to the use of fire by the indigenous people. Native Americans throughout the region used intentionally-set fires for a variety of reasons, including the clearing of land and forests surrounding settlements (Barrett and Arno 1982), travel corridors (Lewis and Ferguson 1999), driving wild game, preparing pastures, facilitation of food gathering (Lewis 1985), and for warfare (Hughes 1983). While the landscape-level effects of these actions are still debated (Vale 2002, Pyne 2003), significant impacts to local vegetation structure and communities around occupied sites have been documented throughout the region (Arno *et al.* 1997, Barrett and Arno 1999).

3.1.5.2 Mining History

The Lolo National Forest is relatively rich in mineral resources, and mining operations have existed in the region nearly continuously following a gold and silver rush in the mid-1860s (Safford 2004). Prospecting occurred throughout the region, and several abandoned mines are now scattered across the landscape. Following the initial rush for precious metals, mining interests broadened to include numerous mineral resources including antimony, barite, copper, sapphire, gold, and silver. By the late 1980s, mining activity covered 107 hectares of the National Forest. Sand and gravel extraction also occurs at several sites, and while oil and gas have not yet been exploited within the forest, large-scale exploration began in the mid 1980s, with over 360,000 hectares under lease (USFS 1986).

3.1.5.3 Logging History

While the area has been settled since the late 1800s, large-scale logging was restricted due to the rugged terrain and did not begin until the region was opened to rail at the turn of the century (Pyne 1982, DeBlander 2000). Since then, extensive harvesting has continued throughout the more productive low- and mid-elevation forests of ponderosa pine, Douglas-fir, western larch, and lodgepole pine, and the structural legacy of clear-cutting is still widely evident on the landscape (USFS 1986). Due to inaccessibility, many high elevation forests in the Lolo have never been logged (DeBlander 2000).

3.1.5.4 Agriculture

Agriculture has had a relatively minimal impact on the Lolo National Forest as natural resource utilization has focused primarily on timber (DeBlander 2000). The largest agricultural land use is for pasture, with cattle grazing permitted on just under 90,000 hectares of bottomland range and forestland. The impacts of grazing on the fire regimes of this region have not been studied, but are likely similar to those found in the American Southwest, where research shows a reduction in fire occurrence due to the removal of fine fuels (Savage and Swetnam 1990, Grissino-Mayer and Swetnam 1995, Touchan *et al.* 1995). These impacts would predominantly occur in lower elevation forests where grazing was concentrated, but sheep and cattle pasturage at high elevations may have altered those regimes as well (Belsky and Blumenthal 1997).

3.1.6 Forest Management

The current forest plan for the Lolo National Forest was published in 1986 and an updated management plan is currently undergoing review. The 1986 Forest Plan delineated 28 management areas across the forest according to different management goals, resource potentials, and limitations (USFS 1986). Of the total area, 147,000 hectares are designated as wilderness, and receive minimal management intervention. The management objectives of the remaining areas vary, but the following broad objectives apply to management decisions throughout the forest (USFS 1986):

- Provide a sustained yield of timber and other outputs at a level that will help support the economic structure of local communities and provide for regional and national needs.

- Provide habitat for viable populations of all indigenous wildlife species and for increasing populations of big-game animals.
- Provide for a broad spectrum of dispersed recreation involving sufficient acreage to maintain a low user density compatible with public expectations.
- Provide a pleasing and healthy environment, including clear air, clean water, and diverse ecosystems.
- Emphasize conservation of energy resources.
- Encourage a "Good Host" concept when dealing with the public.
- For threatened and endangered species occurring on the Forest, including the grizzly bear, gray wolf, peregrine falcon, and bald eagle, manage to contribute to the recovery of each species to non-threatened status.
- Meet or exceed state water quality standards.

3.1.6.1 Timber Management

Over 410,000 hectares of the Lolo National Forest have been deemed suitable for timber production (USFS 1986). The estimated volume of saw timber on these lands, based on the annual average volume change from 1976–1985, is 8.8 billion board feet (USFS 1986), with Douglas-fir, western larch, and lodgepole pine accounting for 75% of this number (DeBlander 2000). The projected annual output of timber from 1996 through 2035 is 131 million board feet, with reforestation and stand improvement projects on over 1,000 acres per year (USFS 1986).

3.1.6.2 Pest Management

The major pest concern for the Lolo National Forest is the mountain pine beetle, and outbreaks in the early 1900s and the 1980s led to widespread mortality in lodgepole and whitebark pine forests throughout several regions of the Forest (Logan and Powell 2001). Management of mountain pine beetle includes a risk-rating system, with treatment priorities applied accordingly (USFS 1986). Integrated pest management techniques include the removal of highly susceptible, heavily infected or infested individual trees and small-scale (< 200 acres) clear cutting (USFS 1986).

3.1.6.3 Fire Management

The 1986 Forest Plan recognizes the ecological importance of fire on the landscape, and encourages the use of prescribed fire within the guidelines of the annually revised Fire Management Action Plan and federal fire policy (USFS 1986). The primary objectives of fire management in the Lolo National Forest are fire suppression to protect resources and property, habitat improvement for elk and grizzly bears, maintenance and restoration of the composition and structure of plant communities, and hazard reduction in high-risk areas. The goal for average annual acreage burned across the forest is 1,200 hectares for wildfires and 3,800 hectares for prescribed fires and prescribed natural fires (USFS 1986), although this will likely change in the revised Forest Plan in response to recent extreme fire years.

3.1.6.4 Whitebark Pine Management

The 1986 Lolo Forest Plan makes no mention of whitebark pine as a resource or an at-risk species. Management Area 27 is composed of scattered parcels of steep, rocky forestland, and includes much of the whitebark pine in the forest (USFS 1986), but these sites are deemed not economically or environmentally suitable for timber extraction with current technologies, and the most recent forest resources survey found no whitebark pine in suitable timber production areas (DeBlander 2000). The revisions to the 1986 Forest Plan will include whitebark pine as an "at-risk" species, with special conservation considerations (Vick Applegate, Lolo National Forest Silviculturalist, personal communication).

3.2 Morrell Mountain

3.2.1 Environmental Setting

Morrell Mountain (47° 11' N, 113° 21' W) is a 2,380 m peak at the southern edge of the Swan Range, within the Seeley Lake Ranger District of the Lolo National Forest (Figure 3.3). The mountain is composed of Precambrian argillite and quartzite, overlain by the Piegan group of limestone and shale and unconsolidated Quaternary glacial deposits of silt, sand, gravel, and hot spring tufa (Ross *et al.* 1955, Raines and Johnson 1996). Slopes near the peak of the mountain (2,350–2,370 m) generally ranged from 30–40% (Table 3.1).

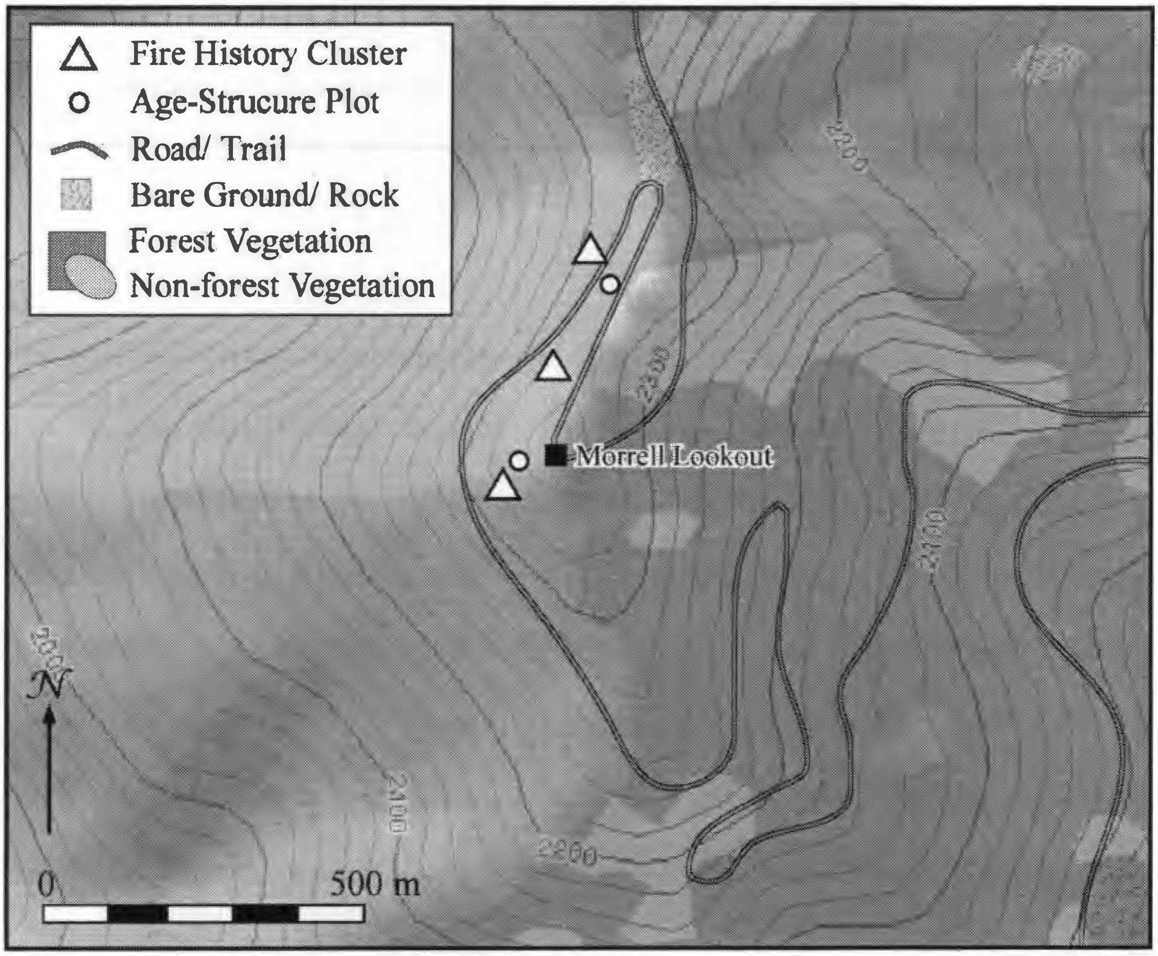


Figure 3.3 The study site on Morrell Mountain.

Table 3.1 General setting of the study sites in whitebark pine forests on three mountains in the Lolo National Forest, Montana.

Site	Lat./Lon.	Elevation (m)	Slope (%)	Community type[†]
Morrell Mountain	47°11' N, 113°21' W	2,350–2,370	30–40	*Abies lasiocarpa -Pinus albicaulis / Vaccinium scoparium*
Mineral Peak	47°00' N, 113°49' W	2,200–2,250	30–40	*Pinus albicaulis-Abies lasiocarpa*
Point Six	47°02' N, 114°00' W	2,250–2,350	25–45	*Abies lasiocarpa /Luzula hitchcockii*

[†] from Pfister *et al.* 1977

Western larch dominates the valley bottoms of this area, with ponderosa pine and Douglas-fir occupying the xeric and mesic lower slopes, respectively. Douglas-fir and lodgepole pine mix at the lower elevations, eventually moving to pure lodgepole pine stands from *ca.* 1,800 m to 2,100 m. The subalpine zone extends from 2,100 m to 2,380 m. The lower subalpine zone is characterized on the south side of the peak by a continuous canopy of mature whitebark pine and subalpine fir that opens up in the upper alpine zone into clusters of subalpine fir and whitebark pine, interspersed with alpine meadows (Figure 3.4). The northern slopes of the subalpine zone are covered with dense subalpine fir forests. A belt of the *Abies lasiocarpa-Pinus albicaulis/Vaccinium scoparium* habitat type covers the highest elevations of Morrell Mountain (Pfister *et al.* 1977). Evidence of past disturbances exists throughout the subalpine zone, including fire scars, lightning scars, and injuries from tree and rock falls. Numerous beetle-killed whitebark pine snags are scattered across the forest, and the effects of blister rust are evident throughout, with dead crowns and red-needles on the majority of the living whitebark pine.

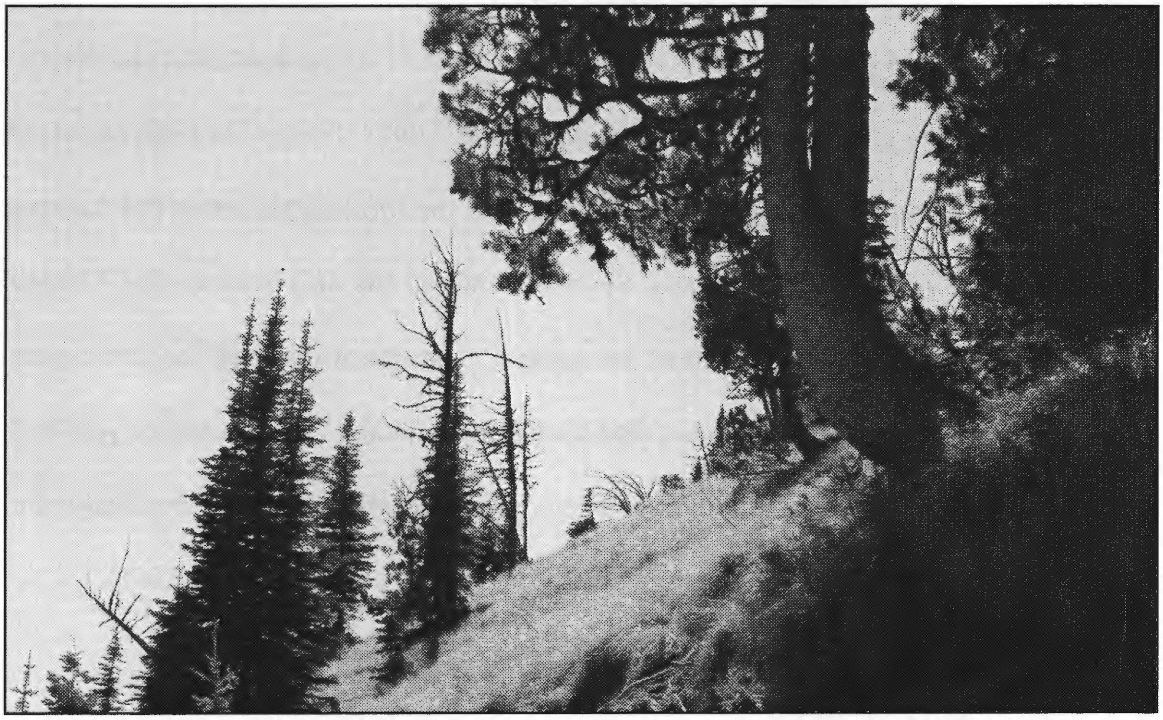


Figure 3.4 A south-facing alpine meadow in the transition between the lower and upper subalpine forest types on Morrell Mountain. The dead whitebark pine trees in the background were killed by a mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak in the 1980s and recent white pine blister rust (*Cronartium ribicola* (A. Dietr.) J.C. Fisch.) infections.

3.2.2 Land Use and Disturbance History

Morrell Mountain has been a site of near continuous anthropogenic activity in recent history. Native American activity is evident in the middle elevation lodgepole pine stands on Morrell Mountain in the form of bark peel scars (Grissino-Mayer, personal communication), and research also suggests the fire regime of the lowlands near Seeley Lake was altered by anthropogenic activity (Arno *et al.* 1997). Timber has been extracted from the surrounding area since the early 1900s, and the Morrell Mountain fire lookout was established in 1921 (USFS 1986). Several stands in the area surrounding Morrell Mountain were harvested in the 1960s, including a clear cut of diseased lodgepole pine on the southwest flank of the mountain (Bill Oelig, Seeley Lake Ranger District, personal communication). The Bureau of Land Management issued resource exploration leases for the area from 1980 to 1985, but no mining or extraction has occurred (BLM 2001).

3.3 Mineral Peak

3.3.1 Environmental Setting

Mineral Peak (47° 00' N, 113° 49' W) rises to 2,270 m in the southeast corner of the 26,300 hectare Rattlesnake National Recreation Area and Wilderness (RNRAW), in the Missoula Ranger District of the Lolo National Forest (Figure 3.5). The peak is at the head of the Gold Creek valley, a primary watershed for the city of Missoula (USFS 1986). The geology of Mineral Peak is composed of the Missoula Group of Precambrian argillite, quartzite, sandy or quartzitic argillite, impure quartzite, and impure limestone, with some Precambrian shale and siltstone deposits (Ross *et al.* 1955, Raines and

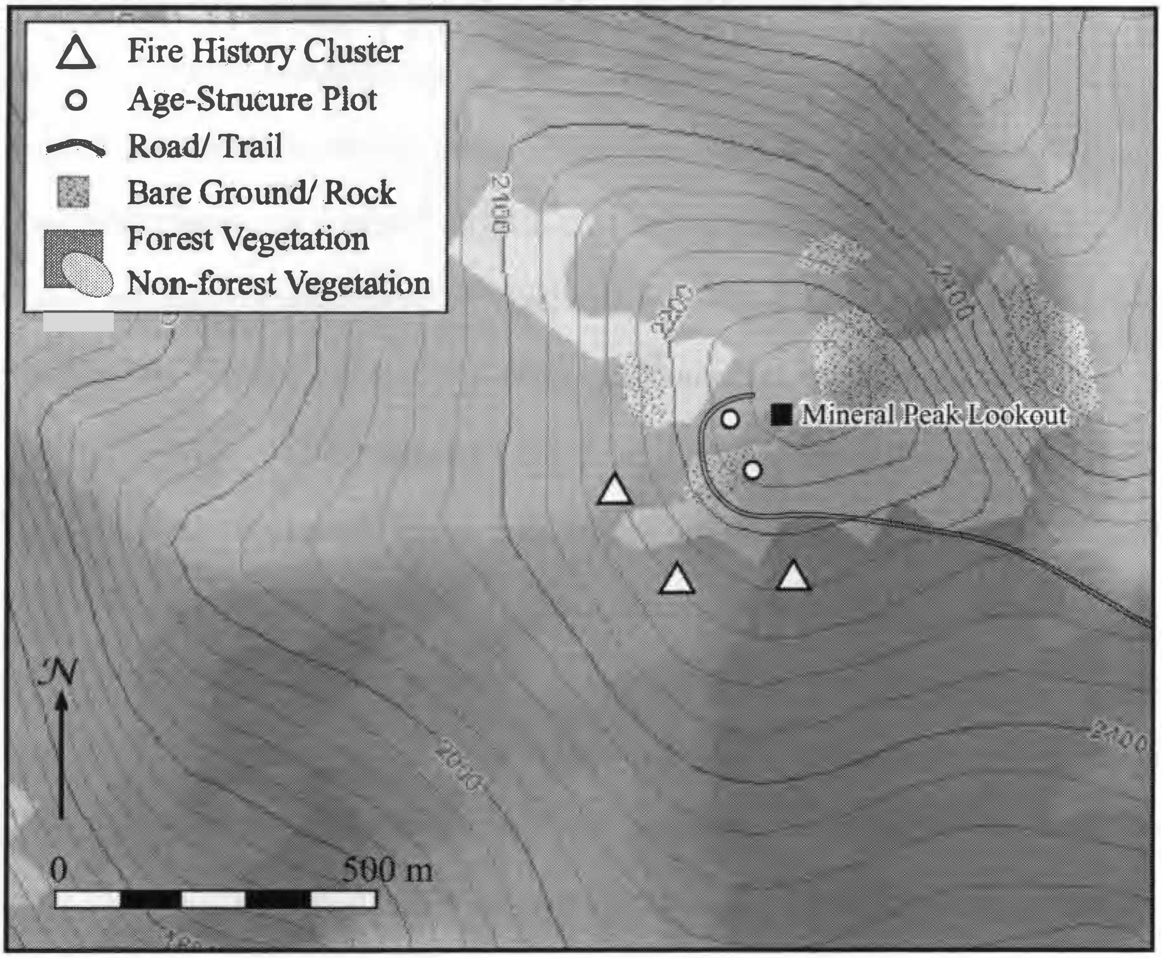


Figure 3.5 The study site on Mineral Peak.

Johnson 1996). Slopes generally range from 30–40% throughout the upper elevations (2,200–2,250 m) of the peak (Table 3.1).

The mesic valley and lower slopes are covered with nearly pure western larch forests, with Douglas-fir and ponderosa pine occupying the more xeric aspects and ridges. The mid-elevation forests (1,500–1,800 m) are composed predominantly of Douglas-fir and lodgepole pine, and surround the 31 hectare Shoofly Meadows wetland, one of two locations in the contiguous United States where a rare moss, *Sphagnum riparium* Ångstr., has been documented (USFS 1986). Above the wetlands, the forest shifts through a belt of pure lodgepole pine (1,800–1,950 m) into subalpine forest types composed of subalpine fir, whitebark pine, and Engelmann spruce (2,000–2,270 m). Whitebark pine, fir, and spruce create a continuous canopy in the lower subalpine zone, thinning out in the upper subalpine zone to scattered clumps of living and dead whitebark pine, often surrounded by fir and spruce saplings and trees, with extensive layering in the lower branches (Figure 3.6). Mature *Pinus albicaulis-Abies lasiocarpa* community type (Pfister *et al.* 1977) covers the uppermost elevations and extends downslope on the west, west-southwest, and southwest aspects from the peak in narrow bands separated by open talus. Evidence of past fires on Mineral Peak is common, with numerous whitebark pine trees displaying one or multiple fire scars. Lightning scars extending from the crown of a tree to the base are also common. The talus is generally stable, but some trees displayed injuries that were potentially caused by physical abrasion or impact. Whitebark pine snags are scattered throughout the forest and across the talus slopes, with beetle galleries evident on most. Blister rust is ubiquitous.

Figure 3.6 An example of the forest structure on the talus slopes of the upper subalpine forest zone on Mineral Peak. This area experienced high levels of mortality among whitebark pine due to mountain pine beetle activity and blister rust infections. The layering exhibited by the subalpine fir in this photograph is common throughout the study site.

3.3.2 Land Use and Disturbance History

A fire lookout was constructed on Mineral Peak in 1920, and staffed continuously until the 1970s (NHLR 2005). The area was logged in the early 1900s (USFS 1986), and gold prospecting took place on the lower slopes of the mountain in the 1950s (USBM 1992), but Mineral Peak has since experienced relatively little human disturbance. Due to the area's value as a municipal watershed for Missoula, the RNRAW was established in 1980. Mineral Peak was incorporated into the non-wilderness portion of the reserve to function as a buffer between the wilderness area and the land directly to the east of Mineral Peak, which is owned and has been actively managed by the Plum Creek Timber Company for the past 50 years (USFS 1986). In 2003, the Mineral-Primm Fire Complex burned over 10,000 hectares in the Gold Creek Valley, over half of which was on Plum Creek land and the rest in the Lolo National Forest, including several hundred hectares of the RNRAW (NIFC 2005). While Mineral Peak did not burn, the effects of the fire are clearly visible from the mountain (Figure 3.7). Suppression costs for the fire exceeded $22 million, and in 2004, the burn site was designated as a Healthy Forests fire salvage project.

3.4 Point Six

3.4.1 Environmental Setting

The peak of Point Six (47° 02’ N, 114° 00’ W) sits on the border between the Lolo National Forest and the Flathead Indian Reservation (Figure 3.8), and at 2,417 m is readily visible from downtown Missoula, Montana. The study site is within the Missoula Ranger District, and is classified as Lolo National Forest Management Unit 2 due to the

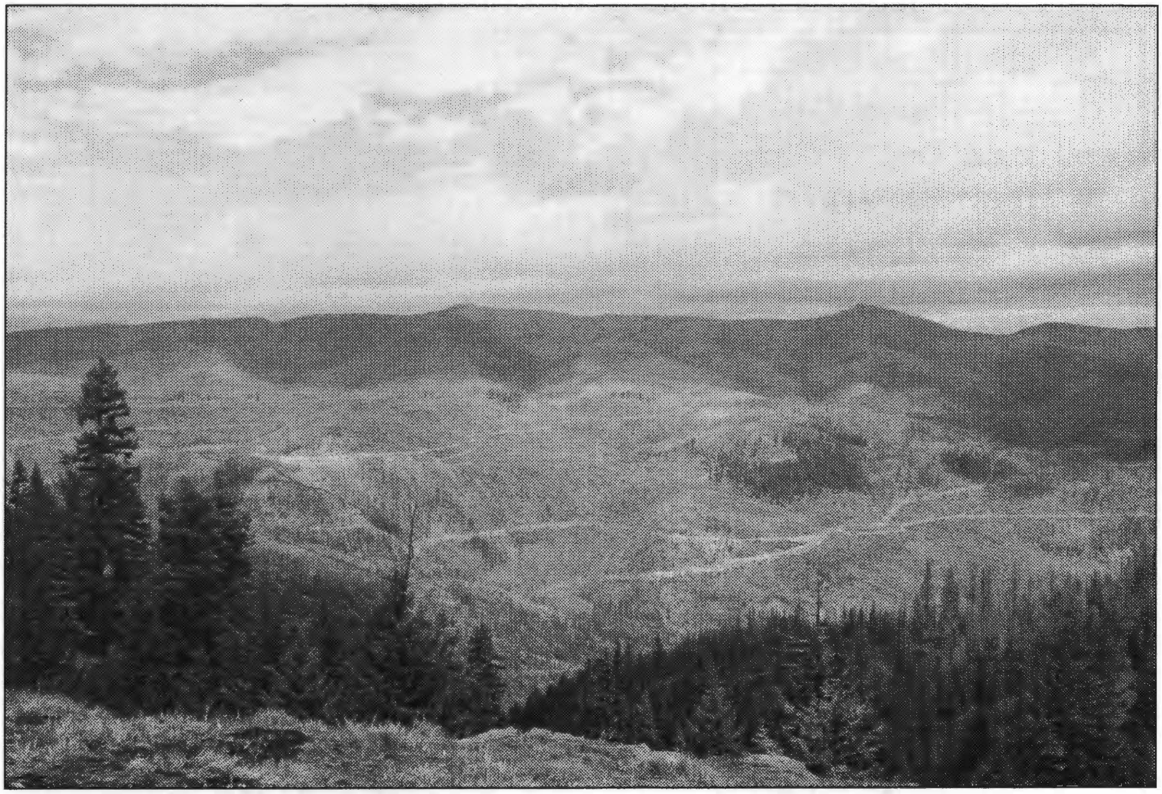


Figure 3.7 The results of the 10,000-hectare Mineral-Primm fire complex that burned throughout the Gold Creek drainage in 2003, as seen from the trail to the summit of Mineral Peak. The slopes directly across the Gold Creek Valley were nearly denuded, except for a few patches of unburned forest seen mid-slope on the right of the photograph.

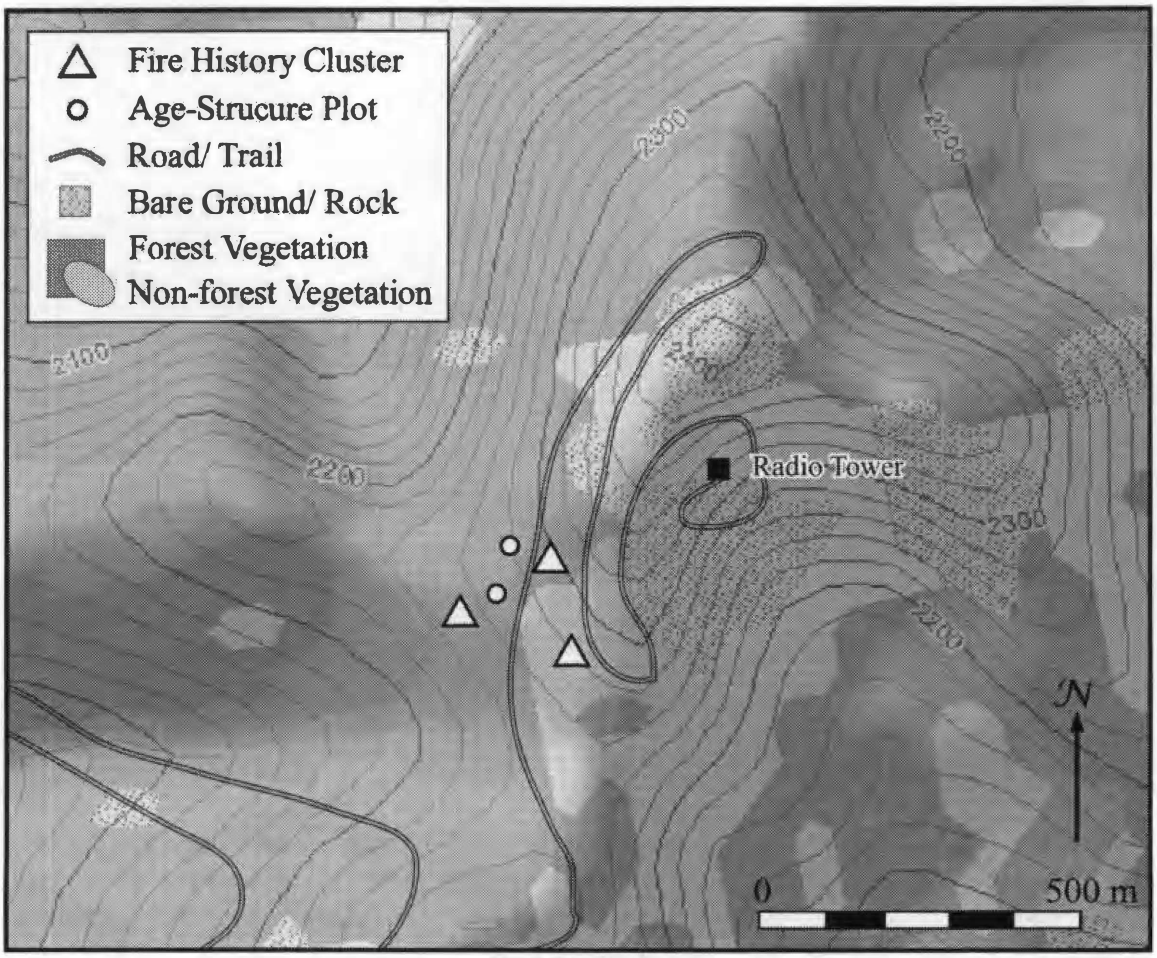


Figure 3.8 The study site on Point Six.

presence of the Montana Snowbowl ski area on the southern and eastern slopes of the mountain (USFS 1986). The headwaters of the Grant Creek Basin originate on the east slope of Point Six and the south slope of neighboring Murphy Peak, with Grant Creek joining the Clark Fork River in Missoula. Point Six is composed geologically of the Missoula group, but also includes part of a Precambrian pluton composed of diorite, alkali feldspar, metagabbro, and unconsolidated Cenozoic glacial till (Ross *et al.* 1955, Raines and Johnson 1996). Upper-elevation slopes ranged from 25–30% at 2,250 m to 40–45% at 2,350 m (Table 3.1).

The lower forest zone is predominantly Rocky Mountain ponderosa pine and Douglas-fir, with some western larch along waterways and on the more mesic slopes. The forest shifts to a continuous canopy of mixed Douglas-fir/ponderosa pine stands at the mid-elevations (1,500–1,850 m), with lodgepole pine becoming increasingly common near the upper boundary. Lodgepole pine dominates a relatively narrow band (1,850–2,000 m), and shares dominance with Douglas-fir at the lower elevations, and whitebark pine on the upper elevations of this zone. The lower subalpine zone (2,000–2,250 m) is a mix of species and structures, including mature whitebark pine and subalpine fir, numerous saplings of both species, and a few mature lodgepole pine near the bottom of the zone. The canopy thins with elevation, and by the upper subalpine zone (2,250–2,350 m) the forest is predominantly of the *Abies lasiocarpa/Luzula hitchcockii* habitat type (Pfister *et al.* 1977), with mature whitebark pine and scattered subalpine fir of all ages. A remnant stand of weathered whitebark pine exists on the southwest-facing talus slope just below the peak and above the current treeline. Nearly every whitebark pine in the study site displayed single or multiple fire scars, but I did not observe any scarred subalpine fir. Beetle-killed whitebark pine snags were scattered throughout the forest, but mortality levels appeared to be lower than at either Morrell Mountain or Mineral Peak. Blister rust infections were also less extensive, but several whitebark pines exhibited flagging (*i.e.* red needles due to the recent mortality of a branch or stem) in their upper canopies.

3.4.2 Land Use and Disturbance History

The subalpine zone is fragmented by several ski runs and a utility road to the radio facility on the peak of the mountain. Part of the Snowbowl ski area burned in 1988, but the fire did not spread to the slopes of Point Six (Guth 1991). Several communities extend from Missoula onto the foothills of Point Six, reaching up to the border of the national forest. The Snowbowl ski area was established in 1961, and includes over 385 hectares of ski runs and facilities. Access to the area is provided by a public road that runs up the southeast flank of the mountain. Tree removal activities are limited to eliminating safety hazards or for permitted construction or expansion of facilities. The Management Area that includes Point Six is currently classified as unsuitable for timber production, but the mid-elevation forests and lower subalpine zone contain numerous stumps as evidence of past management. Leases exist for gold, copper, and silicon exploration in the area, but not on Point Six (USBM 1992).

Chapter Four

4. Methods

4.1 Field Methods

4.1.1 Fire History

Fire history data were collected from fire-scarred whitebark pines on each of the three mountains. I used a chainsaw to collect 10–15 partial cross-sections from living trees (Arno and Sneck 1977) and full cross-sections from snags, stumps, or logs in three clusters on each mountain. Clusters were placed evenly through the whitebark pine stands on each site to provide fire history data for the complete stand. The area of each cluster depended on the density of the forest at the site, and varied from 0.5–1.5 hectares. I sampled all fire-scarred material within each cluster and did not specifically target trees that displayed multiple fire scars.

A variety of disturbances can injure trees in the subalpine environment (Burrows and Burrows 1976, Stuart *et al.* 1983, Butler *et al.* 1986, Morgan and Bunting 1990). I therefore sampled only trees that displayed classic characteristics of fire injury (Gutsell and Johnson 1996), including:

- the presence of charcoal on the scar face or on the bark of the tree
- an inverted V-shaped scarred surface that extended to ground level
- injuries located on the upslope side of the bole
- smooth surface beneath the healing lobe of the scar

Descriptions of the condition of each sampled tree (living, declining, or dead) were recorded to aid the crossdating process by providing a general estimate of the outer ring date. Sketches were drawn of each cross section to facilitate reassembly of broken samples back in the laboratory. I recorded the presence or absence of beetle galleries and blue stain fungus on each sample as this information may be of interest to other researchers working in whitebark pine forests. All samples were labeled and then wrapped with plastic wrap for transport back to the laboratory.

4.1.2 Age Structure

Stand age-structure data were collected in two 0.05 ha fixed-radius (r = 12.66 m) plots within the areal distribution of fire history clusters on each mountain. The center of the first plot at each site was located by walking 50 m in a random direction, selected by the seconds hand on a watch, from a random point within the fire history clusters. The center of the second plot was located 100 m along the contour from the first plot center. I recorded the species and diameter at breast height (dbh; height = 1.47 m) of all trees ≥ 5.0 cm dbh within each plot. I then collected increment cores from two radii of each tree by either coring the tree twice or by coring straight through the tree. All cores were taken at or below 30 cm above the root collar and along the contour of the slope to minimize the effects of reaction wood on the growth patterns in each sample (Fritts 1976). Saplings less than 5.0 cm dbh but greater than 1.3 cm diameter at ground level (dgl) were tallied by species in a nested 0.01 ha plot (r = 5.66 m). I cut 4–8 subalpine fir saplings in each plot to obtain general age estimates for the saplings at each site.

4.2 Laboratory Methods

4.2.1 Sample Preparation

All samples were frozen at -40° C for 48 hours to kill any pathogens and/or insects that may have been transported along with the samples. After allowing all samples to dry, fragile cross-sections were mounted on plyboard. Cores were glued to wooden core mounts, ensuring the cells were vertically aligned by examining the end and sides of the core for the "shiny sides" indicative of vertical wood cells (Stokes and Smiley 1996). Cross-sections were given an initial flat surface using a band saw to remove deep chain saw cuts prior to sanding, then each fire-scarred and core sample was sanded using a 4″×24″ belt sander, beginning with ANSI 80-grit (177–210 µm) and using progressively finer-grit belts until ANSI 400-grit (20.6–23.6 µm) (Orvis and Grissino-Mayer 2002). A final polish was applied to each sample by buffing the surface with superfine steel wool. This resulted in clear, cellular resolution under standard 7–10x magnification to aid the identification of possible narrow and missing rings.

4.2.2 Crossdating and Chronology Construction

I used visual, graphical, and statistical crossdating to assign precise calendar years to the growth-rings of my samples. Visual crossdating relied on patterns of wide and narrow rings common to all three sites that were likely related to regional climate (Fritts 1976), graphical crossdating was accomplished using the skeleton-plot method (Stokes and Smiley 1996), and statistical crossdating was accomplished using ring-width measurements and the computer program COFECHA (Holmes 1983, Grissino-Mayer

2001a). Samples that did not conclusively crossdate with these methods were excluded from all additional analyses.

I collected several fire-scarred samples from living trees, but extreme growth suppression in the outer 100+ years of most samples created uncertainty in the date of the outer rings of these samples. I therefore considered all of the fire-scarred cross-sections as floating, undated samples. To crossdate these samples, I first conducted ring-counts from the innermost ring to the outermost ring along two to four radii of each cross-section, and as far away from the fire scars as possible to minimize the effects of erratic growth that often occurs around an injury to a tree. I used a variable-power binocular microscope to facilitate ring identification, and marked every tenth ring along each radius. The number of radii per sample depended on the shape and condition of the sample, with more radii used when visible breaks in the tree-ring series were evident or when the scar tip was not visible and the healing lobe required individual dating. I visually crossdated the radii within each sample, then measured the rings along each radii to the nearest 0.001 mm using a Velmex measuring system interfaced with Measure J2X software.

I began statistical crossdating by first crossdating the radii within each cross-section. To accomplish this, I used COFECHA to conduct correlation analyses on 50-yr ring-width segments, overlapped 25 years, between two radii at a time. Potential problems identified by COFECHA within the sample were visually checked and corrections were marked on the cross-section and made to the measurement series. After the radii of each sample were statistically crossdated, I conducted similar correlation analyses of 50-yr segments between the measurement series of two different samples to date each relative to the other. Significant correlations for the majority of 50-yr segments indicated the most likely relative date for each sample, and I visually and graphically checked the suggested position before using the program EDRM (Holmes 1999) to shift the series to the new date. I combined the measurement series of the relatively-dated cross-sections into a single file, and dated additional undated samples relative to these dated samples. Once each sample was dated relative to the others, it was added to the file to create a floating tree-ring chronology for each site, eventually creating a master chronology that included the measurement series from all of the fire-scarred cross-sections.

To anchor my floating chronologies, I crossdated them with a whitebark pine tree-ring chronology developed on Carlton Ridge in the northeast corner of the nearby Selway-Bitterroot Wilderness Area (Kipfmueller 2003). To facilitate the statistical crossdating of the chronologies, I maximized the climate-related growth patterns common among my samples by transforming each floating chronology into a standardized ring-width chronology with the computer program ARSTAN (Cook 1985). The standardization process included the removal of the age-related growth trend of each sample by fitting a negative exponential trend line to the growth of the sample using the least squares technique, then obtaining a ring-width index (RWI) by dividing the actual ring-width by the value predicted by the regression (Fritts 1976). The RWI were then averaged for each year of the chronologies to create a single RWI series for each chronology. Crossdating between the chronologies was conducted using overlapping 50-yr segments, and the absolute dates suggested by the results were visually crossdated and checked for realistic outer dates on the samples taken from living trees. All individual measurement series were adjusted to their absolute dates using EDRM.

The cores collected from living trees in the age structure plots were first ring-counted using a variable-power binocular microscope, marked by decade from the outermost complete growth-ring toward the center of the core, and visually crossdated. As my field work was conducted in the early part of the 2004 growing season, the outer-most complete ring was formed during the 2003 growing season. The cores collected from dead trees were ring-counted from the innermost ring out and marked every tenth ring. I then measured the rings of each sample to the nearest 0.001 mm and statistically crossdated them to the ring-width chronology developed from fire-scarred samples at each site with COFECHA. I visually checked the suggested dates, and only assigned calendar years to the rings of samples that were conclusively dated.

4.2.3 Fire History

I used fire scars and trauma rings to identify disturbance events recorded in the rings of all absolutely dated samples (Grissino-Mayer 1995). An injury was only considered a fire scar if it followed a smooth path through a ring or along a ring boundary, while the remaining injuries were classified as "other injuries." The intra-ring position of each fire scar and injury was identified where possible and assigned a date and season (Baisan and Swetnam 1990) relative to the growing season of whitebark pine. Whitebark pine cambial activity in the Northern Rocky Mountains extends from *ca.* 24 May to *ca.* 12 September in a typical year (Weaver 2001), and I used the following definitions to assign seasonality:

- *Early season* (E): The injury is located in the first one-third of the earlywood, indicating the injury occurred in the early spring (May).
- *Middle season* (M): The injury is located in the middle one-third of the earlywood, indicating a late spring to early summer injury (June to early July).
- *Late season* (L): The injury is located in the latter one-third of the earlywood, indicating an early to mid summer injury (late July to early August).
- *End of growing season* (A): The injury is located in the latewood, indicating a late summer injury (late August to early September).
- *Dormant season* (D): The injury is located on the boundary between the latewood of the previous tree ring and the earlywood of the following ring, indicating that the tree was in dormancy during the fire event. The fire season in the Northern Rocky Mountains typically begins in the late summer or early fall (Brown *et al.* 1994), near the end of the growing season for high elevation forests (Schmidt and Lotan 1980). Fire scars that occurred at this position were therefore assigned to the preceding year (September to October).

Pine trees become more likely to record fire scars after an open wound is established on the bole of the tree due to the flammable resin created by the tree to compartmentalize the injury (Romme 1980). Therefore, the rings of each sample were designated as either “recorder” or “non-recorder” years based on the presence or absence of an open wound on the sample at that position in the rings (Figure 4.1). This method ensures the validity of subsequent statistical analyses (Grissino-Mayer 1995, Grissino Mayer 1999). I delineated the range of years considered suitable for statistical analyses, or the period of reliability (POR; Grissino-Mayer 1999), for each site as the first year

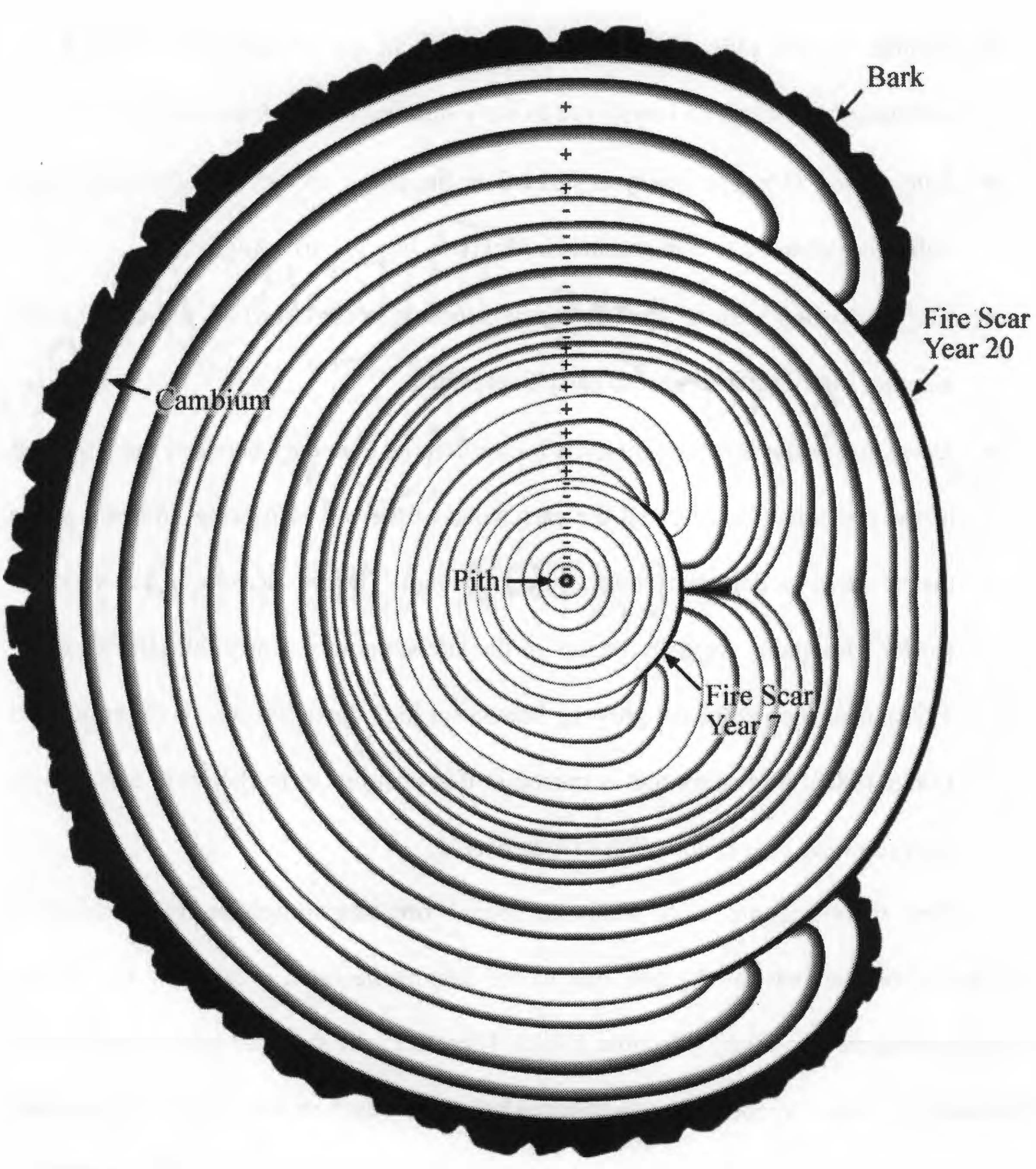


Figure 4.1 Illustration of recorder and non-recorder rings on a fire-scarred cross-section. Recorder years are indicated with a '+' and non-recorder years are indicated with a '-.'

with two or more recorder trees until the end of the chronology. Positively identified disturbance events and recorder/non-recorder status were entered into the fire history software FHX2 to construct fire charts, calculate descriptive statistics of the fire regimes, and conduct temporal and spatial analyses (Grissino-Mayer 2001b). I constructed four fire chronologies for my research, one for each of the three separate mountains, and a master fire chronology based on the combined data from all three sites to represent regional fire occurrence.

4.2.4 Age Structure

The age structure for each stand was determined by obtaining or estimating the establishment dates for the living and dead trees within each age-structure plot. I used the pith date to identify the establishment date of cores that included pith. Establishment dates were estimated for cores that did not contain pith by adding a correction to the innermost ring based on the curvature of the innermost rings and a pith estimator made of concentric circles that represented different growth rates (Applequist 1958). For solid cores that contained neither pith nor the curvature necessary to use pith estimators, the innermost ring was used to represent the minimum age of the tree (Soulé and Knapp 2000). If the inner date of any samples could not be determined due to rot, extremely tight growth rings, erratic ring structure, or lack of ring curvature, the sample was excluded from the age-structure data. Due to the variability in growth rates for seedlings and sapling at these sites (Daniels *et al.* in press), I did not apply a correction for the age at coring height and these data should be considered the minimum age of the stand rather than the absolute establishment date for the stand.

4.3 Graphical Analyses

4.3.1 Fire History Charts

I constructed fire charts for each fire chronology using the graphics module in FHX2 (Grissino-Mayer 2001b). Individual-site fire charts displayed the fire history information contained in each sample, while the master fire chart displayed the composite fire charts from the individual sites to illustrate the variability between sites. I visually examined each chart to identify changes in the temporal pattern of fires (*i.e.* changes in fire frequency) and the spatial patterns of fire activity (both intra-site and inter-site).

4.3.2 Age Structure Charts

I constructed age-structure charts to visually examine patterns in tree establishment at each individual site, as well as for the study area as a whole. To accommodate the uncertainty prevalent in tree establishment dates (Villalba and Veblen 1997), the data were grouped into 20-yr age classes for construction of age-structure charts. I created a graphical representation of the relationship between periods of increased fire activity and tree establishment by overlaying the 20-yr moving average of the number of fire scars in the fire history data for each site over the respective age-structure data. I used a 20-yr moving average to emphasize prolonged periods of increased fire activity while still maintaining sufficient resolution to observe peak fire years.

4.4 Statistical Analyses

My statistical analyses of the four fire chronologies included calculating descriptive statistics, assessing possible temporal and spatial changes in fire regimes, conducting seasonality analyses, and examining the relationship between fire and tree growth at individual-site and regional scales (Grissino-Mayer 2001b). All statistical analyses were conducted using the composite fire chronologies (Dieterich 1980) of each site over the POR.

4.4.1 Fire History Descriptive Statistics

I used eleven statistical descriptors for the central tendency, dispersion, range, and shape of the fire interval distributions (Table 4.1) to characterize the historical range of variability of each fire chronology.

4.4.1.1 Measures of Central Tendency

I used four statistics to describe the central tendency within the fire interval distribution of each site: 1) Mean Fire-free Interval (MFI); 2) Median Fire-free Interval (MDI); 3) Weibull Median Interval (MEI); and 4) Weibull Modal Interval (MOI). The MFI is a simple mean calculated by dividing the total number of recorder years by the number of fire events in a chronology. The MDI is the mid-point of a distribution of fire-free intervals, and is more resistant to outliers than the MFI. The MEI and MOI are derived by modeling the fire-free interval data with the Weibull distribution (Weibull 1951), which is more flexible than the normal distribution and has been shown to provide a superior fit for the often positively-skewed distributions of fire-free intervals (Grissino-

Table 4.1 Abbreviations and definitions of the descriptive statistics used to characterize the fire regimes and their historical range of variability on three mountains in the Lolo National Forest, Montana.

Statistic Name	Abbreviation	Description
Mean Fire-free Interval	MFI	The average number of years between fire events.
Median Fire-free Interval	MDI	The middle value of the distribution of fire-free intervals, more resitant to outliers than the mean.
Weibull Median Interval	MEI	The fire interval associated with the 50th percentile of the Weibull distribution.
Weibull Modal Interval	MOI	The theoretical mode of the Weibull distribution that represents the greatest area under the probability distribution function.
Minimum Fire-free Interval	MIN	The shortest fire-free interval at a site.
Maximum Fire-free Interval	MAX	The longest fire-free interval at a site.
Lower Exceedence Interval	LEI	The interval that delimits a significantly short fire-free interval, derived from the Weibull distribution.
Upper Exceedence Interval	UEI	The interval that delimits a significantly long fire-free interval, derived from the Weibull distribution.
Maximum Hazard Interval	MHI	The maximum theoretical fire-free interval that an ecosystem can experience before the event of a fire becomes highly probable; derived from the Weibull hazard function.
Standard Deviation	SD	The dispersion of fire intervals around the mean.
Coefficient of Variation	CV	A standardized measure of dispersion within a data set; enables comparisons between distributions with different means and/or variances.
Skewness	SKW	Describes the symmetry of a distribution.
Kurtosis	KUR	Describes the peakedness of a distribution.

Mayer 1999). The MEI is the fire interval associated with the 50th percentile of the fitted distribution, providing a measure of central tendency that is highly resistant to outliers (Grissino Mayer 1999). The MOI represents the theoretical mode in the frequency distribution that represents the greatest area under the probability distribution function (Grissino-Mayer 2001b).

4.4.1.2 Measures of Range

I described the range in fire interval data using five statistics: 1) minimum fire-free interval; 2) maximum fire-free interval; 3) Lower Exceedence Interval (LEI); 4) Upper Exceedence Interval (UEI); and 5) Maximum Hazard Interval (MHI). The minimum and maximum fire-free intervals are the shortest and longest fire-free intervals at a particular site, as described by the actual data. The LEI and UEI correspond to the 12.5 and 87.5 percentiles of the Weibull distribution, respectively, and delimit significantly short and long fire-free intervals (Grissino-Mayer 1999). The MHI represents the maximum theoretical fire-free interval that an ecosystem can experience before a fire becomes highly probable based on the preceding fire-free intervals, and is derived from the Weibull hazard function (Grissino-Mayer 1999).

4.4.1.3 Measures of Dispersion

The variability about the mean of the fire interval distributions for each site was described using the standard deviation (SD) and the coefficient of variation (CV). The SD, calculated by taking the square root of the variance, describes the dispersion of fire intervals around the mean, with plus or minus one SD bracketing 68% of the fire-free intervals, and plus or minus two SD bracket 95% of the fire intervals. The CV, calculated by dividing the mean by the standard deviation, provides a standardized value and enables comparisons between fire-free interval distributions with different means or variances (Grissino-Mayer 2001b).

4.4.1.4 Measures of Shape

I calculated the skewness and kurtosis to describe the shape of the fire-free interval distributions for each site. Skewness describes the symmetry of a distribution. Due to the lower bound of fire-free intervals (a fire-free interval can be no less than 1 yr) distributions of fire-free interval data are often positively skewed (skewness > 0). Kurtosis describes the peakedness of a distribution relative to the normal distribution (kurtosis = 0). Clustered data with few outliers are highly peaked, or leptokurtic (kurtosis > 0), and diffuse data, or data with numerous outliers are flat, or platykurtic (kurtosis < 0). I also graphed each distribution and the Weibull probability density function (pdf) for each fire chronology to provide a visual display of the shape of each fire interval distribution (Grissino Mayer 1999).

4.4.2 Temporal Analyses

Each fire chronology was examined for changes in fire frequency over the following periods based on historical records and settlement patterns (USFS 1986, Smith 1992): 1) Pre-settlement period, POR–1850; 2) Settlement period, 1851–1920; and 3) Fire suppression period, 1921–POR. To determine if fire activity during any of these periods was statistically unique, I conducted three statistical tests on the normalized fire interval data (Grissino-Mayer 1995): 1) Student's t-tests to test whether differences exist in MFI of periods; 2) folded F-tests to test whether differences exist in the variability about the MFI from one period to the next; and 3) two-sample Kolmogorov-Smirnov tests to test for differences in the distributions of fire-free intervals between periods.

4.4.3 Spatial Analyses

My spatial analyses included the same tests as my temporal analyses to compare the fire chronologies of each site to one another. The analyses were conducted over the common set of years for which both chronologies contained data.

4.4.4 Fire Seasonality Analyses

I analyzed the seasonality of fire activity for each chronology by grouping fires as either early-season (seasons E, M, and L) or late-season (seasons A and D). I then determined the historically dominant season of fire activity at each site and for the master composite chronology by calculating the percent of fire events that were included in each seasonality group.

4.4.5 Fire-Tree Establishment Relationships

I quantitatively analyzed the fire-tree establishment relationships in my study area by using a variation on the traditional superposed epoch analysis (SEA). SEA are conducted by stacking events, in this case fire events, then examining the average conditions of a particular variable (such as tree growth or climate) before, during, and after each event (Baisan and Swetnam 1990, Grissino-Mayer 1995). The window of analysis, as traditionally used in fire history research, commonly includes the 5 years leading up to the event, the event year, and up to two years after the event. Bootstrapped confidence intervals are calculated for the window of analysis from 1000 randomly selected events from the population of observations. To examine trends that occur on longer time scales, I extended the window of analysis to include 40 years; the 19 years leading up to the event, the event year, and the 20 years following the event. While individual statistically significant values become less meaningful as more years are included in the analysis, this multi-decadal superposed epoch analysis (MDSEA) can identify meaningful trends in data.

To conduct my analyses of fire-tree establishment relationships, I created an event chronology from the composite fire history of the master chronology, filtered to include only those fires that scarred ≥ 10% and ≥ 2 sampled trees during any given year. I used two tree-establishment chronologies as input variables for my analyses. The first chronology was the total number of tree establishments for all samples in the study area for each year from AD 1300–2000. The second chronology was the five-year moving average of the first chronology. Because I wished to conduct these analyses on the study area as a whole, I included the establishment dates from the fire-scarred samples with the age structure data to increase the sample depth.

I conducted my MDSEA using the event analysis module in FHX2 (Grissino-Mayer 2001b). The maximum extent for the window of analysis in this program is 40 years, including at least 1 year before the event, and the year of the event itself. To expand this window, I first conducted my MDSEA from one year before each fire event (t-1) to 38 years after the event (t+38). I then adjusted the tree-establishment chronologies to lags of 20 years, 40 years, and 60 years (Figure 4.2) and used the same window (t-1 to t+38) on each of the lagged chronologies. This resulted in four separate MDSEA output files that spanned 100 years, with 20-yr overlaps between each analysis. After ensuring the overlaps were identical, I compiled the results into one output file, in effect creating a continuous MDSEA window, with bootstrapped confidence intervals, of 100 years (t-1 to t+98).

4.4.6 Fire-Tree Growth Relationships

I examined trends in tree growth at the local and regional scales with respect to fire events to determine if local tree growth would decrease directly after a fire event due to damage to the roots, bole, and branches of the tree, but then shift to above average growth due to decreased competition and the release of nutrients associated with wildfires. In contrast, I expected regional growth trends to show no relationship to the fire event. I used MDSEA to test this relationship.

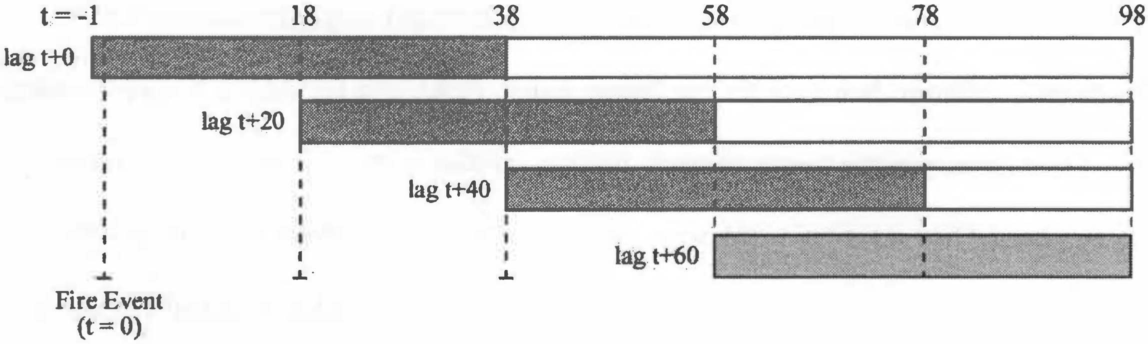


Figure 4.2 Graphical representation of the years included in the multi-decadal superposed epoch analyses examining the relationship between fire and tree establishment. Shaded regions indicate the years included in each successive analysis.

I used two event chronologies in my MDSEA. First, I conducted the analyses using the composite master fire chronology that included all fires recorded in my study area. I then focused my analyses on more widespread fire events by using a filtered composite master fire chronology that included only those fires that scarred ≥ 10% and ≥ 2 recorder trees in the master fire chronology during a particular year (Swetnam 1990). My condition variable for the local fire-tree growth analyses was the standardized master ring-width chronology developed from the fire-scarred samples collected in my study area. The condition variable I used to explore the relationship between regional trends in tree growth and the occurrence of fire events was a tree-ring chronology developed from non-fire-scarred whitebark pine in the nearby Selway-Bitterroot Wilderness Area (Kipfmueller 2003). All of my MDSEA examined a 40-year window around the respective fire events: the 19 years leading up to the fire (t-19), the fire year (t =0), and the 20 years following the fire (t+20).

4.5 Fire-Climate Relationships

I assessed possible relationships between fire activity and specific climate variables (temperature, precipitation, the Palmer Drought Severity Index (PDSI), the Southern Oscillation Index (SOI), the Nino3 index, PDO, and the AMO) by constructing charts that displayed the trends of each climate variable with a 20-yr moving average of the number of fire scars recorded across all three sites. I also plotted the fire events that scarred multiple trees in my study area to examine the relationship between climate and specific years when fire was likely more widespread. The climate data used in my analyses were tree-ring based reconstructions available from the National Climatic Data

Center World Data Center for Paleoclimatology (http://www.ngdc.noaa.gov/paleo/) and included:

- Temperature for station 14 (45° N, 110° W; Briffa *et al.* 1992);
- Precipitation for Kalispell, Montana (48° N, 114° W; Fritts 1991);
- PDSI for grid point 83 (47.5° N 112.5° W; Cook *et al.* 1999);
- Southern Oscillation Index (Stahle *et al.* 1998);
- Nino3 index (D'Arrigo *et al.* in press);
- PDO (D'Arrigo *et al.* 2001);
- AMO (Gray *et al.* 2004).

I first plotted all data by annual values, and then used a moving average of 5 years for the climate variables with short-term (< 10 years) variability (temperature, precipitation, and PDSI) and 20 years for the climate variables with longer-term (≥ 10 years) variability (PDO and AMO) to smooth the series and highlight trends in the data. To facilitate my interpretations of ENSO activity, I transformed the reconstructed SOI values into z-scores, and then multiplied the z-scores by -1 to compensate for the inverse relationship between the SOI and the Nino3 index. This resulted in positive SOI and Nino3 values being associated with El Niño events, and negative values being associated with La Niña events. I conducted my analyses from 1650 to 2000 because few of the climate reconstructions extended beyond AD 1650.

4.6 Fire Regime Type Classification

I used the results of my analyses to assess the accuracy of the FRCC fire regime types (Schmidt *et al.* 2002) assigned to my study sites. I examined the fire regime type of each site with respect to the actual frequency and severity of fires recorded in the fire chronologies and age structure of each stand. For the sites that did not match their classification, I placed the stands in the appropriate fire regime type as defined by Hann and Schmidt (2003). I then used the results of my statistical analyses as a framework to examine these classifications within the natural range of variability of my study sites.

Chapter Five

5. Results

5.1 Crossdating and Chronology Construction

I collected1 10 fire-scarred samples and 411 age-structure samples from the three sites. Visual and graphical crossdating were aided by especially narrow growth rings formed in AD 1641, 1688, 1782, 1799, 1817, 1838, 1899, and 1906, and a light ring (*i.e.* extremely narrow latewood) in 1801. A pattern of consecutive narrow rings in 1753, 1754, and 1755, followed by a wide ring in 1756, also provided a strong ring signature at all three sites. Visual crossdating was further facilitated by a frost injury in AD 1601 that provided an excellent marker ring in 33 of the 47 fire-scarred samples that extended beyond the year 1600 (Figure 5.1). The cellular damage caused by this event led to a separation in the ring structure of stumps and logs throughout the study sites (Figure 5.2), and enabled rough estimations of tree age in the field for many samples.

The ring-width chronologies were constructed from 233 measurement series from the 110 fire-scarred samples (Table 5.1). The site chronologies varied in length, with the shortest record from Point Six and the longest from Mineral Peak. Individual series ranged from 60–726 years in length. The mean inter-series correlations and mean sensitivity of the three individual site chronologies and the master ring-width chronology were relatively similar, and correlations between all four chronologies and the Carlton Ridge chronology were highly significant at the anchored dates (Morrell Mountain: $r = 0.319$, $n = 521$, $p < 0.001$; Mineral Peak: $r = 0.483$, $n = 911$, $p < 0.001$; Point Six: $r = 0.286$, $n = 417$, $p < 0.001$; combined chronology: $r = 0.46$, $n = 911$, $p < 0.001$).

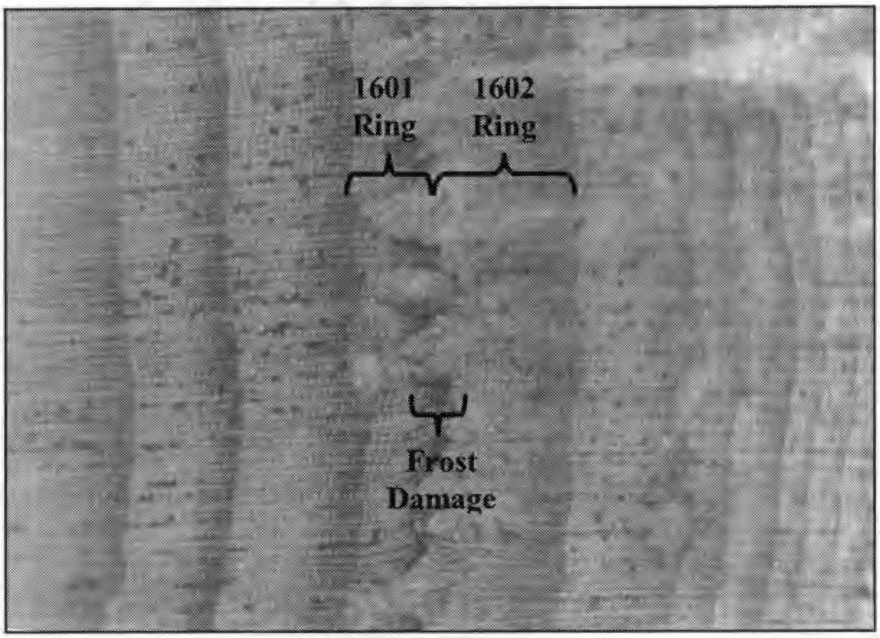


Figure 5.1 A frost event in 1601 damaged 17 of 22 samples from Morrell Mountain, 15 of 25 samples on Mineral Peak, and the only sample on Point Six alive that year. The image was taken under 40x magnification.

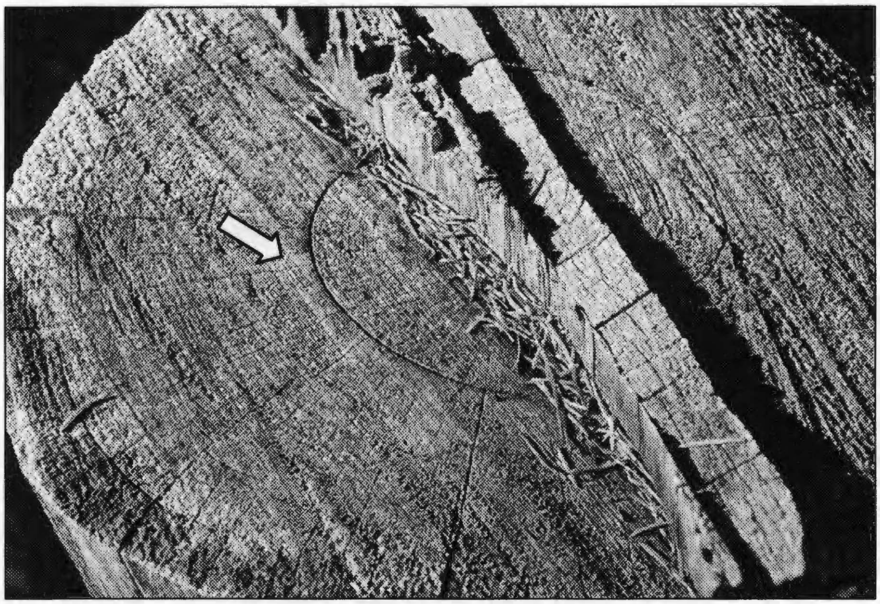


Figure 5.2 A weathered stump near the summit of Morrell Mountain. The ring separation indicated by the arrow is the result of a weak layer in the structure of the tree due to frost damage in AD 1601.

Table 5.1 Statistics for tree-ring chronologies developed from fire-scarred whitebark pines on three mountains in the Lolo National Forest, Montana, and for all sites combined.

	Morrell Mountain	Mineral Peak	Point Six	All Sites
No. Trees/Series	30/60	38/82	42/91	110/233
Time Span	1467–1999	1087–2000	1581–2003	1087–2003
M.S.L.[1]	283	307	202	259
I.S.C.[2]	0.484	0.426	0.431	0.404
M.S.[3]	0.24	0.22	0.23	0.23

[1] Mean series length (yrs)
[2] Mean inter-series correlation
[3] Mean sensitivity

5.2 Fire History

I identified 152 fire scars recorded in the fire-scarred samples, representing 68 unique fire events between the three sites (Table 5.2). I assigned seasonality to 89% (n = 116) of the fire scars, with the majority of those in the dormant season (89%, n = 103). Several fire events only scarred 1–3 trees, but each fire chronology included at least one fire that scarred trees throughout the site. Indications of mortality related to mountain pine beetle were present on 86% (n = 95) of the samples.

5.2.1 Morrell Mountain

The fire history data from Morrell Mountain suggest a fire regime dominated by relatively frequent, patchy fires (Figure 5.3). Few fires were recorded during the first 150 years of the fire history, but fires became increasingly frequent during the late 1600s and early 1700s until a widespread fire in 1754 that scarred most trees throughout the stand. This fire was followed by a period of less frequent but moderately widespread fires from 1796 to 1898. Only two fires were recorded in the study site in the 20th century, in 1919 (n = 2) and 1974 (n = 1). Multiple trees were scarred in 1711 (n = 2), 1751 (n = 2), 1754 (n = 7), 1796 (n = 3), 1830 (n = 3), 1836 (n = 3), 1843 (n = 4), 1898 (n = 3), and 1919 (n = 2). Beetle-caused mortality peaked in the 1970s and 1980s, but a cluster of mortality dates in the early 1900s suggests the stand may have been affected by previous outbreaks.

Table 5.2 Descriptive statistics for fire history chronologies developed from whitebark pines on three mountains in the Lolo National Forest, Montana.

Statistic[1,2]	Morrell Mountain	Mineral Peak	Point Six	All Sites
No. Trees .	30	38	42	110
No. Fire Scars/Events	54/33	40/20	59/15	153/68
Earliest Fire	1531	1488	1661	1488
POR	1613–1999	1497–2000	1719–2003	1497–2003
MFI (yrs)	14	25	15	7
MDI (yrs)	10	20	11	6
MEI (yrs)	10	22	11	6
MOI (yrs)	2	15	2	2
MIN (yrs)	1	5	2	1
MAX (yrs)	55	64	67	35
LEI (yrs)	2	8	3	1
UEI (yrs)	27	44	30	14
MHI (yrs)	>1000	>1000	>1000	>1000
SD	12.97	16.96	16.67	6.27
CV	0.94	0.69	1.11	0.86
SKW	1.62	0.89	2.27	1.82
KUR	2.39	-0.32	4.37	4.56

[1] Descriptive statistics calculated over the POR

[2] See table 4.1 for definitions

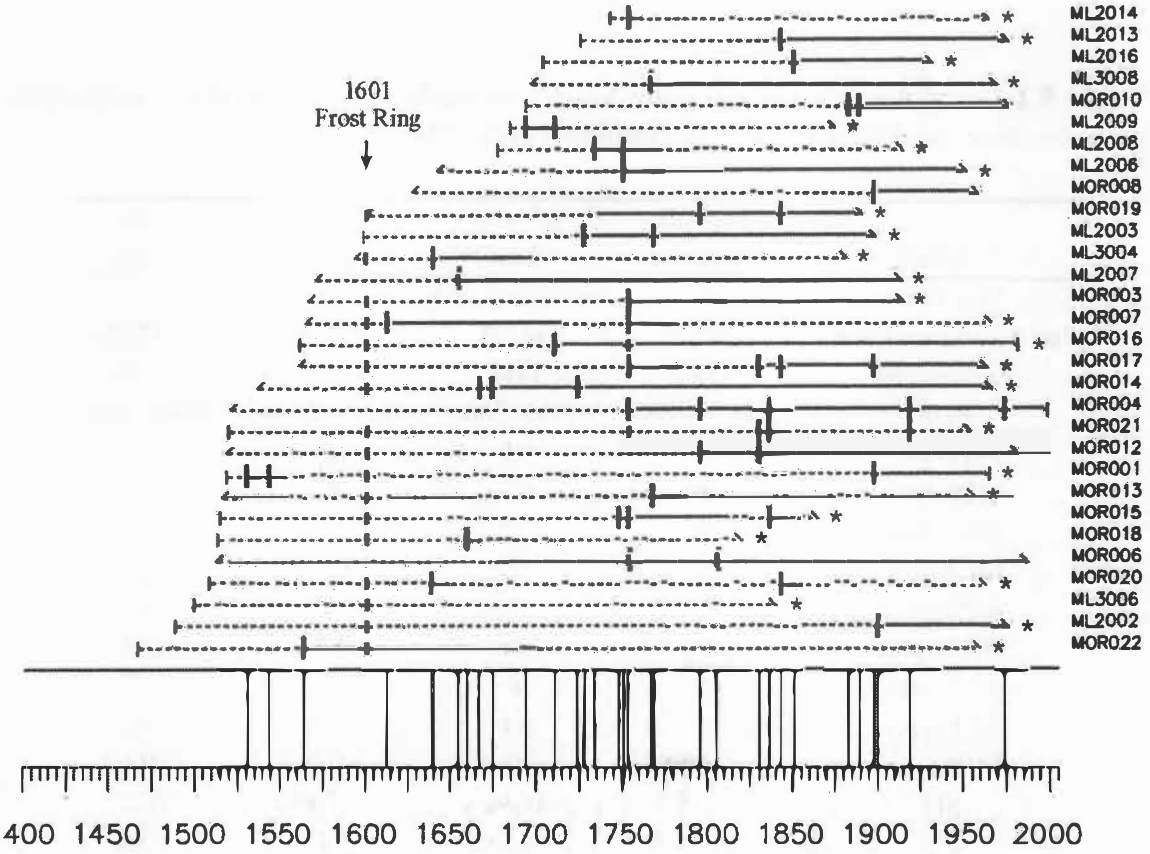


Figure 5.3 The fire history chart for Morrell Mountain in the Lolo National Forest, Montana. Each horizontal line represents a tree. Dashed portions of the line indicate non-recorder years and solid lines indicate recorder years. Long tic-marks indicate a year when that sample recorded a fire, and short tic-marks indicate other injuries. A star at the end of a sample indicates evidence of beetle-caused mortality. The composite fire chronology at the bottom of the chart uses vertical lines to represent years during which at least one tree within the study site recorded a fire event.

5.2.2 Mineral Peak

Although the fire chronology for Mineral Peak is the longest of the three sites, it includes the fewest number of fire events (Figure 5.4). The majority of fire activity occurred during the late 1700s and early 1800s, with relatively few fires recorded before or after this period. Most of the fires recorded in the site scarred only a single tree. Two or more trees recorded fire events in the south-facing cluster in AD 1781 (n = 4), the southwest-facing cluster in 1497 (n = 2) and 1889 (n = 3), and all three clusters in 1834 (n = 14). Only two fire events were recorded in the 1900s (1901 and 1965), both of which scarred only single trees. Signs of beetle-caused mortality were identified on individual samples dated to the 1700s and 1800s, and a distinct period of widespread mortality during the late 1900s suggests beetle activity throughout the site.

5.2.3 Point Six

The fire chronology for Point Six suggests a fire regime characterized by higher severity and more widespread fires than the other two sites (Figure 5.5). Two large fire events scarred trees throughout the site in 1719 (n = 6) and 1816 (n = 37). Potential post-fire cohorts are evident in the age-structure of the fire-scarred samples *ca.* 1600 to 1650 and again after the 1719 fire. A shift toward patchier fires occurred after the 1816 fire. Additional years when multiple trees were scarred include 1861 (n = 2) and 1930 (n = 2). The 1930 fire was the last recorded within the study site. The majority of dead trees displayed evidence of mortality related to mountain pine beetle activity in the 1920s and 1970s.

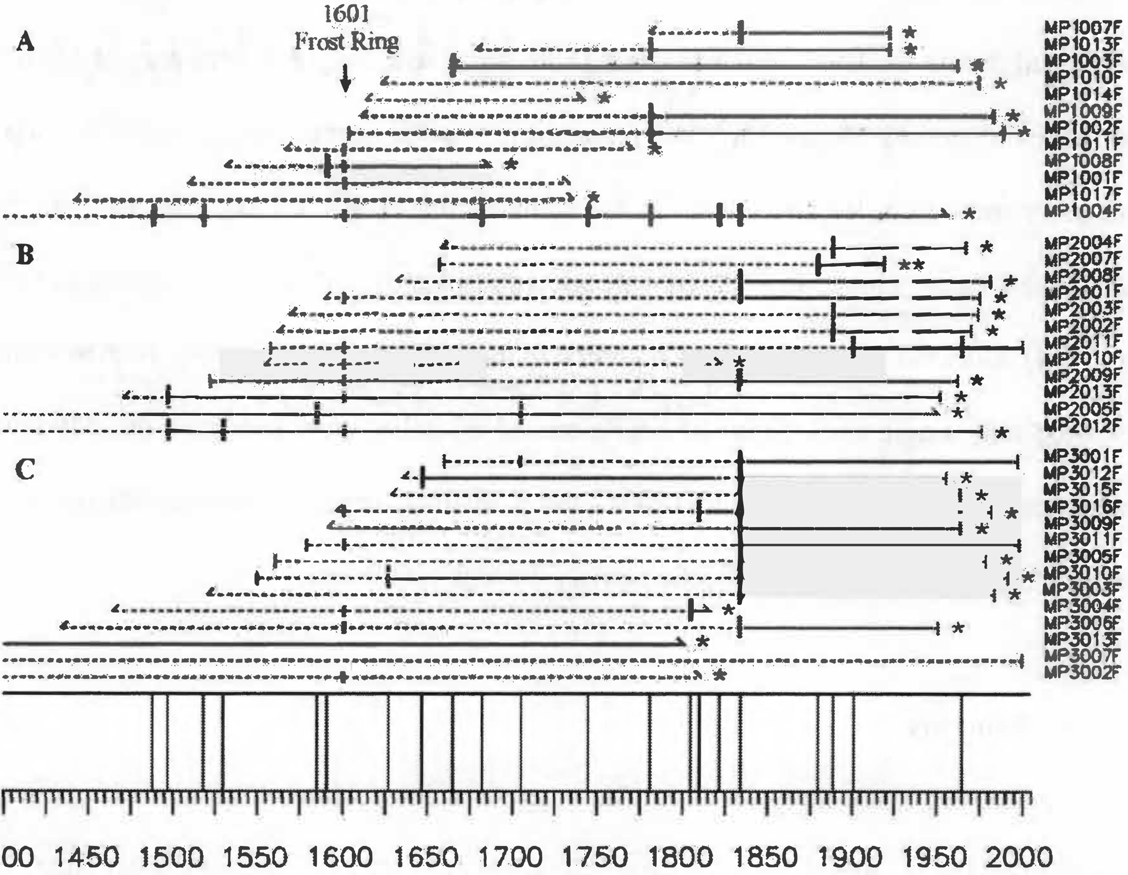


Figure 5.4 The fire history chart for Mineral Peak, in the Rattlesnake National Recreation Area and Wilderness, Lolo National Forest, Montana. See Figure 5.2 for an explanation of symbols used in the chart. The (A) south-facing cluster, (B) southwest-facing cluster, and (C) west-facing cluster are plotted separately to emphasize spatial variability in fire activity.

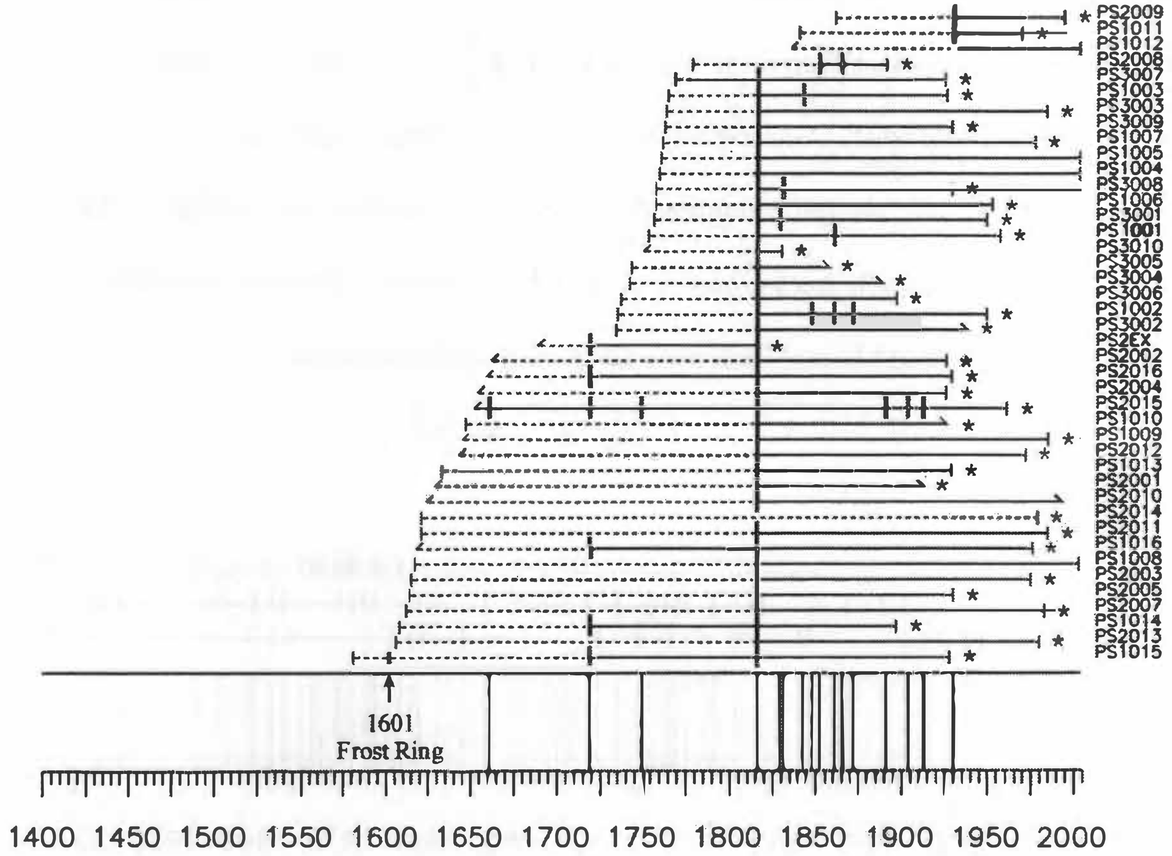


Figure 5.5 The fire history chart for Point Six, in the Lolo National Forest, Montana. See Figure 5.2 for an explanation of the symbols used in the chart.

5.2.4 All Sites

The composite master fire chronology provides evidence of relatively continuous fire activity throughout the study area from *ca.* AD 1500 to *ca.* 1920 (Figure 5.6A), but the majority of fires that scarred multiple trees in the study area occurred from *ca.* 1700 to *ca.* 1850 (Figure 5.6B). A near-complete cessation of fire activity occurred at all three sites after 1930. The Morrell Mountain fire chronology included the greatest number of fires that scarred multiple trees grouped in the tightest clusters. Fires that scarred multiple trees on Point Six and Mineral Peak were temporally more dispersed.

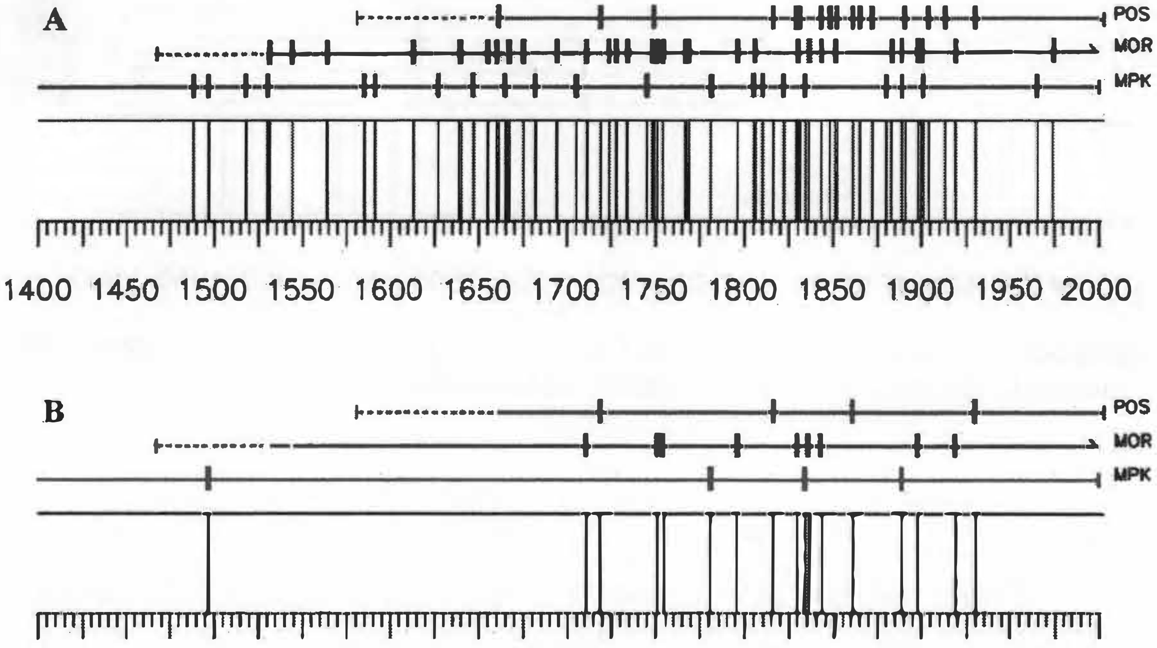


Figure 5.6 The master fire charts of (A) all fires and (B) fires that scarred multiple trees on three mountains in the Lolo National Forest, Montana. The horizontal lines represent the individual site composite fire chronologies, and the composite master fire chart at the bottom of both figures includes all of the fire years for the three sites at each respective level of analysis. POS = Point Six, MOR = Morrell Mountain, and MPK = Mineral Peak.

5.3 Age Structure

The age-structure data are based on an inventory of 862 trees and saplings, with 372 trees $\geq$ 0.05 cm dbh (Table 5.3). Subalpine fir was the most common species at all three sites. For trees $\geq$ 0.05 cm dbh, whitebark pines were more numerous than subalpine firs at Mineral Peak and Point Six. Subalpine fir saplings outnumbered whitebark pine saplings at all sites. I was able to crossdate 263 of the cores collected for age-structure analyses. The average correction for cores that did not contain pith was 6–7 years, with a maximum correction of 12 years on one sample. Inner-ring dates varied by site and species, but the oldest trees at all three sites were whitebark pines, with a general shift toward increasing subalpine fir establishments in the 19th and 20th centuries.

5.3.1 Morrell Mountain

The majority (61%, n =14) of whitebark pine establishment occurred on Morrell Mountain from AD 1480–1559, while I identified only two whitebark pine trees that established in the plots more recently than 1640 (Figure 5.7A). Establishment levels were consistently low from 1560–1679, although the inner rings of several of the fire-scarred samples dated to this period (Figure 5.3). The oldest subalpine fir trees in the plots established *ca.* 1700, after which the presence of subalpine fir increased through the 18th, 19th, and 20th centuries despite several periods of increased fire activity in the 1700s and 1800s. The subalpine fir saplings on Morrell Mountain contained inner dates as early as 1769. Because these small trees are highly susceptible to fire, this suggests that a widespread fire has not burned throughout the stand since the 1754 fire event.

Table 5.3 Age-structure data from three stands in the Lolo National Forest, Montana.

Whitebark Pine	Morrell Mountain	Mineral Peak	Point Six	All Sites
Saplings Inventoried	45	18	24	87
No. Crossdated	*	*	*	*
Inner Dates	*	*	*	*
Trees Inventoried	39	58	80	177
No. Crossdated	24	34	35	93
Inner Dates	1333–1843	1392–1937	1753–1879	1333–1937
Subalpine Fir				
Saplings Inventoried	121	50	232	403
No. Crossdated	15	7	17	39
Inner Dates	1769–1975	1880–1976	1871–1966	1769–1976
Trees Inventoried	79	48	68	195
No. Crossdated	79	29	62	170
Inner Dates	1703–1978	1784–1984	1847–1953	1703–1984

* no whitebark pine saplings were cut

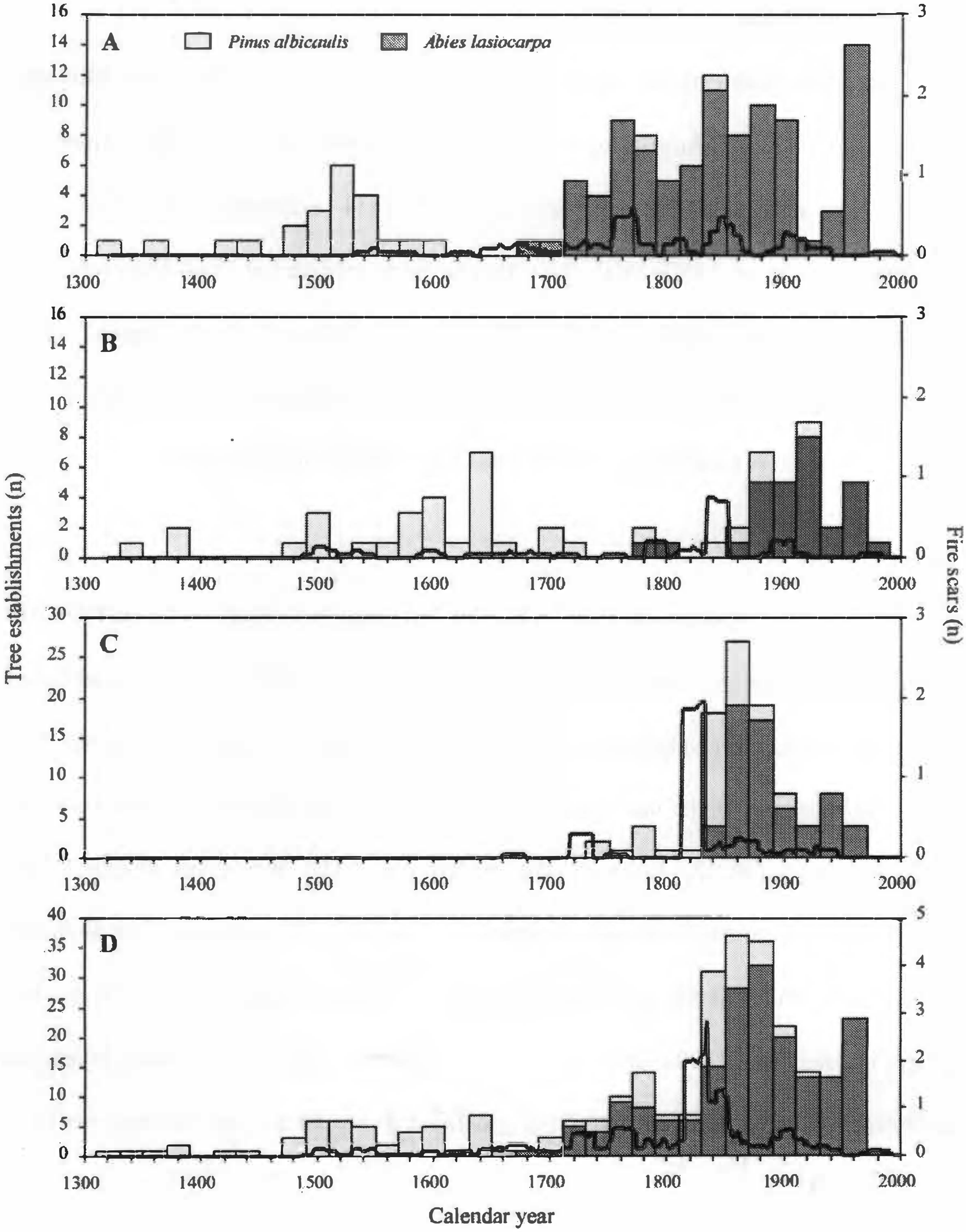


Figure 5.7 Age structure of trees on (A) Morrell Mountain, (B) Mineral Peak, (C) Point Six, and (D) all three sites combined. The dark line represents the 20-yr moving average of the number of fire scars recorded in the tree-ring based fire history of each site.

5.3.2 Mineral Peak

Whitebark pine establishment peaked on Mineral Peak *ca.* AD 1580–1640, with occasional minor establishments up to the early 1900s (Figure 5.7B). The majority of subalpine firs established in the plots after the 1834 widespread fire, with peak establishment from *ca.* 1880–1920. Only two fir trees predate the 1834 fire event. The plots on Mineral Peak contained the lowest number of saplings for both species, which reflects the relatively open, harsh environment at the site. Similar to Morrell Mountain, the oldest fir saplings established soon after the most recent widespread fire.

5.3.3 Point Six

The majority of inner dates for both whitebark pine and subalpine fir on Point Six are clustered from *ca.* AD 1840–1880 (Figure 5.7C). Several whitebark pines established before this period, while subalpine fir dominated the age structure after this period. The earliest whitebark pine inner dates followed the 1719 fire, and the peaks in whitebark and fir establishment directly followed the widespread 1816 fire event (Figure 5.5). Whitebark pine dominated the age-structure for the first 20 years after the fire, and subalpine fir dominated the age-structure from 40–80 years after the fire. Patchy fire activity in the late 1800s and early 1900s coincided with decreasing levels of establishment, although the abundance of subalpine fir saplings at the site suggests fir is still regenerating.

5.3.4 All Sites

The age structure for all sites combined was dominated by whitebark pine from AD 1300–1700, after which subalpine fir dominated these stands (Figure 5.7D). The period of increased whitebark pine establishment between 1840 and 1880 is associated with the post-fire cohort on Point Six, and provides evidence of the pioneering nature of whitebark pine. Fire scars are rare before 1500, with small peaks in fire activity before or concurrent with the earliest tree establishments at all three sites. Fire activity in the study area peaked in the early to middle 1800s. This period coincided with relatively low levels of tree establishment and was immediately followed by the peak in tree establishment for the study area. The absence of subalpine fir in these data prior to AD 1700 may occur simply because evidence of earlier cohorts no longer exists due to subsequent fires and decay, and is not direct evidence of past forest composition.

5.4 Statistical Analyses

5.4.1 Descriptive Statistics

Fire was a common disturbance across the study area, with 68 fire events that occurred within the study area during the last 506 years (Table 5.2). The characteristics of fire activity among the three sites varied, however. Fire events were most frequent on Morrell Mountain and Point Six according to all measures of central tendency, while Mineral Peak showed fire-free intervals that were approximately twice as long. The measures of central tendency on Morrell Mountain and Point Six followed patterns similar to those found in other fire history studies (Grissino-Mayer *et al.* 2004), where the MFI ≥ MDI ≥ MEI ≥ MOI. The measures of central tendency of the Mineral Peak fire chronology were an exception to this pattern, however, with a MDI (20 years) lower than the MEI (22 years). This difference is related to the relatively long fire-free intervals recorded on Mineral Peak.

The minimum fire-free intervals of the three fire chronologies ranged from 1 to 5 years, while the maximum fire-free intervals ranged from 55 to 67 years. The LEIs of the Morrell Mountain and Point Six fire chronologies were 2 and 3 years, respectively, while the LEI of the Mineral Peak fire chronology was 8 years. The UEIs followed a similar pattern, with Morrell Mountain and Point Six fire chronologies recording lower values than the Mineral Peak fire chronology. The MHIs for all of the fire chronologies were >1000 years. These high values are related to the skewed, amodal distributions of the fire-free intervals of the fire chronologies (Figure 5.8), suggesting that a better measure for the upper limit in fire-free intervals at these sites is the UEI (Grissino-Mayer 1999).

The SD of the fire-free intervals was lowest on Morrell Mountain, while Mineral Peak and Point Six showed nearly identical standard deviations. The SD of a distribution, however, is highly affected by skewed data (Grissino-Mayer 1995), and the CV often provides a better measure to compare the variability of fire-free intervals between sites. The CV indicated that the variability of fire-free intervals was greatest on Point Six and least on Mineral Peak, with the variability of fire-free intervals on Morrell Mountain between the two. The distributions of all three sites were positively skewed (Figure 5.8). Kurtosis varied considerably between sites, with the distribution of fire-free intervals on Mineral Peak being platykurtic while distributions for Morrell Mountain and Point Six were more peaked (leptokurtic).

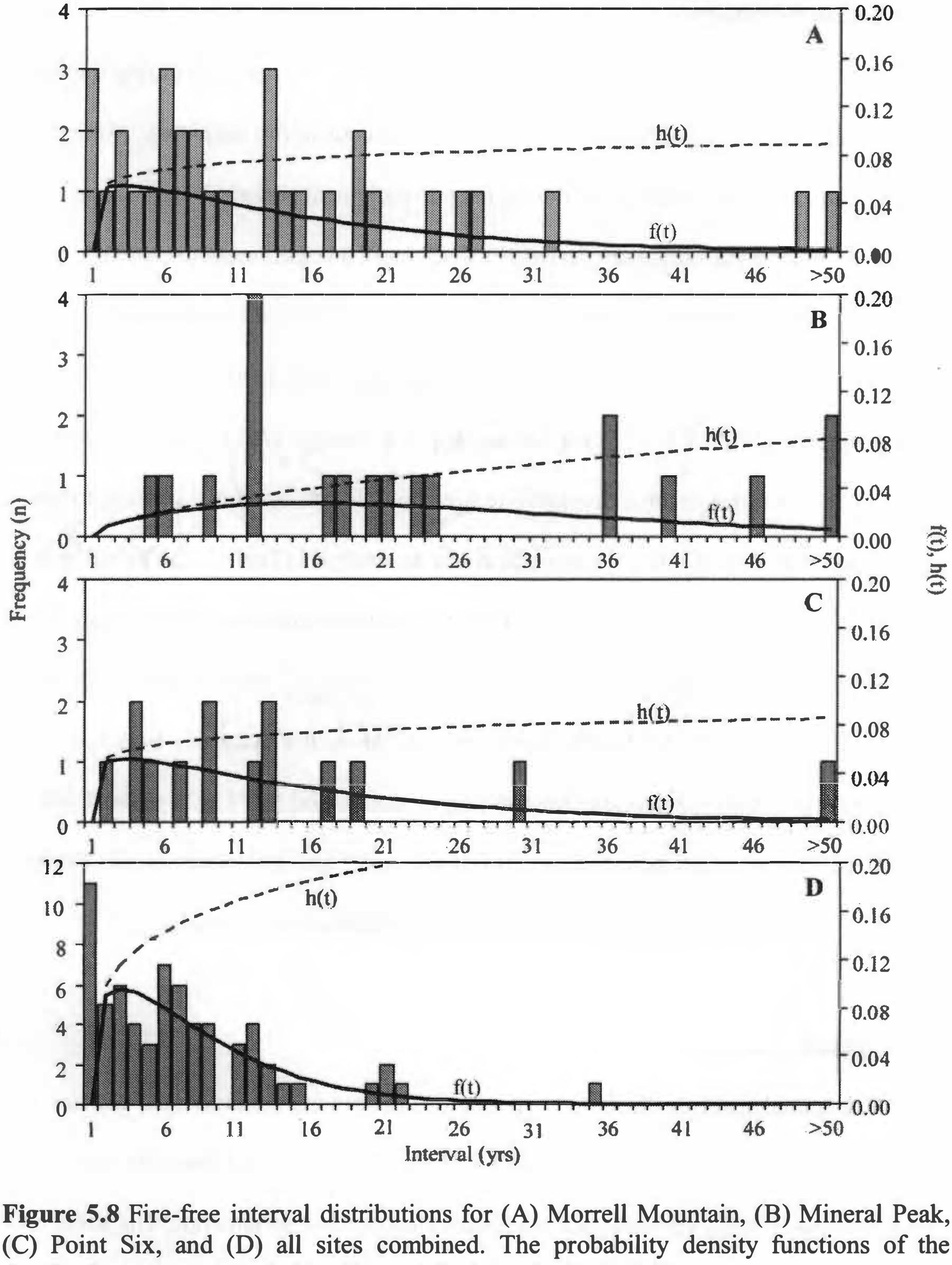


Figure 5.8 Fire-free interval distributions for (A) Morrell Mountain, (B) Mineral Peak, (C) Point Six, and (D) all sites combined. The probability density functions of the distributions are represented by f(t), and the hazard rates by h(t).

5.4.2 Temporal Analyses

The temporal analyses were limited by a lack of fire-free intervals during the fire suppression era (Table 5.4A), but still identified some trends in fire frequency. Mineral Peak and Point Six had similar MFIs during the pre-settlement period (22 years) and shorter MFIs during the settlement period (11 years and 10 years, respectively). In contrast, Morrell Mountain increased from a pre-settlement MFI of 10 years to a settlement period MFI of 14 years (Table 5.4B). The MFI based on all sites combined shows a decrease in MFI from 7 years during the pre-settlement era to 5 years during the settlement period. None of the individual site fire chronologies contained sufficient fire-free intervals to include the fire suppression era in the analyses (Table 5.5A, Table 5.6A), but analysis of the combined data for all three sites showed an increase in MFI from the pre-settlement period (7 years) to the fire suppression period (22 years; Table 5.5B), and a significant shift ($p < 0.01$) to less frequent fires throughout the study area from the settlement period (MFI = 5 years) to the fire suppression period (MFI = 22 years; Table 5.6B). The analyses of variances (Tables 5.4C, 5.5C, and 5.6C) and distributions (Tables 5.4D, 5.5D, and 5.6D) found no statistical differences between any periods.

5.4.3 Spatial Analyses

The spatial analyses illustrated two relationships among the individual site fire chronologies (Table 5.7). The fire histories for Morrell Mountain and Point Six were similar in terms of MFI, variance, and the distribution of fire-free intervals. The MFIs of Mineral Peak and Morrell Mountain were significantly different ($p < 0.01$), as were their distributions ($p < 0.05$). No differences were found between Mineral Peak and Point Six.

Table 5.4 Results of the temporal analyses between the pre-settlement (POR–1850) and settlement (1851–1920) periods. (A) number of fire-free intervals in period; (B) difference in means; (C) differences in variance; (D) difference in distributions.

		Morrell Mountain	Mineral Peak	Point Six	All Sites
A					
	POR–1850	22	15	6	48
	1851–1920	5	2	6	14
B					
	POR–1850	10	22	22	7
	1851–1920	14	11	10	5
	$\|t\|$-value	0.52	1.18	0.75	0.90
	$p > t$	0.61	0.25	0.48	0.37
C					
	POR–1850	66	193	592	34
	1851–1920	145	5	27	8
	F-value	1.13	11.16	6.82	1.64
	$p > F$	0.65	0.46	0.06	0.34
D					
	K-S d-statistic	0.22	0.80	0.33	0.29
	$p > d$	0.99	0.21	0.89	0.32

Table 5.5 Results of the temporal analyses between the pre-settlement (POR–1850) and fire suppression (1921–POR) periods. (A) number of fire-free intervals in period; (B) difference in means; (C) differences in variance; (D) difference in distributions.

	Morrell Mountain	Mineral Peak	Point Six	All Sites
A				
POR–1850	22	15	6	48
1921–POR	*	*	*	2
B				
POR–1850	10	22	22	7
1921–POR	*	*	*	22
$\|t\|$-value	*	*	*	1.73
$p > t$	*	*	*	0.32
C				
POR–1850	66	193	592	34
1921–POR	*	*	*	338
F-value	*	*	*	1.21
$p > F$	*	*	*	0.54
D				
K-S d-statistic	*	*	*	0.69
$p > d$	*	*	*	0.32

* too few intervals to test between periods

Table 5.6 Results of the temporal analyses between the settlement (1851–1920) and fire suppression (1921–POR) periods. (A) number of fire-free intervals in period; (B) difference in means; (C) differences in variance; (D) difference in distributions. Bold indicates significantly different ($p \leq 0.01$).

	Morrell Mountain	Mineral Peak	Point Six	All Sites
A				
1851–1920 (n)	5	2	6	14
1921–POR (n)	0	0	0	2
B				
1851–1920 mean (yrs)	14	11	10	5
1921–POR mean (yrs)	*	*	*	22
$\lvert t \rvert$-value	*	*	*	**3.22**
$p > t$	*	*	*	0.01
C				
1851–1920 var (yrs)	145	5	27	8
1921–POR var (yrs)	*	*	*	338
F-value	*	*	*	4.63
$p > F$	*	*	*	0.10
D				
K-S d-statistic	*	*	*	0.86
$p > d$	*	*	*	0.15

* too few intervals to test between periods

Table 5.7 Results of the spatial analyses of fire chronologies developed from whitebark pine on three mountains in western Montana. The analyses tested for differences between sites in (A) MFI (|*t*|-value); (B) variance (F-value); and (C) distributions (K-S *d*-statistic).

	Mineral Peak	Point Six
A		
Morrell Mountain	**2.90****	0.79
Mineral Peak	--	1.52
B		
Morrell Mountain	1.99	1.31
Mineral Peak	--	1.07
C		
Morrell Mountain	**0.45***	0.19
Mineral Peak	--	0.30

* $p \leq 0.05$
** $p \leq 0.01$

5.4.4 Fire Seasonality Analyses

The majority of fire events recorded in the fire chronologies of all three sites occurred during the late portions of the growing season, *i.e.* late August to October (Table 5.8; Figure 5.9), which agrees with the modern late-summer fire season of the Northern Rocky Mountains (Brown *et al.* 1994). The fire chronologies of Point Six and Mineral Peak showed little variability within the dominant fire seasonality for the sites, with only one (2%) and two (8%) early season fire events, respectively. Seasonality of fire events in the Morrell Mountain fire chronology was more variable, however, with 10 early season fire events (28%).

5.4.5 Fire-Tree Establishment Relationships

The MDSEA conducted on overlapping 40-yr windows resulted in identical tree establishment values during the overlaps for both the annual tree-establishment chronology (Figure 5.10) and the 5-yr moving average tree-establishment chronology (Figure 5.11). The confidence intervals varied slightly between the 40-yr windows, but the level of statistical significance was identical for all values in the overlaps. These findings justified the union of these results into two 100-yr MDSEA windows.

In general, the trends displayed by both the MDSEA of annual tree establishments (Figure 5.12A) and the 5-yr moving average (Figure 5.12B) are similar. An initial period of low establishment followed the fire event, after which the number of tree establishments increased steadily and peaked *ca.* 50–75 years after the fire event. Tree establishment frequencies decline after the peak period, but are still above the level of establishments that immediately followed the fire event. The relatively erratic values in

Table 5.8 Fire seasonality in whitebark pine forests on three mountains in the Lolo National Forest, Montana, and all sites combined.

	No. fire scars (% of total)			
Fire season	Morrell Mountain	Mineral Peak	Point Six	All Sites
E: May	9 (25)	0 (0)	0 (0)	9 (8)
M: June to early July	1 (3)	1 (4)	0 (0)	2 (2)
L: late July to early August	0 (0)	1 (4)	1 (2)	2 (2)
A: late August	0 (0)	0 (0)	0 (0)	0 (0)
D: September to October	26 (72)	22 (92)	55 (98)	103 (88)

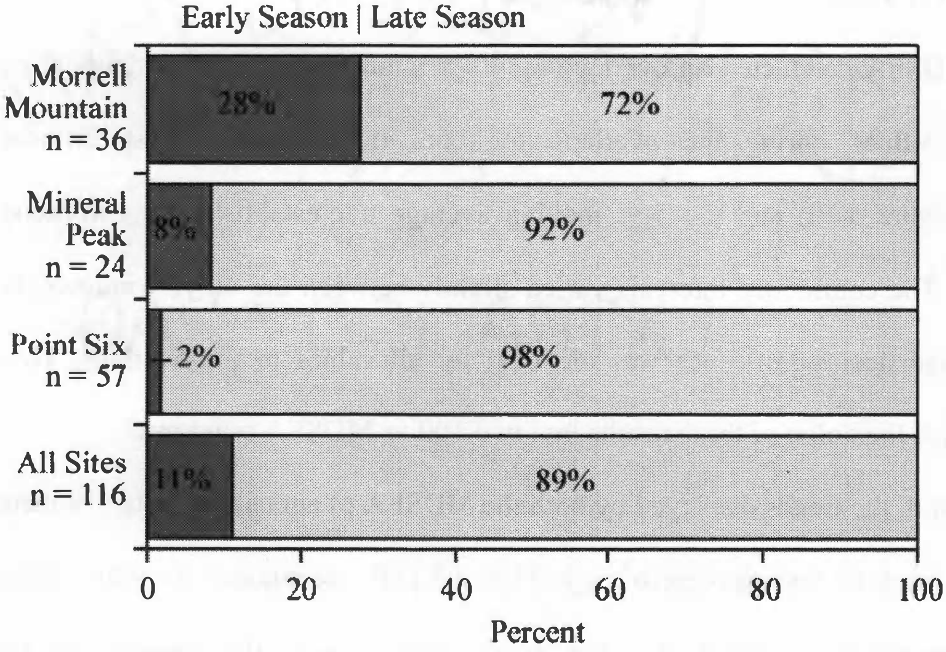


Figure 5.9 Fire seasonality in whitebark pine forests on three mountains in the Lolo National Forest, Montana, and all sites combined.

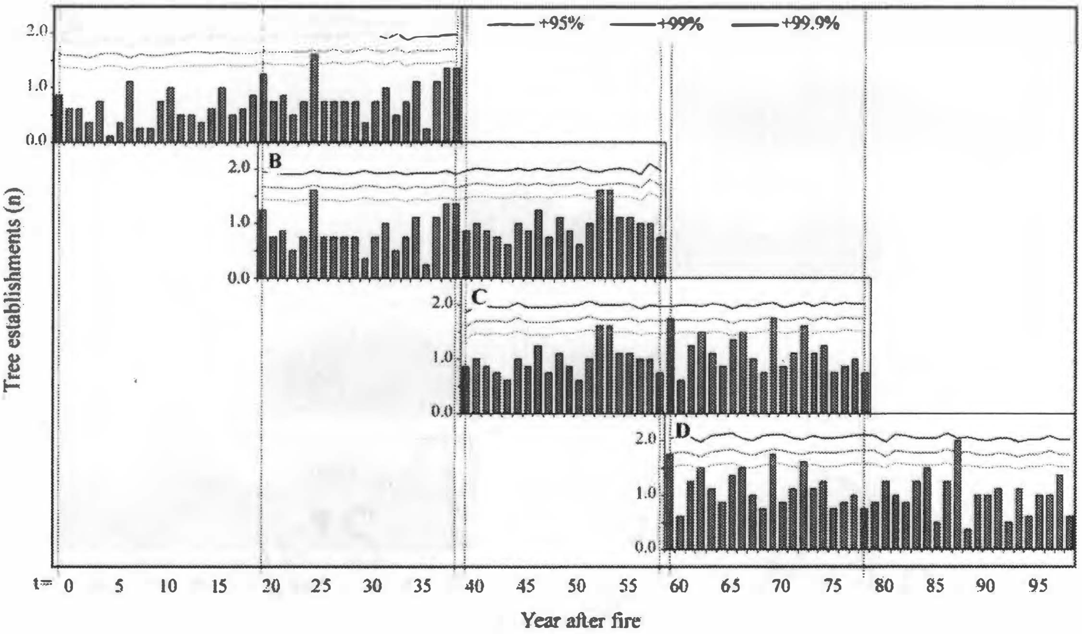


Figure 5.10 Results from four multi-decadal superposed epoch analyses examining the relationship between fire and annual tree establishment. The analyses included tree establishment dates lagged (A) 0 years, (B) 20 years, (C) 40 years, and (D) 60 years. Dotted lines connect the first and last year of each overlapping segment. See Figure 4.2 for the methods used to create the lagged chronologies.

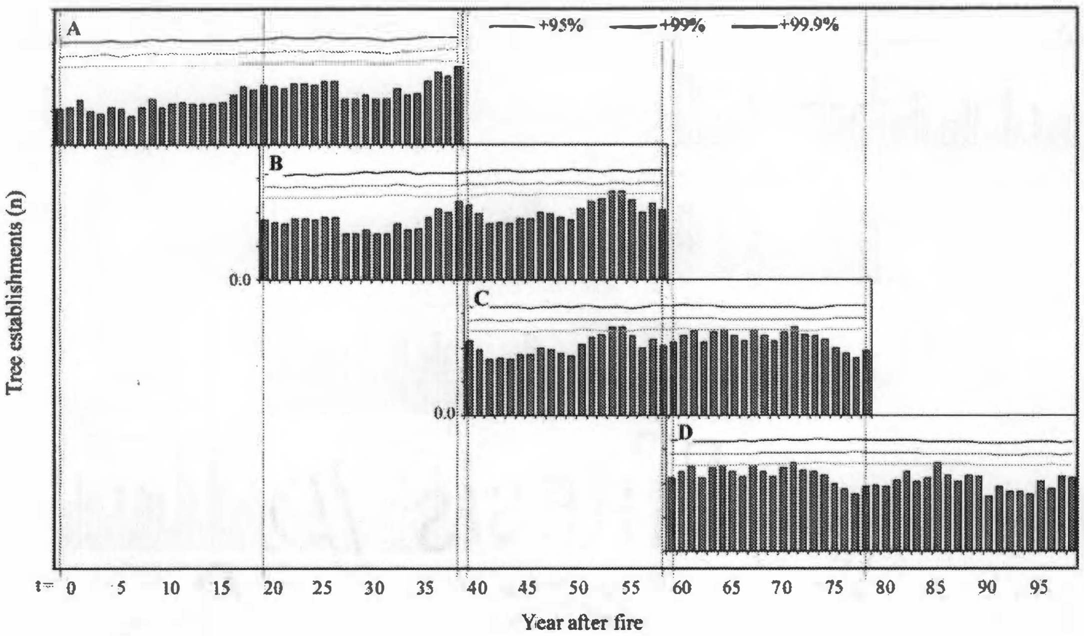


Figure 5.11 Results from four multi-decadal superposed epoch analyses examining the relationship between fire and the 5-yr moving average of tree establishments. See Figure 5.12 for explanations of the methods used.

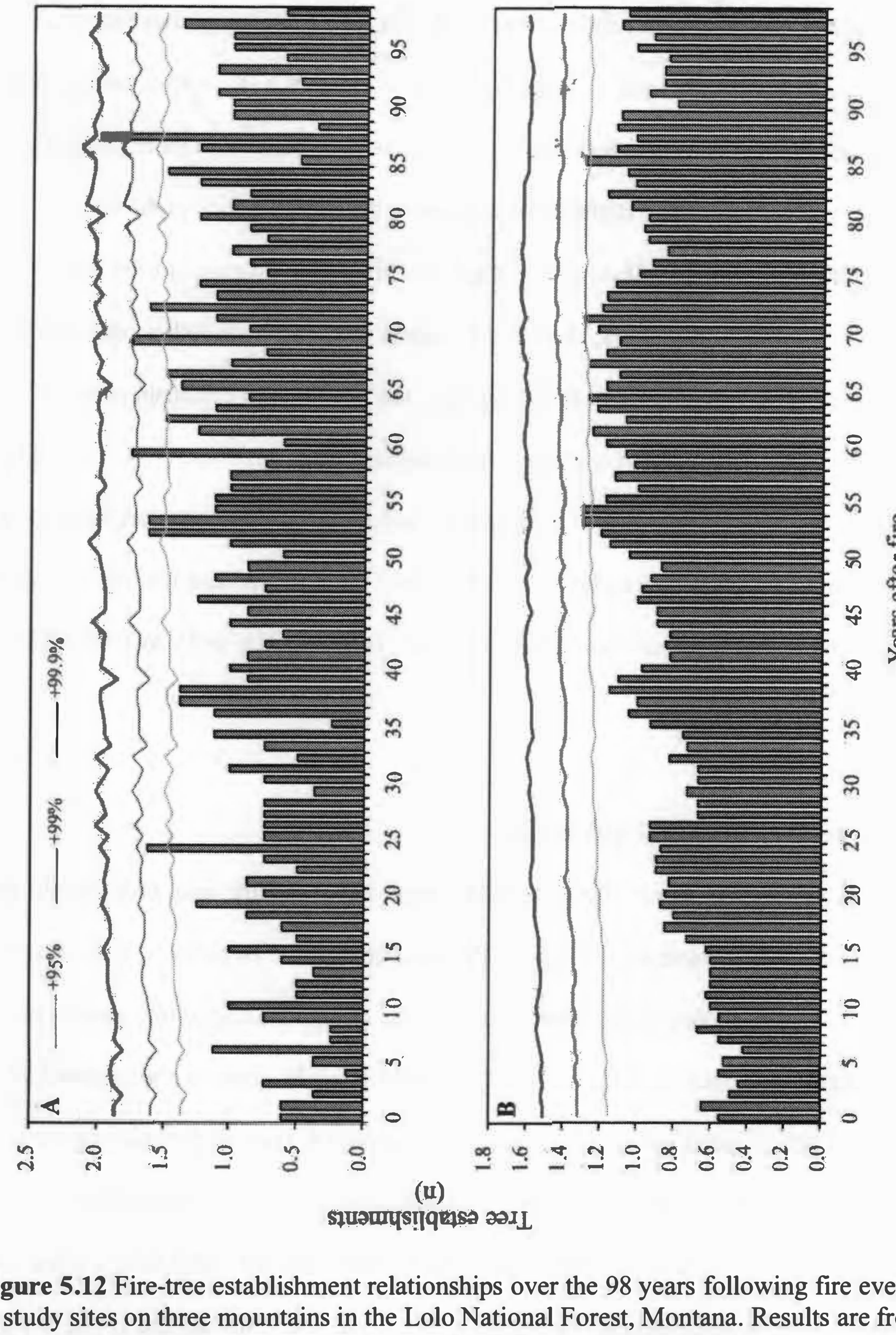


Figure 5.12 Fire-tree establishment relationships over the 98 years following fire events in study sites on three mountains in the Lolo National Forest, Montana. Results are from multi-decadal superposed epoch analyses using (A) annual tree establishments and (B) 5-yr moving average of tree establishments.

the annual tree establishment resulted in several years of significantly above-average tree establishments that range from t+24 to t+87, with a cluster of significant values during the peak period of establishment (t+52, t+53, t+59, t+62, t+66, t+69, and t+72), but these individual years mean little statistically compared to the overall trends of the data.

Although the MDSEA using the 5-yr moving average introduced some autocorrelation into the analysis, the overall pattern provided a smoother representation of the trends in tree establishment following fire. The peak in tree establishment, centered on years of significantly above-average tree establishments at t+53, t+54, t+64, t+67, t+71, includes several independent 5-yr periods and indicates the results are likely not a result of autocorrelation. Variations from the overall trend of the data include periods of relatively more frequent tree establishments from t+16 to t+26, t+35 to t+40, t+50 to t+55, and t+81 to t+89.

5.4.6 Fire-Tree Growth Relationships

The MDSEA found several relationships between fire and both local- and regional-scale tree growth, as well as similarities between the two scales. Results of the MDSEA based on all fire events identified a pattern of below-average tree growth for 39 of 40 years at the local scale (Figure 5.13A) and 35 of 40 years at the regional scale (Figure 5.13B). A trend of strongly below-average growth from t-15 to t-7 is present in both local and regional tree growth, with significantly below average growth in both analyses at t-14 ($p < 0.05$) and t-13 (local = $p < 0.05$; regional = $p < 0.01$). Local tree growth was significantly below average ($p < 0.05$) one year after the fire (t+1), but this relationship was not identified at the regional scale. While the dominant pattern of tree

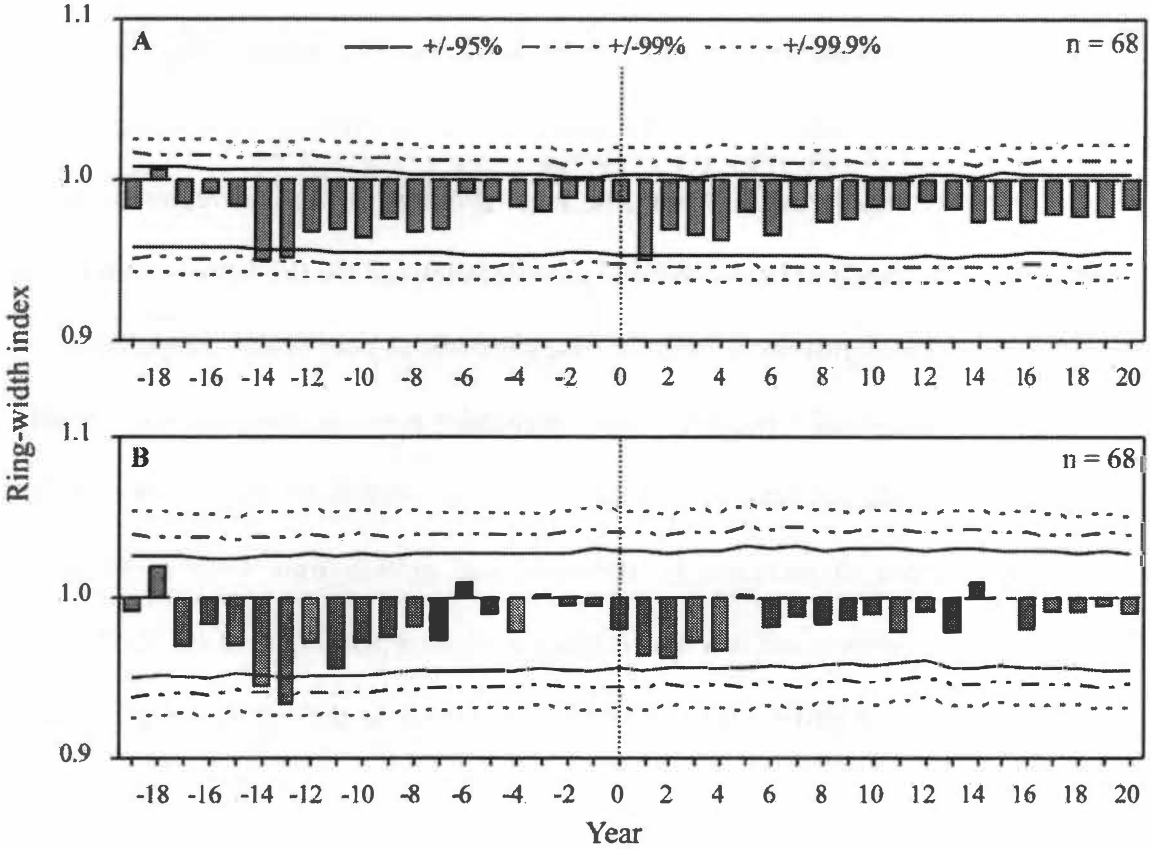


Figure 5.13 Results from multi-decadal superposed epoch analyses of the relationship between all fires and tree growth at (A) local and (B) regional scales. The local analysis used the standardized master ring-width chronology developed from the fire-scarred samples collected in the Lolo National Forest, while the regional analysis used a standardized ring-width chronology developed from whitebark pine on Carlton Ridge in the neighboring Selway-Bitterroot Wilderness Area (Kipfmueller 2003). Bars represent the departure of the average actual ring-width indices (RWI) from the chronology mean RWI of 1.00. The dashed vertical lines indicate the year of the fire event (t = 0).

growth was below average, the magnitude of this trend increased and decreased on *ca.* 4–10-yr intervals, with the year of the fire occurring at a transition from near-average growth rates to relatively lower growth rates at both scales.

The MDSEA conducted with the filtered composite master fire chronology indicated widespread fire events occurred during a transition from near-average growth to strongly below-average growth at both the local (Figure 5.14A) and regional (Figure 5.14B) scales. The trends of below-average growth following the fire lasted several years at both scales, with significantly below-average growth at both scales identified at t+1 (local = $p < 0.05$; regional = $p < 0.01$) and t+4 (local = $p < 0.01$; regional = $p < 0.001$). The years t+7 to t+12 are relatively nearer to average growth for both scales, and are followed by a trend of increasingly above-average growth from t+15 to t+20. An oscillation between above- and below-average growth on a periodicity of *ca.* 20–25 years is evident at the local scale (Figure 5.14A), but less so at the regional scale (Figure 5.14B).

5.5 Fire-Climate Relationships

I identified several relationships between fire activity and climate at multiple scales in my study area over the past 350 years. The overall relationship between temperature and fire activity showed relatively little association (Figure 5.15A). Fires occurred during cool years (*e.g.* the fires of 1781 and 1816) and warm years (*e.g.* the fires of 1754 and 1889), but were not associated with years of either extreme. Generally cooler temperatures occurred during the period of peak fire activity in my sites. Precipitation showed a relatively weak association with fire activity (5.15B). A period of above-

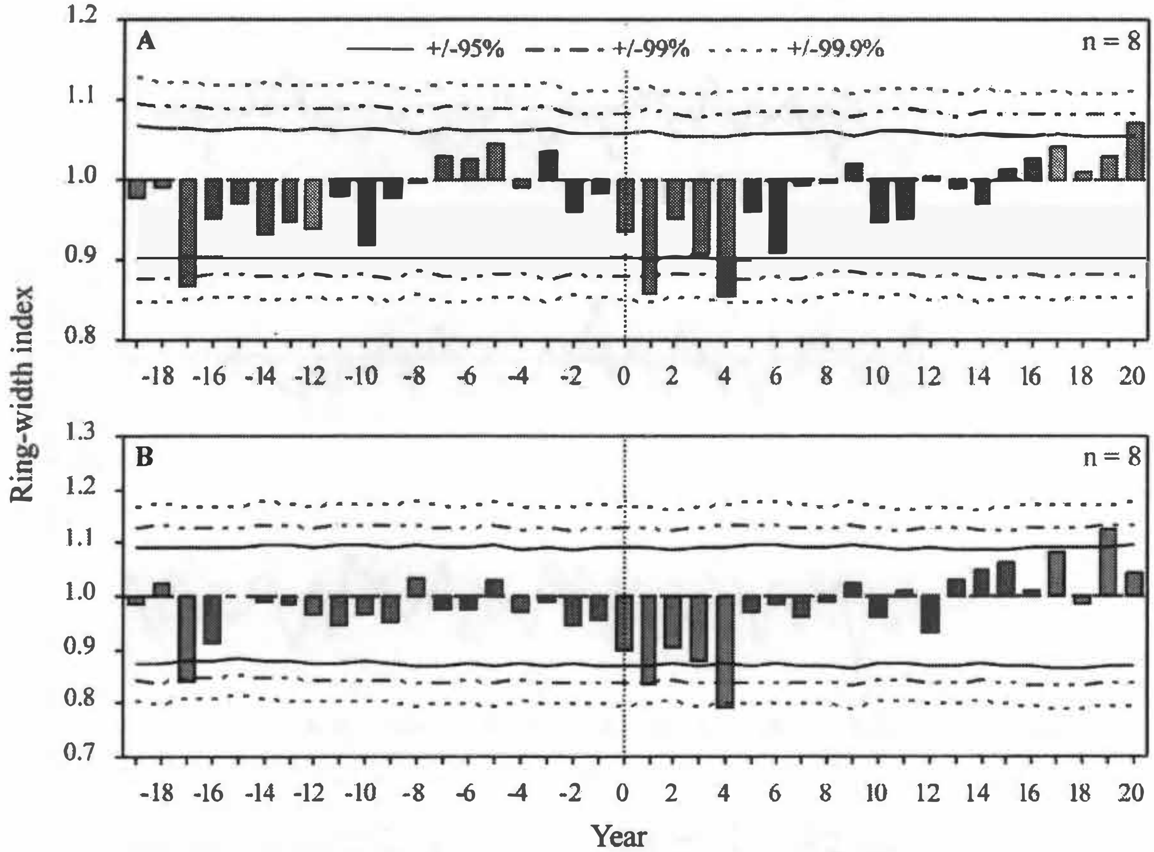


Figure 5.14 Results from multi-decadal superposed epoch analyses of the relationship between widespread fires and tree growth at (A) local and (B) regional scales. See Figure 5.10 for explanation.

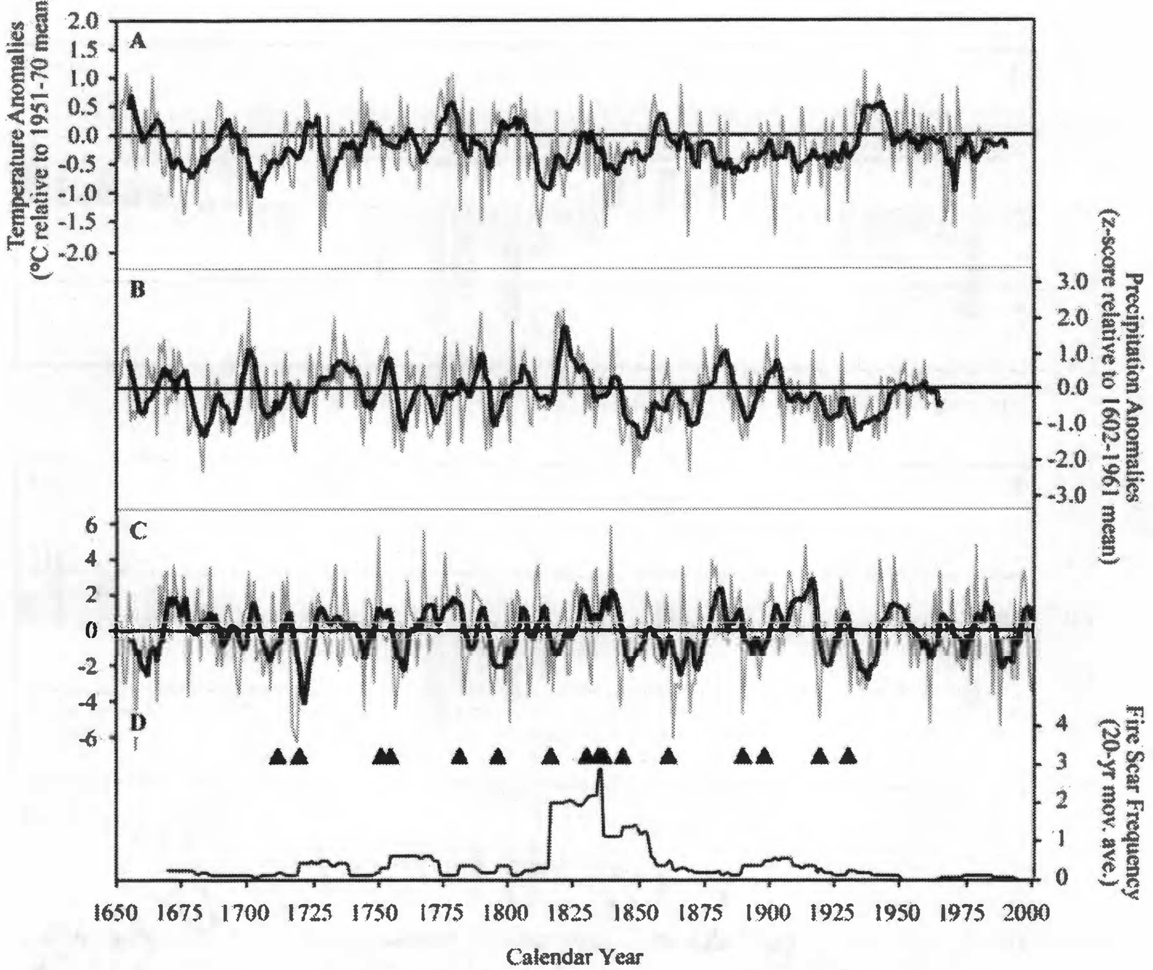


Figure 5.15 Visual representation of the relationships between: (A) temperature (annual and 5-yr moving average; Briffa *et al.* 1992); (B) Precipitation (annual and 5-yr moving average; Fritts 1991); (C) Palmer Drought Severity Index (annual and 5-yr moving average; Cook *et al.* 1999); and (D) fire activity, including a 20-yr moving average of the number of fire scars recorded at all sites. Triangles represent years when multiple trees recorded fire events.

average precipitation coincided with a gap in fire activity from *ca.* 1725–1750, but the wettest period in the reconstruction directly overlapped with the period of peak fire activity in the study area. Comparisons with the reconstructed PDSI showed a somewhat stronger relationship, as several widespread fires (*e.g.* 1719, 1889, and 1919) were recorded during drought years (5.15C). However, both the fires that scarred the greatest numbers of trees (1754, 1816, and 1834) and the peak period of fire activity (*ca.* 1816–1850) occurred during years of generally average to above-average moisture availability.

Several fires were closely timed with specific periods of ENSO activity, but my analyses did not find a consistent pattern between the two (Figure 5.16). Widespread fires occurred during or near strong El Niño events (1719, 1889, and 1919) and La Niña events (1751, 1754, and 1898), but the largest fires (1816 and 1834) and the peak in fire activity coincided with a period of dampened ENSO variability from *ca.* 1810–1850, during which no El Niño events occurred (Cleaveland *et al.* 1992).

Fire activity in my study area appears to be strongly influenced more by multidecadal climate variability (Figure 5.17). No fire events were recorded during the warm phase of the AMO from *ca.* AD 1650–1700. The two widespread fires that burned in the early 1700s occurred during a short cool phase of the AMO, and the widespread fire in 1754 coincided with a transition to a period of extremely low PDO indices in both PDO reconstructions. A strong relationship exists between widespread fire events and the PDO, with 14 of 15 widespread fire events occurring during cool phases of the PDO, and 10 of these within one year of the lowest PDO index of the respective oscillations. The peak period of fire activity is nested within synchronous prolonged, deep-cool phases of

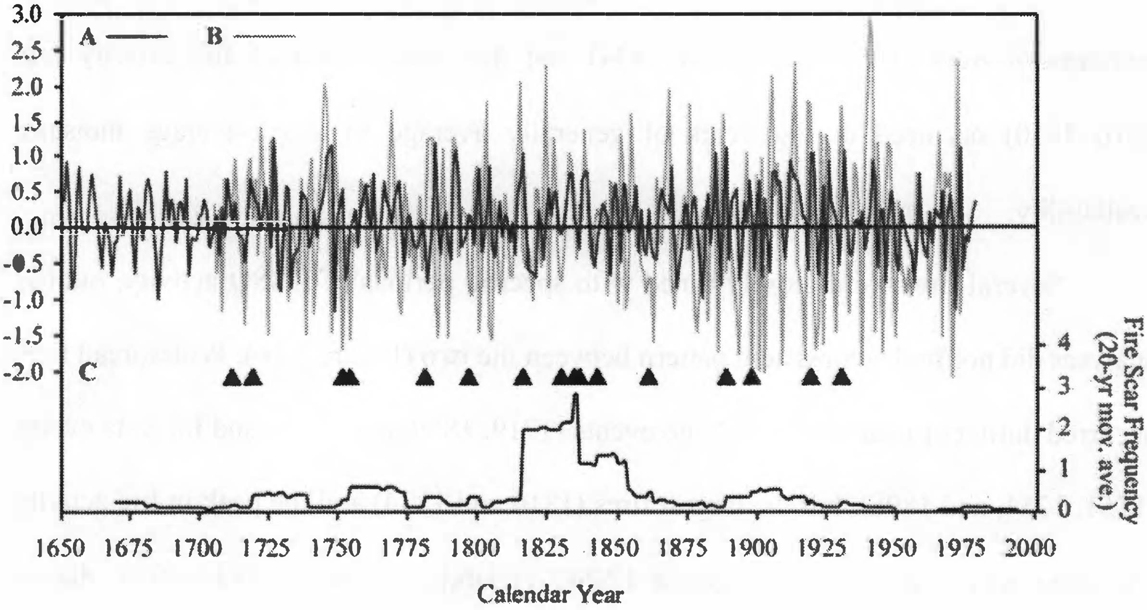


Figure 5.16 Visual representation of the relationship between: (A) Nino3 (D'Arrigo *et al.* in press) and (B) Southern Oscillation Index (inverse z-scores; Stahle *et al.* 1998), with (C) fire activity, including a 20-yr moving average of the number of fire scars recorded at all sites. Triangles represent years when multiple trees recorded fire events.

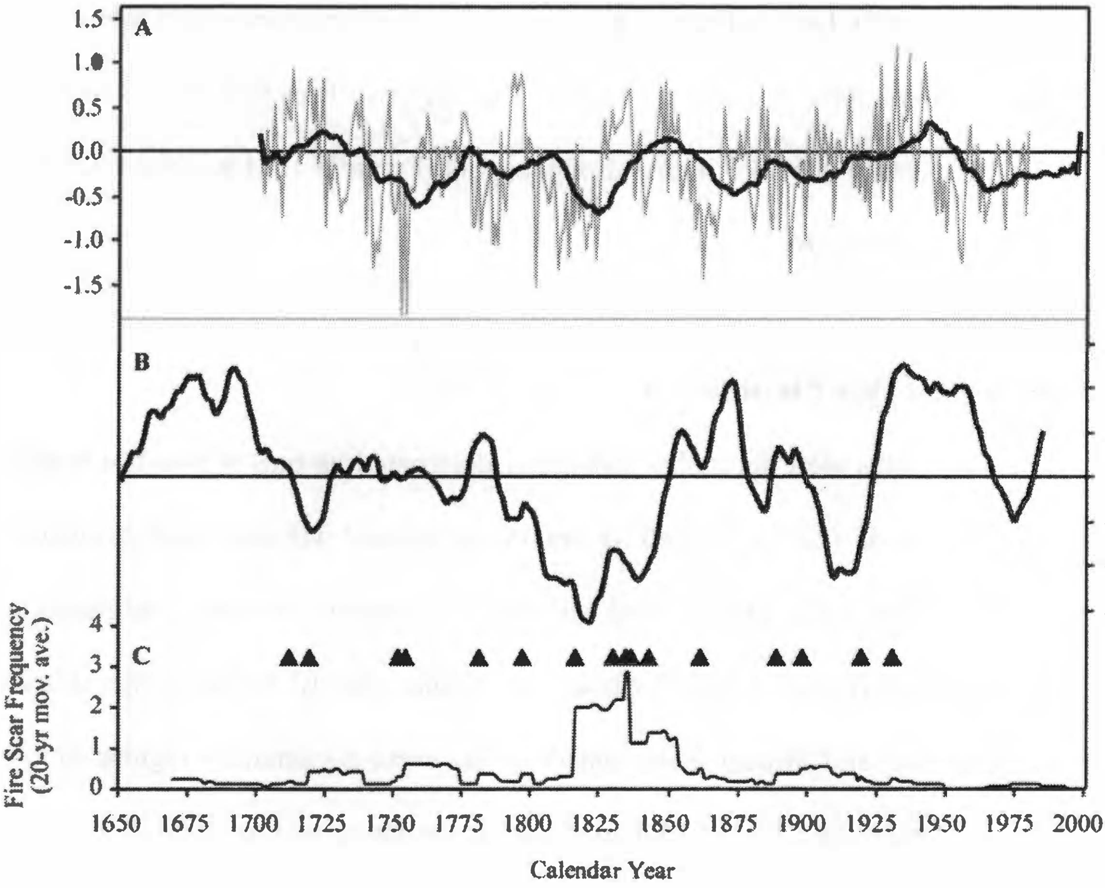


Figure 5.17 Visual representation of the relationship between (A) Pacific Decadal Oscillation (annual and 20-yr moving average; D'Arrigo *et al.* 2001), and (B) the Atlantic Multidecadal Oscillation (Gray *et al.* 2004), with (C) fire activity, including a 20-yr moving average of the number of fire scars recorded at all sites. Triangles represent years when multiple trees recorded fire events.

the AMO and the PDO. This period is followed by *ca.* 50 years during which only one fire scarred multiple trees and coincided with a strongly low PDO index and a downturn in the AMO. The fire activity recorded during the late 1800s occurred during generally cool phases of the PDO, but as all three multi-decadal oscillations moved to warm phases in the early- to mid-1900s, fire activity ceased. The only two fires that scarred multiple trees in the 20th century occurred during drought years (Figure 5.15) that were related to El Niño events (Figure 5.16).

5.6 Fire Regime Type Classification

The study sites were located within areas designated as one of two fire regime types by Schmidt *et al.* (2002). Morrell Mountain was located within an area designated as a type I fire regime, while Mineral Peak and Point Six were within areas designated as type III fire regimes (Figure 5.18). Areas of fire regime type III bordered the Morrell Mountain study site, and Mineral Peak and Point Six were bordered by regions of fire regime type V. Using the LEI and UEI to delineate the range of fire intervals for each site, coupled with evidence of post-fire cohorts in the age-structure data to describe fire severity, the study site on Morrell Mountain would be classified as fire regime type I, while the study sites on Mineral Peak and Point Six could be classified as either fire regime type I or III due to the ranges in fire frequency (Table 5.9).

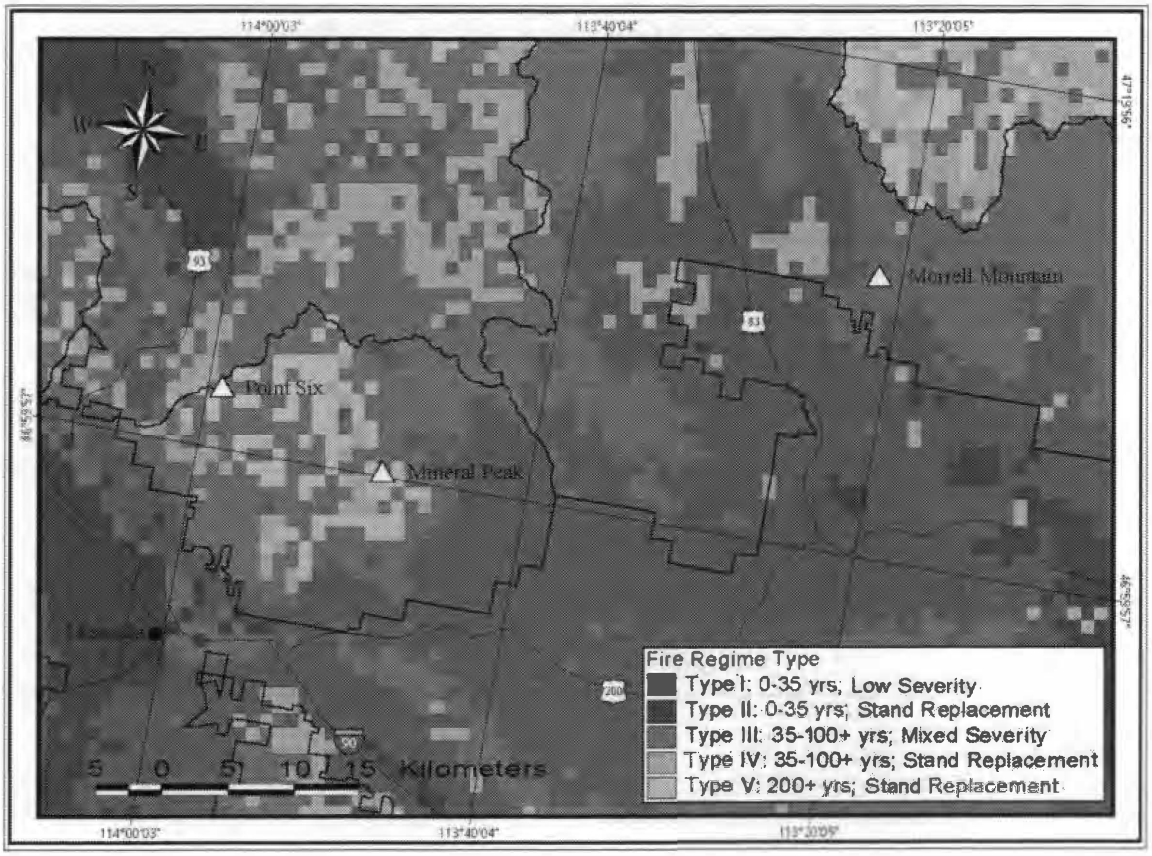


Figure 5.18 Fire regime types for three study sites in the Lolo National Forest, Montana. Classified by Schmidt *et al.* (2002). The national forest is outlined in black, and triangles represent the individual study sites. See Table 1.1 for descriptions of the fire regime types.

Table 5.9 Fire regime classifications for study sites on three mountains in the Lolo National Forest. See Table 1.1 for FRCC fire regime type definitions.

			Fire regime type	
Site	Range[1]	Fire Severity[2]	FRCC[3]	Site Specific[4]
Morrell Mountain	2–27 yrs	Low to mixed severity, replacing less than 75% of the dominant overstory vegetation	Type I	Type I
Mineral Peak	8–44 yrs	Low to mixed severity, replacing less than 75% of the dominant overstory vegetation	Type III	Type I/ Type III
Point Six	3–30 yrs	Mixed severity fires replacing less than 75% of the dominant overstory vegetation	Type III	Type I/ Type III

[1] As defined by the LEI and UEI

[2] As indicated by age-structure data

[3] As defined by Schmidt *et al.* 2002

[4] As derived from dendrochronological research

Chapter Six

6. Discussion

6.1 Fire History and Age Structure of Whitebark Pine Forests

The fire regimes of all three of my study sites were clearly mixed-severity. The stand structure, fire frequency, and fire severity descriptions that I derived from the fire-scar and age-structure data fit the descriptions of forests maintained by this fire regime type (Arno *et al.* 2000). These descriptors include a generally uneven age structure with limited evidence of one or more post-fire cohorts, and fire histories that include numerous small, patchy fires punctuated by less frequent, widespread fires. Fire-scar data alone are insufficient to characterize many subalpine fire regimes (Kipfmueller and Baker 1998), but coupling crossdated fire-scar data with age-structure data proved effective in describing the forests in my study sites.

Comparisons to Previous Fire History Research in Whitebark Pine Forests

While previous research has described the fire regimes of whitebark pine forests as mixed-severity (Arno 2001), fire events recorded in my study sites are more frequent than reported by nearly all other fire history studies conducted in this ecosystem (however, see Morgan and Bunting 1990). When compared to the findings of previous research in whitebark pine forests, the LEI, each measure of central tendency, and the UEI were all lower for my sites than values reported in the studies that did not implement crossdating (Table 2.1). Additionally, the MFIs found by Kipfmueller (2003) were for entire watersheds, and at the scale of individual stands, fire was more common in my study sites.

The disparity between fire frequency at my sites and previous research in whitebark pine forests may be related to several factors, including geographic location, elevation, topography, and the research methods used. The relatively broad geographic range represented by these different studies may create sufficiently different local climate regimes that contribute to different disturbance regimes. In general, the MFIs found in previous fire history studies shift from longer intervals in the southern areas in and around Yellowstone National Park to shorter intervals in the Northern Rockies (Table 2.1). However, latitudinal differences are unlikely to be the main cause of variation in MFIs between sites. Morgan and Bunting (1990) reported a very short MFI in Wyoming, while Keane *et al.* (1994) reported relatively long MFIs for their sites in the Northern Rockies, most of which were within *ca.* 50 km of Morrell Mountain. The lack of a consistent relationship between fire frequency and the geographic location of previously studied whitebark pine forests suggests that other factors likely cause differences in these fire regimes.

Elevation and topography both influence fire regimes in the Pacific Northwest (Heyerdahl *et al.* 2001), the American Southwest (Grissino-Mayer *et al.* 2004), and the Colorado Front Range (Hadley 1994). With respect to the fire regimes of whitebark pine in the Northern Rockies, elevation is unlikely to be the sole source of variation in fire frequency because whitebark pine forests are already limited to elevations above *ca.* 1850 m throughout the region (Arno and Hoff 1990). However, the elevational relief of a site relative to the surrounding area may play an important role in determining fire activity. Many of the previous studies on fire history in whitebark pine forests were conducted within watershed basins, but my sites were located on the upper slopes of peaks that were the highest points in the immediate area. The concave topography of watersheds likely reduces lightning activity in the basin, while the convex topography of my sites creates "islands" of higher elevation that may act as focal points for lightning strikes and lead to more frequent fires, similar to the "Sky Islands" of southern Arizona (Grissino-Mayer and Fritts 1995, Grissino-Mayer *et al.* 1996) and the lake islands of Quebec (Bergeron 1991). Some of the previous studies included fire history data from ridge tops (*e.g.* Arno and Petersen 1983, Keane *et al.* 1994, and Barrett 1994), but only one study specifically collected fire-scarred samples on a peak (Morgan and Bunting 1990), and they in fact reported the shortest MFIs. Additional evidence for increased fire activity on ridges and peaks in whitebark pine forests comes from Barrett (1994a), who noted several whitebark pine trees with multiple fire scars on ridge tops near his study area. The high relief and convex topography of my study sites may therefore have led to the short MFIs recorded at my sites.

While the location, elevation, and topography may have played a role in creating the exceptionally short fire-free intervals recorded at the sites examined using crossdating methods, the fact that all three studies that used crossdating reported lower MFIs than any study that did not use crossdating (Table 2.1) suggests that this pattern is also likely related to the research methods applied. Extremely narrow and locally absent rings are common in high-elevation trees due to episodes of extreme climate and disturbance events (Fritts 1976, Romme 1982), and many of my samples included narrow or missing rings directly after a fire scar (Figures 5.13A and 5.14A). The combined effects of a harsh climate and the relatively high frequency of small, patchy fires in subalpine forests

(Barrett 2000), introduces a large amount of uncertainty in ring counts of fire-scarred samples collected from high-elevation trees such as whitebark pine.

Several studies explicitly stated that uncertainty existed in their fire-scar dates (*e.g.* Romme 1982 and Murray *et al.* 1998), and used age-structure data to corroborate fire dates. However, fire history reconstructions that rely on age-structure data often provide confident reconstructions of large fire events in ecosystems dominated by stand-replacing fire regimes (Kipfmueller and Baker 1998), but tend to underestimate the frequency of small fires that leave minimal or obscure evidence of their passage on the landscape (Murray *et al.* 1998). In addition, the methods for non-crossdated fire-scar-based fire history reconstructions were developed in forest systems where fires were commonly widespread, and some researchers suggested that fire scars in close succession be shifted to represent a single fire event rather than separate events (Arno and Sneck 1977). While this may be appropriate in some ecosystems, this technique would lead to underestimations of fire frequency and overestimations in fire size if applied to the mixed-severity fire regimes of the whitebark pine ecosystem. The combination of the uncertainty in fire-scar dates, the low resolution of age-structure data, and the adjustment of multiple fire dates to represent single fire events could be responsible for some of the differences in MFIs reported by studies that either used or did not use crossdating.

Fire Seasonality and Anthropogenic Influences on the Fire Regime of Morrell Mountain

The dominance of dormant season fires at all three sites agrees with the modern fire season of the Northern Rockies (Barrows 1977, Brown *et al.* 1994). However, the greater variability in the seasons of past fires on Morrell Mountain provides an interesting contrast to the other two sites. Lightning appears to be the dominant ignition source in my study sites due to the seasonality and patchy nature of most fire events recorded in my study area (Barrows 1977). The proximity and overall similarity in geographic setting of Morrell Mountain, Mineral Peak, and Point Six suggest the sites are affected by similar weather patterns, such as the late-summer lightning storms common to the region. The similarity in settings and ignition sources among these three sites would seemingly lead to similarity in fire seasonality. However, the variability in fire seasonality on Morrell Mountain suggests that other factors affected the occurrence of fire events at this site, potentially including anthropogenic activity and land use history (Barrett and Arno 1982, Arno 1985).

Research in the American Southwest has investigated anthropogenic influences on local fire regimes by defining the dominant fire season of an ecosystem, then identifying areas of fire activity that are consistently outside the normal fire season (Seklecki *et al.* 1996, Kaye and Swetnam 1999, Grissino-Mayer *et al.* 2004). The greater variation from the dominant fire season on Morrell Mountain may therefore indicate a fire regime modified by human activity. Supporting evidence for this hypothesis is provided by the presence of bark-peeled lodgepole pines on the flanks of Morrell Mountain (Grissino-Mayer *et al.* in press). Culturally modified trees are associated with Native American activity throughout the West (Swetnam 1984), and have been identified along several major Native American trails in the northwestern U.S. (Bergland 1992, Merrell and Clark 2001). This suggests Morrell Mountain may have been along a travel corridor associated with the settlement near Seeley Lake identified by Arno *et al.* (1997).

Additional supporting evidence for anthropogenic influences on the fire regime of Morrell Mountain comes from the diary of Captain William Clark, of the Lewis and Clark expedition, when camping near Lolo Pass with a group of Flathead Indians (DeVoto 1997):

> Wednesday June 25th 1806
>
> last evening the indians entertained us with setting the fir trees on fire. they have a great number of dry limbs near their bodies which when Set on fire create a very sudden and emmence blaize from bottom to top of those tall trees. they are a boutifull object in this situation at night. this exhibition remi[n]de[d] me of a display of firewo[r]ks. the nativs told us that their object in Setting those trees on fire was to bring fair weather for our journey.

The Morrell Mountain fire tower was built due to the broad view it commanded of the surrounding area, and trees set ablaize on the mountain top would be visible for miles in several directions, including the valley around Seeley Lake. The usefulness of this location for communication, the culturally modified trees, and the intentional use of fire by Native American tribes that inhabited this area all suggest that human activity may be responsible for the variability in fire seasonality on Morrell Mountain.

Age Structure Trends in Whitebark Pine Forests and Periods of Increased Fire Activity

The majority of whitebark pine trees in the study plots on Morrell Mountain and Mineral Peak established during a relatively synchronous period during the AD 1500s and early 1600s. Several lines of evidence suggest these trees represent climate and disturbance related cohorts. The relatively close timing of the establishment of numerous trees suggests that conditions were ideal for establishment during this period. The pioneering nature of whitebark pine (Tomback *et al.* 1993) suggests the occurrence of a widespread disturbance that created suitable openings for whitebark pine establishment.

The lag that occurs in tree establishment following a fire (Figure 5.12) has been identified in other high elevation forests (Little *et al.* 1994), and suggests that widespread disturbances likely affected my sites in the mid- to late-1400s. Disturbances that affect the landscape on a broad scale that could lead to increased establishment of whitebark pines include mountain pine beetle outbreaks, drought, and fire.

The Relationship Between Age-Structure and Mountain Pine Beetle Activity

Epidemic-scale mountain pine beetle outbreaks occasionally lead to widespread mortality in the forests of the Northern Rockies (Bartos and Gibson 1990, Kipfmueller *et al.* 2002). Documented outbreaks in the early 1900s and 1980s affected hundreds of thousands of hectares of subalpine forests in this region (Bartos and Gibson 1990), with the ghost forests of whitebark pine that are scattered across the landscape serving as evidence of these outbreaks (Arno and Hammerly 1984). While the mortality caused by these outbreaks undoubtedly created forest openings suitable for regeneration of the disturbance-dependent whitebark pine (Arno 2001), mountain pine beetles preferentially attack larger, seed producing trees which leads to greatly diminished whitebark pine seed sources following beetle epidemics (Kendall and Keane 2001). Whitebark pine trees can produce cones at 20–30 years of age, but large cone crops typically do not occur until a tree is 60–80 years old (McCaughey and Tomback 2001). The potential delay in whitebark pine regeneration following beetle outbreaks likely provides an opportunity for competitive species that commonly coexist with whitebark pine and are unaffected by mountain pine beetle, such as subalpine fir and Engelmann spruce, to gain dominance in stands previously dominated by whitebark pine (Bartos and Gibson 1990).

Mountain pine beetle activity is also strongly affected by climate and weather (Amman 1972). Beetle larvae are susceptible to short term, extremely cold weather events (Bentz *et al.* 1991, Bentz and Mullins 1999), and extended periods of cooler temperatures can limit the potential for widespread outbreaks in subsequent years (Bartos and Gibson 1990, Safranyik and Linton 1998, Kipfmueller *et al.* 2002). A tree-ring based reconstruction of summer temperature in the Selway-Bitterroot Wilderness Area (Kipfmueller 2003) shows below average temperatures for the region during the second half of the 15th century. While these relatively cooler temperatures suggest mountain pine beetle outbreaks likely were not responsible for the whitebark pine establishment in the 16th and 17th centuries, few studies have reconstructed long-term records of previous beetle outbreaks of this region (Perkins and Swetnam 1996, Kipfmueller *et al.* 2002) and the relationship between mountain pine beetle outbreaks and the age structure of my sites is uncertain.

The Relationship Between Age Structure and Drought

Drought conditions can affect forest structure both directly, by killing trees due to a moisture deficiency (Kitzberger *et al.* 1995), and indirectly, by weakening the resistance of trees to mountain pine beetle attacks (Kipfmueller *et al.* 2002) and by curing fine and coarse fuels that facilitate the spread of fires (Kipfmueller 2003). Regeneration pulses would be related to the end of drought conditions and the establishment of trees on the recently disturbed sites. The 1400s were a period of drought in the Northern Rocky Mountains (Cook *et al.* 1999), but relative to the history of the region, this was not a period of severe moisture deficiency. Although whitebark pine is commonly found on dry, exposed sites (Arno and Hoff 1990), the species is extremely drought tolerant (Weaver 2001) and it is unlikely that a drought of this scale would lead to widespread mortality and the resulting pulse in regeneration. The dry conditions were also coupled with below average temperatures that would limit mountain pine beetle regeneration. The most likely relationship between drought and the regeneration pulse of the 16th and 17th centuries that remains is through drought-related fire activity.

The Relationship Between Age Structure and Fire Activity

While relatively little fire history data in the Northern Rockies extend into the late 1400s and early 1500s (Barrett *et al.* 1997), Arno (1981) suggested that a large fire may have burned near Mineral Peak in the 1500s. Additionally, fire history studies conducted in the Lolo National Forest in lower-elevation forest types that are not susceptible to mountain pine beetle also showed cohorts that established in the early- to mid-1500s (Arno *et al.* 1995, Arno *et al.* 1997). This suggests that the late 15th century may have been a period of widespread fire activity, similar to the peak in fire activity in my study area *ca.* 1816–1850, followed by a period of widespread whitebark pine regeneration in the burned areas. Additional research utilizing the long life-span of whitebark pine may be able to provide information on the causes of this broadly-synchronous period of cohort establishment.

The 1601 Frost Ring and Volcanic Climate Forcing

The presence of the AD 1601 frost ring in the majority of samples alive in that year coincides with a known period of increased global volcanic activity, culminated by the eruption of Huaynapatina in the central Peruvian Andes in 1600 (Thouret and Dávila 1999, Thouret *et al.* 2002). This eruption affected global climate by ejecting enough material into the upper atmosphere to cause the summer of 1601 to be the coldest in the Northern Hemisphere over the past 600 years (Briffa *et al.* 1998a, de Silva and Zielinski 1998, Gervais and MacDonald 2001). The event is associated with widespread frost damage recorded by bristlecone pine trees on the White Mountains of California (LaMarche and Hirschboeck 1984) and extremely low latewood density in tree-ring chronologies for northern North America (Jones *et al.* 1995, D'Arrigo and Jacoby 1999, Luckman and Wilson 2005).

Ring-width based temperature reconstructions in central Idaho and along the Idaho-Montana border identified generally cooler temperatures during this period, and while 1601 was the coldest year of the surrounding decades, the event was not as extreme as recorded in other regions (Biondi *et al.* 1999, Kipfmueller 2003). Neither of these studies reported the presence of frost damage in 1601 to the extent that is evident in my samples. Several factors may be responsible for these differences in site sensitivity. Many of the whitebark pine trees on my sites were relatively young in 1601, and, if a widespread disturbance had affected my sites in the late 15th century, they were likely growing in relatively open and harsh environments. The increased occurrence of frost damage at my sites may therefore be related to the physiological characteristics of immature trees (*e.g.* relatively thinner bark) growing in an exposed environment (Schweingruber 1996).

Another factor that may have played a role in the distribution of frost rings in the region is the landscape itself. If the extreme cold associated with the 1601 growing season followed the crest of the Rocky Mountains similarly to polar outbreaks common to this region (Dalavalle and Bosart 1975), the Bitterroot Range may have blocked the cold air to the east. The resulting temperature differences between my sites in the Lolo National Forest and the sites in the Selway-Bitterroot Wilderness Area and central Idaho could explain the differences in the occurrence of frost damage. A gridded network of high-elevation chronologies between these sites could be used to map the occurrence of widespread frost damage and describe the varying effects of this event on the region.

6.2 Spatiotemporal Variations in Fire Activity

Temporal Variations in Fire Regimes of Whitebark Pine Forests

The shift from more frequent fires prior to the settlement era to almost no fire events following the onset of fire suppression documented in my study sites follows the general trends identified in other ecosystems characterized by short-interval fire regimes throughout western North America (Kilgore and Taylor 1979, Dieterich 1983, Swetnam 1983, Barrett 1994b, Grissino-Mayer 1995, Murray *et al.* 1998, Kipfmueller and Baker 2000, Heyerdahl *et al.* 2001, Grissino-Mayer *et al.* 2004). However, research in subalpine and boreal forests characterized by infrequent, severe fires found little evidence of changes in the fire regimes of these ecosystems due to anthropogenic activity (Romme and Despain 1989, Johnson *et al.* 2001, Sherriff *et al.* 2001). The whitebark pine forests in my study area provide an interesting contrast between these findings, as they are both subalpine forests and characterized by short-interval fire regimes.

Comparisons of the MFIs between the pre-settlement and settlement periods for individual sites were limited due to the small number of fire events recorded during the settlement period, but little overall change in fire frequency was found between these periods. Although studies in both short-interval fire regimes (Goldblum and Veblen 1992, Hadley 1999) and long-interval fire regimes (Johnson *et al.* 1990) have identified increased fire activity during initial Euro-American settlement, the activities associated with these changes (*e.g.* mining, road construction) did not take place near my study sites until the 20th century, and therefore had no impact on the settlement-period fire regimes of my sites.

The near-cessation of fire activity after 1920 in my study sites coincides with several improvements in the effectiveness of fire suppression in the Northern Rocky Mountains. The fire towers on Morrell Mountain and Mineral Peak were constructed in the 1920s (NHLR 2005), and the ensuing continual human presence would make fire suppression highly effective in extinguishing the small fires that commonly occurred on these sites. This was also a period of extensive road and trail construction throughout the national forest system (Dilsaver 1994), and with its proximity to Missoula and improved access, fire suppression was also likely effective at minimizing the spread of spot fires on Point Six. Technological advances during this time increased the efficacy of fire suppression in lower-elevation ecosystems (Pyne 1982, van Wagtendonk 1991), which limited the upslope migration of fires into the subalpine zone (Tomback *et al.* 2001a). These factors likely combined to be highly effective at reducing the number of small fires that burned in my study sites.

Similar changes in fire occurrence have been identified in subalpine forests near my study area. Kipfmueller (2003) recorded no fire events that burned more recently than 1934 in three watersheds in the Selway-Bitterroot Wilderness Area. A landscape-scale analysis of the Selway-Bitterroot Wilderness Area found the modern average annual area burned is nearly half of the area burned each year during pre-settlement times (Brown *et al.* 1994). Keane *et al.* (1994) suggested that 60 years of fire suppression significantly reduced fire activity throughout the Bob Marshall Wilderness Complex, just north of the Lolo National Forest. Although fire suppression offers a reasonable explanation for the reduced fire activity at my sites, other potentially influential factors require consideration as well, including stand structure, fuel availability, and climate.

Morgan and Bunting (1990) found fire activity to be greatest in the early and late portions of the life-history of individual stands, and proposed that trends in fire activity were related to successionally determined stand structure and fuel availability. The cycle they describe includes frequent, low-severity fires in young, post-disturbance whitebark pine forests due to the abundant fine fuels provided by the herbaceous species that commonly establish under the relatively open conditions created by high-intensity fires. As the stand develops and canopy cover increases, the herbaceous species become less abundant, and the resulting reduction in fine fuels leads to fewer spreading ground fires. This in turn allows subalpine fir to begin establishing in the site. As subalpine fir becomes increasingly common in a stand, the canopy becomes denser and the amount of available light on the forest floor lessens, further decreasing the growth of grasses and other fine fuels. The reduced light levels also lead to less evaporation at the forest floor and increases total moisture availability. This results in minimal fire activity during the middle age of the stand. As the subalpine fir mature and grow into the canopies of the mature whitebark pine, they provide ladder fuels that, under extreme weather conditions, can lead to stand-replacing fires that begin the cycle over again.

While the age-structure data of my sites generally agree with this proposed cycle of stand development, the fire-scar data do not. In all of my sites, whitebark pine established first following severe fire events, after which subalpine fir began moving into the stand, as suggested by Morgan and Bunting (1990). Fire activity showed little temporal variation related to the age of the stands in my study sites. However, the largest fires recorded in my study area occurred within a period from *ca.* AD 1719–1850, which is nearly synchronous with the period of greatest fire activity from *ca.* AD 1700–1850 at Russell Peak (Morgan and Bunting 1990). While the timing of these fires may be related to many factors, this may be evidence of regional-scale climate forcing on the fire regimes of whitebark pine.

The Effects of Fire Suppression on the Structure of Whitebark Pine Forests

The dominant paradigm states that modern fire suppression has exacerbated structural changes and advancing succession in whitebark pine forests throughout its seral distribution (Keane *et al.* 1990b, Arno *et al.* 2000, Tomback *et al.* 2001a). The suppression of lightning ignitions in the subalpine zone has reduced the number of fires that grow and spread through upper-elevation forests, and fire suppression in low elevation forests has limited the upslope migration of fires that may have historically moved into the subalpine zone (Tomback *et al.* 2001a). While fire suppression may be partially responsible for the decreased fire frequency in my study area during the 20th century (Table 5.6), the structural and compositional effects of the shift to less frequent fires are unclear.

The age-structure data indicate that subalpine fir began establishing in my study sites well before fire suppression affected the landscape. Subalpine fir trees are highly susceptible to fire-related damage and mortality (Flint 1925). While the majority of the oldest fir trees on Mineral Peak and Point Six established following widespread and likely severe fires, the numerous small fires recorded at these sites, as well as the fires recorded on Morrell Mountain, showed little reflection in the age-structure data. While fire suppression may have contributed to the reduced occurrence of small fires over the past 70–80 years, the fire-scar and age-structure data indicate that widespread, severe fires were rare in these stands over the past several centuries. This suggests that despite the fact that all three stands are now advancing toward later successional stages, the time since the last widespread fire, and hence age structure, are within the historical range of variability for these sites.

Spatial Variability in the Fire Regimes of Whitebark Pine

Variations in land cover and topography strongly affect fire behavior at local scales (Hadley 1994, Grissino-Mayer 1995, Beaty and Taylor 2001, Heyerdahl *et al.* 2001, Arabas *et al.* in prep). The differences between the fire histories of my three study sites reflect the variability of these site characteristics. The lack of differences identified between the fire histories of Morrell Mountain and Point Six is related to the placement of both study sites within relatively continuous forests on west/southwest-facing slopes of both peaks. In contrast, the more dissimilar study site on Mineral Peak was located within a highly dissected forest that spread in fingers to the south, southwest, and west. The continuity of the land cover on Morrell Mountain and Point Six led to both a greater number of fires and a greater number of fires that scarred multiple trees throughout the sites. The open structure of the forest on Mineral Peak provided limited fuels as ignition sources, and the talus acted as a fire barrier, limiting three of four fires that scarred multiple trees to individual clusters.

The smaller number of fires recorded on Mineral Peak may also be related to the southerly aspect of the clusters compared to the more west-facing sites on Morrell Mountain and Point Six. Aspect has commonly been correlated to fire activity via moisture gradients and forest types (Beaty and Taylor 2001, Heyerdahl *et al.* 2001), but I suggest that in my study sites aspect is more important with respect to ignitions. If weather moves into these sites from the west, storms would break more heavily upon the west-facing slopes, which would lead to higher rates of lightning strikes and ignitions on these aspects.

Additional differences in fire regimes exist among the sites related to topographic effects that warrant discussion. The fire-scar and age-structure data show that Point Six experienced two or three severe fires in the past 400 years (*ca.* AD 1600, 1719, and 1816) compared to Mineral Peak that showed two potential post-fire cohorts (*ca.* AD 1550 and 1880), and Morrell Mountain that showed evidence of one post-fire cohort (*ca.* AD 1500). This change in fire severity may be related to topography and moisture availability. Local relief affects both the severity and pattern of burns (Hadley 1994), and the relatively less steep portion of the study site on Point Six may have led to less patchy fires that burned with more intensity than fires on the other, steeper sites. Another factor that may have contributed to the differences in fire severity between sites is the rain shadow of the Bitterroot Range that extends over much of the Lolo National Forest

(Owenby *et al.* 1991). This rainshadow creates a gradient of moisture from the relatively drier conditions on Point Six, to slightly more moist conditions on Mineral Peak, to the wettest conditions on Morrell Mountain. This gradient is amplified by the orographic influences of the Continental Divide that lies just to the east of Morrell Mountain and further increases precipitation at that site. The drier conditions at Point Six may have facilitated the spread and increased the severity of fire events, while the moderately moist conditions on Mineral Peak may have limited the spread and severity of fires, and the moist conditions on Morrell Mountain inhibited the growth of fires.

To sum up these differences, the fire history of Point Six included the most wide-spread and severest fires due to the relatively drier conditions, less steep topography, and more continuous forest cover. The fire history of Mineral Peak indicated relatively low average fire severity due to the drier conditions, steep topography, and dissected forest cover. The fire history of Morrell Mountain indicated low to moderate fire severity due to the relatively wetter conditions, steep topography, and continuous forest cover.

6.3 Relationships Between Fire Activity, Tree Establishment, and Tree Growth

Fire-Tree Establishment Relationships in Whitebark Pine Forests

The *ca.* 50–75-yr lag I identified in peak tree establishment that followed widespread fires is similar to rates of tree establishment following disturbances in other subalpine ecosystems (Agee and Smith 1984, Little *et al.* 1994). The harsh conditions of my sites would be exacerbated by the exposed site that likely existed after experiencing a widespread fire. The rate of tree regeneration is likely a function of several site conditions, including the depth of the winter snow pack and timing of the spring meltoff

(Douglas 1972), winter and summer desiccation (Hadley and Smith 1983, 1989, Cui and Smith 1991), and microsite conditions (Vale 1981). Individual species appear to respond differently to these conditions, and the age structure of Point Six shows whitebark pine is the first to regenerate following a fire and is soon followed by subalpine fir (Figure 5.7C). In my study, I outlined a use of MDSEA that may prove useful in future research that examines long-term ecosystem responses to disturbance events.

Fire-Tree Growth Relationships in Whitebark Pine Forests

The original intent of my analyses of the relationship between fire events and tree growth was to quantitatively describe the effects of fire on the growth of whitebark pine trees. Instead, I found growth trends in the years that surround the fire events that could only be caused by regional climate. When considering all fires, the trend of nearly 40 years of below-average growth cannot be a response to damage from fire, as tree growth is strongly below average for nearly 20 years leading up to the fire event. Furthermore, the growth trends in the fire-scarred samples from my study sites are nearly identical to the growth trends of the whitebark pines used to develop the Carlton Ridge chronology from the Selway-Bitterroot, which were not scarred by fire (Kipfmueller 2003). The trend of significantly below-average growth during the years after widespread fires that then shifts to strongly above-average growth by the 20th year after the fire must also be a result of climate due to the synchrony and similarity of these trends between the local fire-scarred whitebark pine trees and the regional non-fire-scarred trees. While individual years of significantly above- or below-average growth mean relatively little statistically, the overall trends in the data provide valid evidence of the role of climate in the timing of fire events.

While the actual climate events responsible for these patterns in tree growth are not identified by these analyses, conclusions can be drawn about their nature from the trends in the data with respect to the climate response of whitebark pine trees in the Northern Rocky Mountains. Perkins and Swetnam (1996) found whitebark pine growth to be positively correlated with winter and spring precipitation and inversely correlated with May temperatures in central Idaho. They suggested that, due to the arid environment of their sites, these correlations are likely a response to seasonal snow pack, with increased winter and spring precipitation increasing moisture availability throughout the growing season and higher May temperatures speeding the onset of summer droughts.

Kipfmueller (2003) identified summer temperature as the primary limiting factor of whitebark pine growth in the Selway-Bitterroot Wilderness Area, and in contrast to the findings of Perkins and Swetnam, found the strongest relationship to be a positive correlation between tree growth and average maximum July temperatures. Water stress is less likely in the relatively moist Northern Rocky Mountains, and therefore warmer summer temperatures led to increased levels of growth throughout the growing season. July precipitation was negatively correlated with tree growth, but Kipfmueller suggested this could be due to the effects of cloud cover lowering temperatures rather than increased moisture reducing tree growth. Kipfmueller also examined whitebark pine growth with respect to the PDO, and suggested tree growth may be enhanced during positive phases of the PDO, and climate sensitivity may be dampened during negative phases of the PDO due to greater snowfall.

A shift in the climate response of whitebark pine in the Selway-Bitterroot Wilderness Area occurred in the latter half of the 20th century, as an inverse relationship with spring temperatures became the dominant signal in tree growth (Kipfmueller 2003). During this time, warmer spring temperatures would be accompanied by more early spring precipitation, likely in the form of snow. The insulating layer of snow would keep the ground and soil moisture frozen, while the warmer days would induce respiration and transpiration in the tree when photosynthesis is not occurring, causing a net loss in photosynthates (Fritts 1976). The mechanisms behind this shift in climate-response are complex, but Kipfmueller suggests it may be related to a shorter growing season due to shifting snow pack conditions potentially related to PDO phase changes. While nearly all of the fire events recorded in my study area occurred prior to the identified shift in climate response of whitebark pine, interpretations of the growth trends identified in my MDSEA should be cautious because of the potentially shifting climate response of subalpine tree growth (Briffa *et al.* 1998b, Biondi 2000).

Due to the moist climate of the Lolo National Forest, the climate response of trees in my study area will likely be more aligned with that of the Selway-Bitterroot Wilderness Area than with central Idaho. However, the signal may be somewhat different due to the drying effects of the Bitterroot rainshadow on my sites. I therefore propose that below-average growth identified in my analyses may be the result of: 1) above-average summer temperatures and the resulting moisture stress; 2) lower summer temperatures and the resulting lower growth rates; or 3) warmer spring temperatures, increased snow pack, and a net loss of photosynthates. Above-average growth identified in my analyses may be the result of: 1) cooler summers and more moisture availability; 2) higher summer temperatures and higher growth rates; or 3) cooler spring temperatures, less precipitation, and a longer growing season.

The trend of nearly 40 years of below-average growth indicates that the majority of the fires recorded in my sites occurred during a phase of climate variability that consistently limited growth for multiple decades. The increasing and decreasing amplitude of the below average growth evident from the analyses suggests that another climate oscillation is operating on a shorter wave length within the context of the lower frequency variability. The growth trends that surround the widespread fires also provide evidence of a climate oscillation that operates on a shorter, 20–30 year wavelength. Widespread fires occurred during a transition of this oscillation from a phase that encouraged average to above-average growth to a phase that caused below-average growth.

6.4 Fire-Climate Relationships

Effects of Climate on Whitebark Pine Fire Regimes

Variability of fire regimes in nearly all ecosystems has been linked to climate (Clark 1989, Johnson and Larsen 1991, Swetnam 1996, Swetnam and Betancourt 1998, Grau and Veblen 2000, Grissino-Mayer and Swetnam 2000, Veblen *et al.* 2000, Kitzberger *et al.* 2001, Sherriff *et al.* 2001, Heyerdahl *et al.* 2002, Kipfmueller 2003, Westerling and Swetnam 2004). Increasingly, ocean-atmospheric teleconnections that operate on different time scales and source from different regions of the world are shown to affect regional climate and fire activity in the high-elevation forests of North America (Gray *et al.* 2003, Schoennagel *et al.* 2005, Sibold and Veblen 2005). The fire regimes of my sites were influenced by a multi-scale hierarchy of interacting climate conditions that affected fire occurrence.

At the annual scale, widespread fires in the Rocky Mountains are commonly associated with individual years of significant drought (Kipfmueller and Swetnam 2000, Sherriff *et al.* 2001). Precipitation also plays a significant role in the fire regimes of dry forests throughout western North and South America (Baisan and Swetnam 1990, Grau and Veblen 2000, Veblen and Kitzberger 2002, Norman and Taylor 2003), with years of above average precipitation increasing the growth of fine fuels, and subsequently increasing the likelihood of fires in the years that follow. The relatively limited relationships between temperature, precipitation, drought, and fire activity in my sites (Figure 5.15) may be related to the limited spatial scale of my study area. No clear relationship between precipitation and fire activity was found in my data. Some fire events were preceded by several years of below-average precipitation (*e.g.* 1889 and 1919), while other individual fire events occurred during years of above-average precipitation (*e.g.* 1754, 1781, and 1817). The association between extended periods of precipitation and fire activity also varied, with a gap in widespread fires aligning with a period of above-average growth from 1725–1750, and the peak in fire activity for the study area coinciding with the wettest period of the reconstruction (*ca.* 1815–1835).

Temperature and drought, on the other hand, both show stronger relationships with fire activity when considered on a broader temporal scale and in the context of additional climatic conditions. At the semi-annual scale, years of drought that coincided with El Niño events were more likely to result in regionally widespread fires (e.g. 1889 and 1919; Kipfmueller 2003) than when either of these conditions occurred alone. The generally cooler than average temperatures that occurred during the peak period of fire activity in my sites did not likely increase fire activity, but were rather a local expression of a climate event that encouraged fire activity on a multi-decadal time scale.

My fire-tree growth analyses found that most fires were associated with prolonged periods of decreased growth, perhaps associated with cooler temperatures, which compares well with the phases of the PDO and AMO during the peak period of fire activity (Figure 5.13). Additionally, the 20–30 year oscillation in tree growth identified in my MDSEA match the synchroneity of widespread fire events with periods of cool phase PDO (D'Arrigo *et al.* 2001), and suggest that conditions immediately surrounding and following the minima of PDO cool phases reduce tree growth and are conducive to widespread fire events in my study sites.

The period of cool PDO and AMO centered on the early 1800s, coupled with decreased ENSO variability from *ca.* 1810–1850, appears to have acted synergistically to create the peak period of fire activity in my site. This directly contrasts the findings of nearly all other fire history research in western North and South America that identified a distinct gap in fire activity during this time (Swetnam 1990, Grissino-Mayer and Swetnam 2000, Veblen *et al.* 2000, Kitzberger *et al.* 2001, Heyerdahl *et al.* 2002, Grissino-Mayer *et al.* 2004, Sibold and Veblen 2005). Additionally, the relatively less frequent fires prior to this time in my study sites contrasts with a period of more frequent fires in several of these studies (*e.g.* Grissino-Mayer 1995). The location of my study site is at the convergence of contrasting regional climate boundaries and influences of some ocean-atmospheric teleconnections (Dettinger *et al.* 2001). While this may partially explain the inverse pattern of fire activity at my sites in comparison with other research, the mechanisms behind these differences are unclear.

6.5 Management of Whitebark Pine

Fire Regime Condition Classification Fire Regime Types for Whitebark Pine Forests

The FRCC fire regime types assigned to my study sites were generally appropriate with respect to the fire regime types identified by my data, and portrayed some spatial differences between the sites. My data from the three sites portrays mixed-severity fire regimes similar to those assigned by the FRCC data. The FRCC data also delineated the difference in fire severity between the relatively more severe fires that burned on Point Six and Mineral Peak and the less severe fires that burned on Morrell Mountain. However, potentially important inadequacies included an underestimation of the fire frequency in the forests on Mineral Peak and Point Six and a failure to account for the temporal variability in past fire activity.

The FRCC fire regime type III assigned to Mineral Peak and Point Six described fire return intervals that ranged from 35–100+ years, but both sites recorded fire frequencies well below this range with lower bounds of 8 and 3 years, respectively (Table 5.9). The discrepancies between the FRCC fire frequency and the actual data for Mineral Peak and Point Six are due to the high number of small fires recorded at these sites. The ecological significance of such small fires in subalpine forests is thought to be relatively minor (Romme 1982), but this conclusion is drawn from research conducted in subalpine forests predominantly composed of lodgepole pine and spruce. Relatively little research has addressed the role of small fires in the whitebark pine ecosystem, and the research that has examined whitebark pine fire regimes may have underestimated the frequency of fire occurrence in this ecosystem (Table 2.1). The use of these data for FRCC fire regime type assignments would explain the underestimation of fire frequency in these stands, but site-specific differences in the fire regimes of these sites relative to their surroundings are lost in the coarse scale of the FRCC data. The precarious situation and ecological importance of the whitebark pine ecosystem warrants a site-specific approach to management practices that may be beyond the scope of the FRCC guidelines.

The temporal variation in fire activity at these three sites highlights a critical aspect of fire management. Statistical measures of central tendency, such as MFI, are often integrated into management plans as static targets that do not account for the dynamic nature of fire regimes (Whitlock *et al*. 2003). While the concept of the natural range of variability in disturbance regimes (Morgan *et al.* 1994a) is increasingly being applied in ecosystem management, this perspective must be based on sound scientific data (Brown 2000). In the case of whitebark pine, these data are lacking for much of the range of the species. Additionally, the variability in the fire regimes of my sites was strongly related to changing climate conditions that operated on annual to multi-decadal time-scales that are difficult to integrate into management plans. While the suite of descriptive statistics provided by my research creates a frame for the historical range of variability of the fire regimes for these three sites, these data must be viewed within the context of a continually shifting climate. The role of a variable climate is substantial in subalpine forest fire regimes (Sherriff *et al.* 2001, Kipfmueller 2003, Schoennagel *et al.* 2005, Sibold and Veblen 2005), and efforts to integrate fire-climate relationship data into the FRCC will be critical for its appropriate application to the landscape.

Implications for the Management of Whitebark Pine Forests

The influence of fire suppression on the forest systems of western North America is a pervasive topic in modern forest management (Arno 1996, Zimmerman 2003), and is particularly salient to the management of whitebark pine. Changes in fire severity and forest structure induced by fire suppression are readily apparent in many fire-dependent ecosystems (*e.g.* Weaver 1959, Covington and Moore 1994, Grissino-Mayer 1995, Swetnam and Baisan 1996), but these changes are less evident in the mixed-severity fire regimes of the Northern Rockies. Due to extensive natural variations in fire activity within this broad and rather enigmatic classification (Arno *et al.* 2000), the sources of change in fire activity and advancing succession are difficult to ascertain. A cautious approach has been suggested for managing subalpine forests (Veblen 2003, Schoennagel *et al.* 2004), but due to the urgency of the situation facing whitebark pine (Kendall and Keane 2001) and based on past research (Arno 1980, Fischer and Bradley 1987), researchers generally accept that fire suppression has reduced the growth and spread of fires and encouraged advancing succession in stands historically dominated by whitebark pine (Tomback *et al.* 2001a).

My results offer contrasting information. While fire suppression did have an effect on fire frequency in my sites, subalpine fir had been established for at least 140–300 years on all three of my sites and did not require fire suppression to begin establishing in these stands. Instead, it appears the ongoing succession at these three sites is related to the time since the last large fire, which is likely climatically driven. Although the unknown effects of past fires that were suppressed introduces uncertainty to this debate (Brown *et al.* 1994), the overall trends of my data suggest fire suppression has not significantly affected the structure or successional status of my sites. These findings complicate the design and implementation of management objectives for whitebark pine forests.

Fire suppression is cited as a major cause for advancing succession in whitebark pine stands throughout the Northern Rocky Mountains (Murray *et al.* 1995, Arno 2001, Keane 2001a). This belief is used to justify the call for active management intervention under the assumption that whitebark pine forests are outside their historical range of variability in terms of forest structure. While this may be true in some areas, my data show it does not apply to all sites. Management efforts focused on preserving whitebark pine forests by returning them to a static, predetermined historical structure are inappropriate for whitebark pine forests that may not have deviated from their "natural" structure. Keane and Arno (2001) suggest that management plans should focus on restoring ecosystem processes to whitebark pine forests rather than historical stand structure. This is a more appropriate approach for my sites, for while the stand structure may be within the historical range of variation, the current fire-free interval at each site is approaching or has surpassed the UEI delineated by the respective fire history data. However, vast tracts of the environment inhabited by whitebark pine have changed significantly with the invasion of white pine blister rust, and replicating the relatively limited size and severity of most fires at my sites may not achieve the conditions required for the preservation of whitebark pine on the landscape.

Management objectives for areas of rapidly diminishing whitebark pine populations must explicitly state the goal of creating conditions that are conducive to whitebark pine regeneration through methods that may not necessarily be in line with historic disturbance patterns, but the sociopolitical ramifications of such an approach are formidable. Nearly all of the range of whitebark pine occurs in areas prized for recreational and aesthetic values (Cole 1990), and much of this range lies within the boundaries of national parks and wilderness areas (Tomback *et al.* 2001a). The philosophical debate over active management in such places is highly contentious (Stankey and McCool 1995, McCool and Freimund 2001). To meet the social, political, and ecological challenges associated with the plight of the whitebark pine, management efforts must couple collaboration among scientists, land managers, conservationists, and the public with transparency in decision making (Mills and Clark 2001, Salwasser and Huff 2001). This will create a solid foundation for the development of management techniques, while building trust among stakeholders that will be of utmost importance for the efficient and timely application of efforts to preserve whitebark pine on the western landscape.

Chapter Seven

7. Conclusions and Future Research

7.1 Conclusions

The fire regimes of the whitebark pine forests in my study area are mixed-severity, but variations in fire activity existed both temporally and spatially.

The fire-scar and age-structure data collected in the whitebark pine forests of my study area showed that the fire regimes of these sites were historically mixed-severity, with numerous small fires interspersed with less frequent and more severe widespread fires. Trees were of relatively mixed ages, but at least one post-fire cohort existed at each site. While the broad classification of mixed-severity could be applied to the fire regimes of these sites, variations existed both temporally and spatially that created unique fire histories for each stand.

Fires burned more frequently in my study sites compared to nearly all other fire history projects conducted in whitebark pine forests.

All measures of central tendency and the UEI were lower for my study sites than the MFI reported for all but two fire history studies conducted in the whitebark pine ecosystem. While the relief and topography of my sites may be the cause of these differences, another consideration is the resolution of the research methods used. The dendrochronological technique of crossdating was applied in only two other studies, both of which reported a range of MFI with lower bounds comparable to those found at my sites. This technique ensures fire events are accurately and precisely dated, and is critical for research in ecosystems that experience numerous small, patchy fires such as the whitebark pine forests.

Historical fires burned predominantly during the dormant portion of the growing season, and variability in fire seasonality may indicate anthropogenic influences on the fire regime of Morrell Mountain.

The majority of fires recorded within all of my sites burned during the dormant portion of the growing season, which includes late summer and early fall. This agrees with the modern fire season for the Northern Rocky Mountains. Fire seasonality varied little on Mineral Peak and Point Six, but numerous early season fires were recorded by the trees sampled on Morrell Mountain. The relatively higher variability in fire seasonality may be a function of unique site characteristics, but evidence of Native American activity in the area suggests anthropogenic influences may also have played a role in forming the fire regime of Morrell Mountain.

The age structure of whitebark pine forests showed similarly timed pulses of regeneration that may be related to periods of widespread disturbance.

The age-structure data of my sites showed pulses of regeneration between *ca.* AD 1500–1600 and *ca.* 1840–1900. The *ca.* 1840–1900 pulse included post-fire cohorts that established following the period of increased fire activity in my sites in the early 1800s. The *ca.* 1500–1600 pulse may also have been related to a regional period of increased disturbance, similar to the mountain pine beetle activity that affected my sites during the 20th century or the fires of the early 1800s. This may be evidence of a pattern of periodic, landscape-scale episodes of whitebark pine establishment following widespread disturbance activity, and if so, has significant implications for the management of this declining species. Additional research on the long-term stand dynamics of whitebark pine forests is required to further explore this issue.

The 1601 frost ring recorded in samples from all three sites was related to volcanic activity in the southern hemisphere and indicates sensitivity to global-scale climatic events.

The widespread occurrence of the AD 1601 frost ring in my samples indicates that these sites were relatively more sensitive to the extreme temperature events related to the eruption of Huaynapatina in the central Peruvian Andes than other nearby high-elevation trees analyzed in Idaho and western Montana. These sites may therefore provide potential locations to examine the spatial characteristics of the climatic influences of this and other global-scale cold events associated with volcanic activity.

Fire activity varied temporally, with the peak in widespread fires occurring in the early 1800s followed by a near cessation of recorded fires after ca. 1920.

The peak in widespread fire activity in my study sites *ca.* AD 1800–1850 contrasted with the gap in fire activity identified around this time in nearly all other fire history studies conducted in western North and South America. The timing of these widespread fire events may have been related to stand dynamics and the development of fuels, but regional- and hemispheric-scale climate patterns also likely influenced the character of fire events at my sites during this time. The decreased fire activity documented during the 20th century at all of my sites has been documented in other high-elevation forests in the region, and is most likely the result of active fire suppression.

Fire suppression may have reduced fire activity on my sites, but is unlikely to be related to ongoing changes in the succession of these forests.

Fire suppression may have reduced the number of fires recorded in my study sites during the 20th century, but the age-structure data indicate that subalpine fir trees have been present in these stands for at least the past 130 years on Mineral Peak and Point Six, and over 300 years on Morrell Mountain. The age structures of these stands are more related to the time since the last major fire event than the onset of fire suppression. Widespread, severe fires are rare at these sites, suggesting that fire suppression is not accelerating or changing the successional patterns in these stands.

The fire regimes of each site varied by fire frequency and severity and were most likely the result of differences in topography, forest cover, and local climate.

Varying site characteristics led to different fire regimes for each of my study sites. Fire frequency was highest on Morrell Mountain, but average fire severity was the lowest with only one post-fire cohort *ca.* AD 1500 and numerous patchy fire events. Mineral Peak experienced the lowest fire frequency, but showed evidence of moderate fire severity, with post-fire cohorts developing *ca.* AD 1600 and 1880. Fire activity on Point Six was moderately frequent, but relatively severe with post-fire cohorts establishing *ca.* AD 1600, *ca.* 1750, *ca.* 1840. The distinct fire regimes of each site were created by the influences of moisture availability, topography, and forest cover on fire activity.

The newly-developed Multi-Decadal Superposed Epoch Analysis provided a viable method to examine tree establishment following fire events, and indicated that the peak in tree establishment occurred between 50 and 75 years following widespread fire events.

The combination of multiple 40-yr windows from separate MDSEA analyses proved feasible and created a continuous 100-yr MDSEA of tree establishment following widespread fire events. Tree establishment peaked *ca.* 50–75 years after fires, although fluctuations in this trend may be related to species-specific responses to the disturbance event. These analyses showed MDSEA provides a viable tool for quantitatively examining the long-term trends in tree establishment following forest disturbance events.

The effects of fire on the growth of whitebark pine trees are not significant when compared to the effects of climate on tree growth.

The effects of fire on the growth of fire-scarred whitebark pine could not be distinguished from the overall trends in growth present in non-fire-scarred whitebark pine trees from the Selway-Bitterroot Wilderness Area. The majority of fire events recorded in my study sites occurred during prolonged periods of below-average tree growth, while widespread fires occurred at a transition from near-average growth to significantly below-average tree growth. The environmental conditions that caused similar growth trends at both the local and regional scales could only be climatically driven. Changes in the amplitude of the growth trends show that fire activity is related to shifts in climate that occur on a multi-decadal time scale of 20–30 years and > 40–80 years.

Climate played an important but complex role in the fire regimes of my study sites, and the strong visual relationship between fire activity and multidecadal-scale oscillations is quantitatively reinforced by the results of my MDSEA.

My analyses of the fire-climate relationships highlighted the complexity in the fire regimes of whitebark pine forests in my sites. I identified multiple environmental factors that were potentially related to individual fire events at some point in the past, including drought, El Niño and La Niña conditions, and variations in the PDO. However, fire activity was more strongly related to interactions between these conditions, and the majority of widespread fire events were driven by cool phases of the PDO, set within the broader context of environmental conditions related to the AMO. The time-scales on which the PDO and AMO operate agree with the oscillations identified in the fire-tree growth MDSEA.

The Fire Regime Condition Classification fire regime types assigned to my sites require refinement to capture the spatial and temporal variations in the fire regimes of these whitebark pine forests.

The coarse-scale FRCC fire regime type classifications provide a strong starting point for land managers, and were generally successful in classifying the mixed-severity fire regimes that existed at my three study sites. However, potentially important spatial and temporal variations in fire frequency and fire severity were not included in the FRCC data due to the coarse-scale data and lack of consideration for the role of climate in fire regimes. While the FRCC fire regime type is appropriate for some forest systems, the critical ecological role and complex fire regimes of whitebark pine ecosystems necessitates site-specific information for ecologically sound management decisions. The current FRCC data require refinement if they are to be used in developing management objectives for whitebark pine forests. Due to the economic limits faced by many land managers, the major challenge for managing whitebark pine ecosystems will be balancing the needs for rapid, efficient management practices with the continued acquisition of site-specific ecological data.

Fire suppression has had a limited effect on the whitebark pine forests in my study area, and a blanket approach toward the restoration of fire to this ecosystem is inappropriate.

My data indicate that the successional status of the whitebark pine forests in my study area is within the historical range of variation for these sites. If management objectives are to maintain these sites within their historical range of variation, active intervention on the assumption that fire suppression has led to unnatural stages of succession is inappropriate. Management objectives must focus on restoring ecosystem processes and encouraging whitebark pine regeneration. A collaborative effort that spans the public and private sectors will be required to successfully meet the challenges faced by managers of whitebark pine forests.

7.2 Future Research

With fire scars dating as early as the AD 1400s, and several individual samples recording multiple fire events, whitebark pine shows a strong potential for providing long-term fire history data over a broad spatial extent in an ecosystem that has been the subject of relatively little research in the past. Additionally, the abundance of whitebark pine snags and downed logs across the subalpine forests of western North America provides a source of dendroecological data obtainable with relatively little impact on this at-risk ecosystem. Urgency exists, however, to collect as much data as possible as rapidly as possible. As wildfires and prescribed fires continue to burn across the landscape, valuable dendroecological information is consumed in flames. These data may prove critical in the development of management prescriptions for whitebark pine across its distribution.

Crossdating will be critical for future fire history research in whitebark pine ecosystems. Crossdating will enable the inclusion of remnant wood in analyses and will ensure that accurate and precise dates are assigned to fire events. This will further facilitate analyses on the role of climate in fire regimes of whitebark pine forests. Extending the spatial scope of this study to include fire history data from previously unexamined areas of whitebark pine forests in central Idaho, eastern Oregon, and northern California will provide a broad spatial network to examine the long-term dynamic influences of regional climate on the fire regimes of whitebark pine forests.

The urgency that surrounds the status of whitebark pine creates an immediate need for additional fire history research in areas of the highest priority for management intervention. Because of this need, extensive collaboration with both federal and private land management agencies will be critical for the efficient transfer of data and application of site-specific ecological knowledge in management activities. Research over the central range of the species will provide data to managers in previously unstudied areas, and will facilitate the development of restoration and management plans.

Future research should also address the utility of the MDSEA for quantitatively describing long-term ecological trends in relation to climate and disturbance events. A major critique of using the traditional SEA over longer periods is the uncertainty inherent in the calculation of the confidence intervals. Statistical methods exist that can account for the shifting of actual confidence intervals as the analyzed period increases, and these methods should be integrated into the MDSEA before widespread application of the technique.

References

Agee, J. K. 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Covelo, California. 493 pp.

Agee, J. K. 1996. Fire regimes and approaches for determining fire history. Pages 12–13 *in* C. C. Hardy and S. F. Arno, editors. The Use of Fire in Forest Restoration, September 14–16, 1995, Seattle, Washington. U.S. Department of Agriculture, Forest Service General Technical Report INT-GTR-341, Intermountain Research Station. Ogden, Utah.

Agee, J. K., and L. Smith. 1984. Subalpine tree reestablishment after fire in the Olympic Mountains, Washington. Ecology **65**:810–819.

Alexander, R. R. 1988. Forest vegetation on national forests in the Rocky Mountain and Intermountain regions: Habitat types and community types. U.S. Department of Agriculture, Forest Service General Technical Report RM-GTR-162, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 47 pp.

Allan, R. J. 2000. ENSO and climatic variability in the past 150 years. Pages 3–56 *in* H. F. Diaz and V. Markgraf, editors. ENSO: Multiscale Variability and Global and Regional Impacts. Cambridge University Press, New York, New York.

Alt, D. D. 2001. Glacial Lake Missoula and Its Humongous Floods. Mountain Press Publishing Company, Missoula, Montana. 199 pp.

Alt, D. D., and D. W. Hyndman. 1972. Roadside Geology of the Northern Rockies. Mountain Press Publishing Company, Missoula, Montana. 280 pp.

Amman, G. D. 1972. Mountain pine beetle brood production in relation to thickness of lodgepole pine phloem. Journal of Economic Entomology **65**:138–140.

Applequist, M. B. 1958. A simple pith locator for use with off-center increment cores. Journal of Forestry **56**:141.

Arabas, K. B., K. S. Hadley, and E. R. Larson. in prep. Fire history of a naturally fragmented Landscape in central Oregon.

Arno, S. F. 1976. The historical role of fire on the Bitterroot National Forest. U.S. Department of Agriculture, Forest Service Research Paper INT-187, Intermountain Forest and Range Experiment Station, Ogden, Utah. 29 pp.

Arno, S. F. 1980. Forest fire history in the Northern Rockies. Journal of Forestry **78**:460–465.

Arno, S. F. 1981. Fire history in the vicinity of Sheep Mountain Bog, Lolo National Forest. Unpublished report on file at the U.S. Department of Agriculture, Forest Service Intermountain Experiment Station Fire Sciences Laboratory, Missoula, Montana.4 pp.

Arno, S. F. 1985. Ecological effects and management implications of Indian fires. Pages 82–83 *in* J. E. Lotan, editor. Symposium and Workshop on Wilderness Fire, November 15–18, 1983, Missoula, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-182, Intermountain Forest and Range Experiment Station, Ogden, Utah.

Arno, S. F. 1986. Whitebark pine cone crops - a diminishing source of wildlife food? Western Journal of Applied Forestry **1**:92–94.

Arno, S. F. 1996. The seminal importance of fire in ecosystem management - impetus for this publication. Pages 2–6 *in* C. C. Hardy and S. F. Arno, editors. The Use of Fire in Forest Restoration, September 14–16, 1995, Seattle, Washington. U.S. Department of Agriculture, Forest Service General Technical Report INT-GTR-341, Intermountain Research Station. Ogden, Utah.

Arno, S. F. 2001. Community types and natural disturbance processes. Pages 74–88 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

Arno, S. F., and S. Allison-Bunnell. 2002. Flames in Our Forest: Disaster or Renewal? Island Press, Washington, DC; London. 227 pp.

Arno, S. F., and R. P. Hammerly. 1984. Timberline: Mountain and Arctic Forest Frontiers. The Mountaineers, Seattle, Washington. 304 pp.

Arno, S. F., and R. J. Hoff. 1990. Silvics of whitebark pine (*Pinus albicaulis*). Pages 268–279 *in* R. M. Burns and B. H. Honkala, editors. Silvics of North America. U.S. Department of Agriculture, Forest Service Agricultural Handbook 654, Ogden, Utah.

Arno, S. F., D. J. Parsons, and R. E. Keane. 2000. Mixed-severity fire regimes in the Northern Rocky Mountains: Consequences of fire exclusion and options for the future. Pages 225–232 *in* D. N. Cole, S. F. McCool, W. T. Borrie, and J. O'Loughlin, editors. Wilderness Science in a Time of Change, May 23–27, 1999, Missoula, Montana. U.S. Department of Agriculture, Forest Service RMRS-P-15-VOL-5, Rocky Mountain Research Station. Ogden, Utah.

Arno, S. F., and T. D. Petersen. 1983. Variation in estimates of fire intervals: A closer look at fire history on the Bitterroot National Forest. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-301, Intermountain Forest and Range Experiment Station, Ogden, Utah. 8 pp.

Arno, S. F., J. H. Scott, and M. G. Hartwell. 1995. Age-class structure of old-growth ponderosa pine Douglas-fir stands and its relationship to fire history. U.S. Department of Agriculture, Forest Service Research Paper INT-RP-481, Intermountain Research Station, Ogden, Utah. 25 pp.

Arno, S. F., H. Y. Smith, and M. A. Krebs. 1997. Old growth ponderosa pine and western larch stand structures: Influences of pre-1900 fires and fire exclusion. U.S. Department of Agriculture, Forest Service Research Paper INT-RP-495, Intermountain Forest and Range Experiment Station, Ogden, Utah. 20 pp.

Arno, S. F., and K. M. Sneck. 1977. A method for determining fire history in coniferous forests of the mountain west. U.S. Department of Agriculture, Forest Service Research Paper INT-RP-301, Intermountain Forest and Range Experiment Station, Ogden, Utah. 28 pp.

Attiwell, P. M. 1994. The disturbance of forest ecosystems: The ecological basis for conservative management. Forest Ecology and Management **63**:247–300.

Baisan, C. H., and T. W. Swetnam. 1990. Fire history on a desert mountain range - Rincon Mountain Wilderness, Arizona, USA. Canadian Journal of Forest Research **20**:1559–1569.

Baker, R. G. 1990. Late Quaternary history of whitebark pine in the Rocky Mountains. Pages 40–48 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Baker, W. L., and D. Ehle. 2001. Uncertainty in surface-fire history: The case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research **31**:1205–1226.

Barrett, S. W. 1994a. Fire regimes on andesitic mountain terrain in northeastern Yellowstone National Park, Wyoming. International Journal of Wildland Fire **4**:65–76.

Barrett, S. W. 1994b. Fire suppression effects on forest succession within a central Idaho wilderness. Western Journal of Applied Forestry **3**:76–80.

Barrett, S. W. 2000. Fire history along the ancient Lolo Trail. Fire Management Today **60**:21–28.

Barrett, S. W., and S. F. Arno. 1982. Indian fires as an ecological influence in the Northern Rockies. Journal of Forestry **80**:647–651.

Barrett, S. W., and S. F. Arno. 1999. Indian fires in the Northern Rockies: Ethnohistory and ecology. Pages 50–64 *in* R. Boyd, editor. Indians, Fire, and the Land in the Pacific Northwest. Oregon State University Press, Corvallis, Oregon.

Barrett, S. W., S. F. Arno, and C. H. Key. 1991. Fire regimes of western larch-lodgepole pine forests in Glacier National Park, Montana. Canadian Journal of Forest Research **21**:1711–1720.

Barrett, S. W., S. F. Arno, and J. P. Menakis. 1997. Fire episodes in the inland Northwest (1540–1940) based on fire history data. U.S. Department of Agriculture, Forest Service General Technical Report INT-GTR-370, Rocky Mountain Research Station, Ogden, Utah. 17 pp.

Barrows, J. S. 1977. Lightning fires in northern Rocky Mountain forests. Department of Forest and Wood Sciences, College of Forestry and Natural Resources, Colorado State University. Prepared under contract-grant 16-440-CA for the U.S. Department of Agriculture, Forest Service Northern Forest Fire Laboratory, Intermountain Forest and Range Experiment Station, Ogden, Utah. 182 pp.

Bartos, D. L., and K. E. Gibson. 1990. Insects of whitebark pine with emphasis on mountain pine beetle. Pages 171–178 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Bassman, J. H., J. D. Johnson, L. Fins, and J. P. Dobrowolski. 2003. Rocky Mountain ecosystems: Diversity, complexity and interactions. Tree Physiology **23**:1081–1089.

Beaty, R. M., and A. H. Taylor. 2001. Spatial and temporal variation in fire regimes in a mixed conifer forest landscape, southern Cascades, California, USA. Journal of Biogeography **28**:1559–1569.

Bebi, P., D. Kulakowski, and T. T. Veblen. 2003. Interactions between fire and spruce beetles in a subalpine Rocky Mountain forest landscape. Ecology **84**:362–371.

Bell, G. D., and J. E. Janowiak. 1995. Atmospheric circulation associated with the Midwest floods of 1993. Bulletin of the American Meteorological Society **76**:681–695.

Belsky, A. J., and D. M. Blumenthal. 1997. Effects of livestock grazing on stand dynamics and soils in upland forests of the interior west. Conservation Biology **11**:315–327.

Bentz, B. J., J. A. Logan, and G. D. Amman. 1991. Temperature-dependent development of the mountain pine beetle (*Coleoptera: Scolytidae*) and simulation of its phenology. Canadian Society of Entomology **123**:1083–1094.

Bentz, B. J., and D. E. Mullins. 1999. Ecology of mountain pine beetle (*Coleoptera: Scolytidae*) cold hardening in the Intermountain West. Environmental Entomology **28**:577–587.

Bergeron, Y. 1991. The Influence of island and mainland lakeshore landscapes on boreal forest fire regimes. Ecology **72**:1980–1992.

Bergland, E. O. 1992. Historic period plateau culture tree peeling in the western Cascades of Oregon. Northwest Anthropological Research Notes **25**:31–53.

Bessie, W. C., and E. A. Johnson. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecology **76**:747–762.

Biondi, F. 2000. Are climate-tree growth relationships changing in north-central Idaho, U.S.A? Arctic, Antarctic, and Alpine Research **32**:111–116.

Biondi, F., D. L. Perkins, D. R. Cayan, and M. K. Hughes. 1999. July temperature during the second millennium reconstructed from Idaho tree rings. Geophysical Research Letters **26**:1445–1448.

BLM. 2001. Oil and gas lease to Mobile Oil Corporation. U.S. Department of the Interior, Bureau of Land Management, Serial number MTM-047702.

Bond, N. A., and D. E. Harrison. 2000. The Pacific Decadal Oscillation, air-sea interaction and central north Pacific winter atmosphere regimes. Geophysical Research Letters **27**:731–734.

Bork, B. J. 1984. Fire history in three vegetation types on the eastern side of the Oregon Cascades. Ph.D. dissertation. Oregon State University, Corvallis, Oregon. 112 pp.

Briffa, K. R., T. S. Bartholin, D. Eckstein, P. D. Jones, W. Karlen, F. H. Schweingruber, and P. Zetterberg. 1990. A 1,400-year tree-ring record of summer temperatures in Fennoscandia. Nature **346**:434–439.

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.

Briffa, K. R., P. D. Jones, F. H. Schweingruber, and T. J. Osborn. 1998a. Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years. Nature **393**:450–455.

Briffa, K. R., F. H. Schweingruber, P. D. Jones, T. J. Osborn, S. G. Shiyatov, and E. A. Vaganov. 1998b. Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. Nature **391**:678–682.

Brown, H. 2001. Policy initiatives in wildland fire management. Fire Management Today **61**:4–6.

Brown, J. K. 1994. Fire regimes and their relevance to ecosystem management. Pages 171–178 *in* Proceedings of the Society of American Foresters National Convention, September 18–22, 1994, Anchorage, Alaska. Society of American Foresters, Bethesda, Maryland.

Brown, J. K. 2000. Chapter 9: Ecological principles, shifting fire regimes and management considerations. Pages 185–204 *in* J. K. Brown and J. K. Smith, editors. Wildland Fire in Ecosystems: Effects of Fire on Flora. U.S. Department of Agriculture, Forest Service General Technical Report RMRS-GTR-42-Vol 2, Rocky Mountain Research Station, Missoula, Montana.

Brown, J. K., S. F. Arno, S. W. Barrett, and J. P. Menakis. 1994. Comparing the prescribed natural fire program with presettlement fires in the Selway-Bitterroot Wilderness. International Journal of Wildland Fire **4**:157–168.

Brown, P. M., and T. W. Swetnam. 1994. A cross-dated fire history from coast redwood near Redwood National Park, California. Canadian Journal of Forest Research **24**:21–31.

Burr, K. E., A. Eramian, and K. Eggleston. 2001. Growing whitebark pine seedlings for restoration. Pages 325–345 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, D.C.

Burrows, C. J., and V. L. Burrows. 1976. Procedures for the study of snow avalanche chronology using growth layers of woody plants. Arctic and Alpine Research **23**:1–54.

Butler, D. R., J. G. Oelfke, and L. A. Oelfke. 1986. Historic rockfall avalanches, northeastern Glacier National Park, Montana, U.S.A. Mountain Research and Development **6**:261–271.

Campbell, E. M., and J. A. Antos. 2000. Distribution and severity of white pine blister rust and mountain pine beetle on whitebark pine in British Columbia. Canadian Journal of Forest Research **30**:1051–1059.

Campbell, I. D., and J. H. McAndrews. 1993. Forest disequilibrium caused by rapid Little Ice Age cooling. Nature **366**:336–338.

Cayan, D. R. 1996. Interannual climate variability and snowpack in the western United States. Journal of Climate **9**:928–948.

Childs, T. W., J. L. Bedwell, and G. H. Englerth. 1938. Blister rust infection on *Pinus albicaulis* in the Northwest. Plant Disease Reporter **22**:139–140.

Clark, J. S. 1989. Effects of long-term water balances on fire regime, north-western Minnesota. The Journal of Ecology **77**:989–1004.

Clark, J. S., and P. D. Royal. 1996. Local and regional sediment charcoal evidence for fire regimes in presettlement north-eastern North America. Journal of Ecology **84**:365–382.

Cleaveland, M. K., E. R. Cook, and D. W. Stahle. 1992. Secular variability of the Southern Oscillation detected in tree-ring data from Mexico and the southern United States. Pages 271–291 *in* H. F. Diaz and V. Markgraf, editors. Paleoclimatic Aspects of ENSO. Cambridge University Press, Cambridge, United Kingdom.

Cole, D. N. 1990. Recreation in whitebark pine ecosystems: Demand, problems, and management strategies. Pages 305–309 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Cole, W. E., and G. D. Amman. 1980. Mountain pine beetle dynamics in lodgepole pine forests. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-89, Intermountain Forest and Range Experiment Station, Ogden, Utah. 56 pp.

Cook, E. R. 1985. ARSTAN v6.05: Chronology development and statistical analysis software. Tree-Ring Laboratory, Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, USA.

Cook, E. R., D. M. Meko, D. W. Stahle, and M. K. Cleaveland. 1999. Drought reconstructions for the continental United States. Journal of Climate **12**:1145–1162.

Cooper, C. F. 1960. Changes in vegetation, structure, and growth of southwestern pine forests since white settlement. Ecological Monographs **30**:129–164.

Covington, W. W., and M. M. Moore. 1994. Southwestern ponderosa pine forest structure: Changes since Euro-American settlement. Journal of Forestry **92**:39–47.

Cui, M., and W. K. Smith. 1991. Photosynthesis, water relations and mortality in *Abies lasiocarpa* seedlings during natural establishment. Tree Physiology **8**:37–46.

D'Arrigo, R., E. Cook, R. Wilson, R. Allan, and M. Mann. in press. On the variability of ENSO over the past six centuries. Geophysical Research Letters.

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. D., and G. Jacoby, C. 1999. Northern North American tree-ring evidence for regional temperature changes after major volcanic events. Climatic Change **41**:1–15.

D'Arrigo, R. D., and G. C. Jacoby. 1991. A 1000-year record of winter precipitation from northwestern New Mexico, USA: a reconstruction from tree-rings and its relation to El Nino and the Southern Oscillation. The Holocene **1**:95–101.

Dalavalle, J., and L. Bosart. 1975. A synoptic investigation of anticyclogenesis accompanying North American polar air outbreaks. Monthly Weather Review **103**:941–957.

Daniels, L. D., S. Butler, P. Clinton, B. Ganesh-Babu, K. Hrinkevich, A. Kanote, E. Keeling, S. Powell, and G. E. Speer. in press. Whitebark pine stand dynamics at Morrell Mountain, Montana. Indiana State University Professional Paper Series **23**.

Dansereau, P. R., and Y. Bergeron. 1993. Fire history in the southern boreal forest of northwestern Quebec. Canadian Journal of Forest Research **23**:25–32.

Daubenmire, R., and J. B. Daubenmire. 1968. Forest vegetation of eastern Washington and northern Idaho. Washington State University, Washington Agricultural Experiment Station Technical Bulletin 60, Pullman, Washington. 104 pp.

Davis, K. P. 1959. Forest Fire: Control and Use. McGraw-Hill Book Company, New York, New York. 584 pp.

de Silva, S. L., and G. A. Zielinski. 1998. Global influence of the AD 1600 eruption of Huaynaputina, Peru. Nature **393**:455–458.

DeBano, L. F., D. G. Neary, and P. F. Ffolliott. 1998. Fire's effects on ecosystems. John Wiley and Sons, Inc., New York, New York. 333 pp.

DeBlander, L. T. 2000. Forest Resources of the Lolo National Forest. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, Utah. 13 pp.

Dettinger, M. D., D. S. Battisti, R. D. Garreaud, G. J. McCabe, Jr., and C. M. Bitz. 2001. Interhemispheric effects of interannual and decadal ENSO-like climate variations on the Americas. Pages 1–16 *in* V. Markgraf, editor. Interhemispheric Climate Linkages. Academic Press, New York, New York.

DeVoto, B., editor. 1997. The Journals of Lewis and Clark, Revised edition. Houghton Mifflin Co., Boston, Massachusetts. 576 pp.

Dieterich, J. H. 1980. The composite fire interval - a tool for more accurate interpretation of fire history. Pages 8–14 *in* M. A. Stokes and J. H. Dieterich, editors. Proceedings of the fire history workshop, October 20–24, 1980, Tucson, Arizona. U.S. Department of Agriculture, Forest Service General Technical Report GTR-RM-81, Rocky Mountain Research Station, Ogden, Utah.

Dieterich, J. H. 1983. Fire history of southwestern mixed conifer forests - a case study. Forest Ecology and Management **6**:13–31.

Dilsaver, L. M., editor. 1994. America's National Park System: The Critical Documents. Rowman and Littlefield Publishers, Inc., Lanham, Maryland. 484 pp.

Douglas, G. W. 1972. Subalpine plant communities of the western North Cascades, Washington. Arctic and Alpine Research **4**:147–166.

Douglass, A. E. 1920. Evidence of climatic effects in the annual rings of trees. Ecology **1**:24–32.

Douglass, A. E. 1921. Dating our prehistoric ruins: How growth rings in trees aid in establishing the relative ages of the ruined pueblos of the Southwest. Natural History **21**:27–30.

Dunwiddie, P. W. 1977. Recent tree invasion of subalpine meadows in the Wind River Mountains, Wyoming. Arctic and Alpine Research **9**:393–399.

Ehle, D. S., and W. L. Baker. 2003. Disturbance and stand dynamics in ponderosa pine forests in Rocky Mountain National Park, USA. Ecological Monographs **73**:543–566.

Farnes, P. E. 1990. SNOTEL and snow course data: Describing the hydrology of whitebark pine ecosystems. Pages 302–304 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Feng, X., and S. Epstein. 1994. Climatic implications of an 8000-year hydrogen isotope time series from bristlecone pine trees. Science **265**:1079–1081.

Ferguson, C. W. 1969. A 7,104-year annual tree ring chronology for bristlecone pine, *Pinus aristata*, from the White Mountains, California. Tree-Ring Bulletin **29**:3–29.

Fischer, W. C., and A. F. Bradley. 1987. Fire ecology of western Montana forest habitat types. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-223, Intermountain Forest and Range Research Station, Ogden, Utah. 95 pp.

Flint, H. R. 1925. Fire resistance of northern Rocky Mountain conifers. Idaho Forester **7**:7–10.

Fritts, H. C. 1974. Relationships of ring widths in arid-site conifers to variations in monthly temperature and precipitation. Ecological Monographs **44**:411–440.

Fritts, H. C. 1976. Tree Rings and Climate. Academic Press, New York. 567 pp.

Fritts, H. C. 1991. Reconstructing Large-Scale Climatic Patterns from Tree-Ring Data: A Diagnostic Analysis. University of Arizona Press, Tucson. 286 pp.

GAO. 2000. Fire management: Lessons learned from the Cerro Grande (Los Alamos) fire. U.S. General Accounting Office GAO/T-RCED-00-257, Washington, D.C.

Garfin, G. M. 1998. Relationships between winter atmospheric circulation patterns and extreme tree growth anomalies in the Sierra Nevada. International Journal of Climatology **18**:725–740.

Gervais, B. R., and G. M. MacDonald. 2001. Tree-ring and summer-temperature response to volcanic aerosol forcing at the northern tree-line, Kola Peninsula, Russia. Holocene **11**:499–505.

Goheen, E. M. 2002. The status of whitebark pine along the Pacific Crest National Scenic Trail on the Umpqua National Forest. U.S. Department of Agriculture Forest Service General Technical Report GTR-PNW-530, Pacific Northwest Research Station, Portland, Oregon. 21 pp.

Goldblum, D., and T. T. Veblen. 1992. Fire history of a ponderosa pine/Douglas-fir forest in the Colorado Front Range. Physical Geography **13**:133–148.

Grau, H. R., and T. T. Veblen. 2000. Rainfall variability, fire and vegetation dynamics in neotropical montane ecosystems in north-western Argentina. Journal of Biogeography **27**:1107–1121.

Gray, S. T., J. L. Betancourt, C. L. Fastie, and S. T. Jackson. 2003. Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains. Geophysical Research Letters **30**:13–16.

Gray, S. T., L. J. Graumlich, J. L. Betancourt, and G. T. Pederson. 2004. A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. Geophysical Research Letters **31**:L12205.

Graybill, D. A., and S. B. Idso. 1993. Detecting the aerial fertilization effect of atmospheric CO2 enrichment in tree-ring chronologies. Global Biogeochemical Cycles **7**:81–95.

Grissino-Mayer, H. D. 1995. Tree-ring reconstructions of climate and fire history at El Malpais National Monument, New Mexico. Ph.D. Dissertation. University of Arizona, Tucson, Arizona. 407 pp.

Grissino-Mayer, H. D. 1999. Modeling fire interval data from the American Southwest with the Weibull distribution. International Journal of Wildland Fire **9**:37–50.

Grissino-Mayer, H. D. 2001a. Evaluating crossdating accuracy: A manual and tutorial for the computer program COFECHA. Tree-Ring Research **57**:205–221.

Grissino-Mayer, H. D. 2001b. FHX2 - Software for analyzing temporal and spatial patterns in fire regimes from tree rings. Tree-Ring Research **57**:115–124.

Grissino-Mayer, H. D., C. H. Baisan, and T. W. Swetnam. 1996. Fire history in the Pinaleño Mountains of southeastern Arizona: Effects of human-related disturbances. Pages 399–407 *in* P. F. Ffolliott, L. F. DeBano, M. B. Baker, Jr., G. J. Gottfried, G. Solis-Garza, C. B. Edminster, D. G. Neary, L. S. Allen, and R. H. Hamre, editors. Proceedings: Effects of Fire on Madrean Province Ecosystems, March 30–April 1, 1993, Tucson, Arizona. U.S. Department of Agriculture, Forest Service General Technical Report RM-GTR-289, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Grissino-Mayer, H. D., and H. C. Fritts. 1995. Dendroclimatology and dendroecology in the Pinaleño Mountains. Pages 100–120 *in* C. A. Istock and R. S. Hoffmann, editors. Storm Over a Mountain Island: Conservation Biology and the Mt. Graham Affair. The University of Arizona Press, Tucson, Arizona.

Grissino-Mayer, H. D., C. M. Gentry, S. Croy, J. Hiatt, B. Osborne, A. Stan, and G. D. Wight. in press. Fire history of western Montana forested landscapes via tree-ring analyses. Indiana State University Professional Paper Series **23**: 19 pp.

Grissino-Mayer, H. D., W. H. Romme, M. L. Floyd, and D. D. Hanna. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. Ecology **85**:1708–1724.

Grissino-Mayer, H. D., and T. W. Swetnam. 1995. Effects of habitat diversity on fire regimes in El Malpais National Monument, New Mexico. Pages 195–200 *in* Proceedings: Symposium on Fire in Wilderness and Park Management, March 30–April 1, 1993, Missoula, Montana. U.S. Department of Agriculture, Forest Service General Technical Report INT-GTR-320, Intermountain Research Station, Ogden, Utah.

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.

Gruell, G. E. 1983. Fire and vegetative trends in the Northern Rockies: Interpretations from 1871–1982 photographs. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-158, Intermountain Forest and Range Experiment Station, Ogden, Utah. 117 pp.

Guth, A. R. 1991. Red Skies of '88. Pictorial Histories Publishing Company, Missoula, Montana. 124 pp.

Gutsell, S. L., and E. A. Johnson. 1996. How fire scars are formed: Coupling a disturbance process to its ecological effect. Canadian Journal of Forest Research **26**:166–174.

Habeck, J. R. 1987. Present-day vegetation in the Northern Rocky Mountains. Annals of the Missouri Botanical Garden **74**:804–840.

Habeck, J. R., and R. W. Mutch. 1973. Fire-dependent forests in the northern Rocky Mountains. Quaternary Research **3**:408–424.

Hadley, J. L., and W. K. Smith. 1983. Influence of wind exposure on needle desiccation and mortality for timberline conifers in Wyoming, U.S.A. Arctic and Alpine Research **15**:127–135.

Hadley, J. L., and W. K. Smith. 1989. Wind erosion of leaf surface wax in alpine timberline conifers. Arctic and Alpine Research **21**:392–398.

Hadley, K. S. 1994. The role of disturbance, topography, and forest structure in the development of a montane forest landscape. Bulletin of the Torrey Botanical Club **121**:47–61.

Hadley, K. S. 1999. Forest history and meadow invasion at the Rigdon Meadows Archaeological Site, western Cascades, Oregon. Physical Geography **20**:116–133.

Hann, W. J., and D. L. Bunnell. 2001. Fire and land management planning and implementation across multiple scales. International Journal of Wildland Fire **10**:389–403.

Hann, W. J., D. Havlina, and A. Shlisky. 2004. Fire regime condition class guidebook, version 1.1. U.S. Department of Agriculture, Forest Service, U.S. Department of the Interior, The Nature Conservancy, and Systems for Environmental Management. 108 pp.

Hann, W. J., and D. J. Strohm. 2003. Fire regime condition class and associated data for fire and fuels planning: Methods and applications. Pages 337–443 *in* P. N. Omi and L. A. Joyce, editors. Fire, Fuel Treatments, and Ecological Restoration, April 16–18, 2002, Ft. Collins, Colorado. U.S. Department of Agriculture Forest Service RMRS-P-29, Rocky Mountain Research Station. Ft. Collins, Colorado.

Hardy, C. C., K. M. Schmidt, J. M. Menakis, and N. R. Samson. 2001. Spatial data for national fire planning and fuel management. International Journal of Wildland Fire **10**:353–372.

Haston, L., and J. Michaelsen. 1994. Long-term central coastal California precipitation variability and relationships to El Nino-Southern Oscillation. Journal of Climate **7**:1373–1387.

Healthy Forests. 2005. Montana Stewardship Contracting Projects. Available: [http://www.healthyforests.gov/initiative/steward-projects states/montana.html].

Heinselman, M. L. 1978. Fire in wilderness ecosystems. Pages 249–278 *in* J. C. Hendee, G. H. Stanley, and R. C. Lucas, editors. Wilderness Management. U.S. Department of Agriculture, Forest Service No. 1365, Washington, D.C.

Heinselman, M. L. 1981. Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. Pages 7–57 *in* H. A. Mooney, T. M. Bonnickson, N. L. Christensen, J. E. Lotan, and W. A. Reiners, editors. Fire Regimes and Ecosystem Properties, December 11–15, 1978, Honolulu, Hawaii. U.S. Department of Agriculture, Forest Service General Technical Report GTR-WO-26, Washington, D.C.

Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2001. Spatial controls of historical fire regimes: A multiscale example from the interior West, USA. Ecology **82**:660–678.

Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2002. Annual and decadal climate forcing of historical fire regimes in the interior Pacific Northwest, USA. The Holocene **12**:597–604.

Hoff, R. J., D. E. Ferguson, G. I. McDonald, and R. E. Keane. 2001. Strategies for managing whitebark pine in the presence of white pine blister rust. Pages 346–366 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

Hoff, R. J., and S. Hagle. 1990. Diseases of whitebark pine with special emphasis on white pine blister rust. Pages 179–190 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Holmes, R. L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin **43**:69–78.

Holmes, R. L. 1999. User's manual for program EDRM. Laboratory of Tree-Ring Research, the University of Arizona, Tucson, Arizona.

Hughes, J. D. 1983. American Indian Ecology. Texas Western Press, El Paso, Texas. 174 pp.

Johnson, E. A. 1992. Fire and Vegetation Dynamics: Studies from the North American Boreal Forest. Cambridge University Press, Cambridge, United Kingdom. 143 pp.

Johnson, E. A., G. I. Fryer, and M. J. Heathcott. 1990. The influence of man and climate on frequency of fire in the interior wet belt forest, British Columbia. The Journal of Ecology **78**:403–412.

Johnson, E. A., and C. P. S. Larsen. 1991. Climatically induced change in fire frequency in the southern Canadian Rockies. Ecology **72**:194–201.

Johnson, E. A., K. Miyanishi, and S. R. J. Bridge. 2001. Wildfire regime in the boreal forest and the idea of suppression and fuel buildup. Conservation Biology **15**:1554–1557.

Jones, P. D., K. R. Briffa, and F. H. Schweingruber. 1995. Tree-ring evidence of the widespread effects of explosive volcanic eruptions. Geophysical Research Letters **22**:1333–1336.

Jorgensen, S. M., and J. L. Hamrick. 1997. Biogeography and population genetics of whitebark pine, *Pinus albicaulis*. Canadian Journal of Forest Research **27**:1574–1585.

Kaye, M. W., and T. W. Swetnam. 1999. An assessment of fire, climate, and Apache history in the Sacramento Mountains, New Mexico. Physical Geography **20**:305–330.

Keables, M. J. 1992. Spatial variability of mid-tropospheric circulation patterns and associated surface climate in the United States during ENSO winters. Physical Geography **13**:331–348.

Keane, R. E. 1995. A coarse scale assessment of whitebark pine in the interior Columbia River basin. Nutcracker Notes **5**:56.

Keane, R. E. 2001a. Can the fire-dependent whitebark pine be saved? Fire Management Today **61**:17–20.

Keane, R. E. 2001b. Successional dynamics: Modeling an anthropogenic threat. Pages 159–192 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

Keane, R. E., and S. F. Arno. 1993. Rapid decline of whitebark pine in western Montana: Evidence from 20-year remeasurements. Western Journal of Applied Forestry **8**:44–47.

Keane, R. E., and S. F. Arno. 2001. Restoration concepts and techniques. Pages 367–400 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

Keane, R. E., S. F. Arno, J. K. Brown, and D. F. Tomback. 1990a. Modeling stand dynamics in whitebark pine (*Pinus albicaulis*) forests. Ecological Modeling **51**:73–95.

Keane, R. E., S. F. Arno, J. K. Brown, and D. F. Tomback. 1990b. Simulating disturbances and conifer succession in whitebark pine forests. Pages 274–288 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Keane, R. E., P. Morgan, and J. P. Menakis. 1994. Landscape assessment of the decline of whitebark pine (*Pinus albicaulis*) in the Bob Marshall Wilderness Complex, Montana, USA. Northwest Science **68**:213–229.

Keane, R. E., K. C. Ryan, T. T. Veblen, C. D. Allen, J. Logan, and B. C. Hawkes. 2002. Cascading effects of fire exclusion in Rocky Mountain ecosystems: A literature review. U.S. Department of Agriculture, Forest Service General Technical Report RMRS-GTR-91, Rocky Mountain Research Station, Fort Collins, Colorado. 24 pp.

Kendall, K. C. 1994. Whitebark pine monitoring network. Pages 109–118 *in* K. C. Kendall and B. Coen, editors. Research and Management in Whitebark Pine Ecosystems. U.S. Department of the Interior, National Biological Service, Glacier National Park, West Glacier, Montana.

Kendall, K. C., and R. E. Keane. 2001. Whitebark pine decline: Infection, mortality, and population trends. Pages 221–242 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

Kilgore, B. M., and D. Taylor. 1979. Fire history of a sequoia-mixed conifer forest. Ecology **60**:129–142.

Kipfmueller, K. F. 2003. Fire-climate-vegetation interactions in subalpine forests of the Selway-Bitterroot Wilderness Area, Idaho and Montana, USA. Ph.D. Dissertation. The University of Arizona, Tucson, Arizona. 322 pp.

Kipfmueller, K. F., and W. L. Baker. 1998. A comparison of three techniques to date stand-replacing fires in lodgepole pine forests. Forest Ecology And Management **104**:171–177.

Kipfmueller, K. F., and W. L. Baker. 2000. A fire history of a subalpine forest in southeastern Wyoming, USA. Journal of Biogeography **27**:71–85.

Kipfmueller, K. F., and T. W. Swetnam. 2000. Fire-climate interactions in the Selway-Bitterroot Wilderness Area. Pages 270–274 *in* D. N. Cole, S. F. McCool, W. T. Borrie, and J. O'Loughlin, editors. Wilderness Science in a Time of Change. U.S. Department of Agriculture, Forest Service Proceedings RMRS-P-15, Rocky Mountain Research Station, Fort Collins, Colorado.

Kipfmueller, K. F., T. W. Swetnam, and P. Morgan. 2002. Climate and mountain pine beetle-induced tree mortality in the Selway-Bitterroot Wilderness Area. Final Report to the U.S. Department of Agriculture, Forest Service Research Joint Venture Agreement #RMRS-99611-RJVA, Rocky Mountain Research Station.41 pp.

Kitzberger, T., T. W. Swetnam, and T. T. Veblen. 2001. Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation. Global Ecology and Biogeography **10**:315–326.

Kitzberger, T., T. T. Veblen, and R. Villalba. 1995. Tectonic influences on tree growth in northern Patagonia, Argentina: The roles of substrate stability and climatic variation. Canadian Journal of Forest Research **25**:1684–1696.

Knight, R. L., W. L. Smith, S. W. Buskirk, W. H. Romme, and W. L. Baker. 2000. Forest Fragmentation in the Southern Rocky Mountains. University Press of Colorado, Niwot, Colorado. 474 pp.

Kotok, E. I. 1930. Fire, a problem in American forestry. The Scientific Monthly **31**:450–452.

Krutovskii, K. V., D. V. Politov, and Y. P. Altukov. 1990. Interspecific genetic differentiation of Eurasian stone pines for isoenzyme loci. Soviet Genetics **26**:440–451.

LaMarche, V. C., Jr., and K. K. Hirschboeck. 1984. Frost rings in trees as records of major volcanic eruptions. Nature **307**:121–126.

LaMarche, V. C., Jr., and C. W. Stockton. 1974. Chronologies from temperature sensitive Bristlecone pines at upper treeline in the western United States. Tree-Ring Bulletin **34**:21–45.

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.

Lanner, R. M. 1982. Adaptations of whitebark pine for seed dispersal by Clark's nutcracker. Canadian Journal of Forest Research **12**:391–402.

Lanner, R. M. 1990. Biology, taxonomy, evolution, and geography of stone pines of the world. Pages 14–24 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Lanner, R. M. 1996. Made for Each Other: A Symbiosis of Birds and Pines. Oxford University Press, New York. 160 pp.

Lauber, P. 1991. Summer of Fire: Yellowstone 1988. Orchard Books, New York, New York. 64 pp.

Leathers, D. J., B. Yarnal, and M. A. Palecki. 1991. The Pacific/North American teleconnection pattern and United States climate. Journal of Climate **4**:517–528.

Lesieur, D., S. Gauthier, and Y. Bergeron. 2002. Fire frequency and vegetation dynamics for the south-central boreal forest of Quebec, Canada. Canadian Journal of Forest Research **32**:1996–2009.

Lewis, H. T. 1985. Why Indians burned: Specific versus general reasons. Pages 79 *in* J. E. Lotan, editor. Symposium and Workshop on Wilderness Fire, November 15–18, 1983, Missoula, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-182, Intermountain Forest and Range Experiment Station, Ogden, Utah.

Lewis, H. T., and T. A. Ferguson. 1999. Yards, corridors, and mosaics: How to burn a boreal forest. Pages 164–184 *in* R. Boyd, editor. Indians, Fire, and the Land in the Pacific Northwest. Oregon State University Press, Corvallis, Oregon.

Little, E. L., Jr. 1971. Atlas of United States trees, volume 1: Conifers and important hardwoods. U.S. Department of Agriculture Miscellaneous Publication 1146, Washington, D.C. 200 maps, 209 pp.

Little, R. L., D. L. Peterson, and L. L. Conquest. 1994. Regeneration of subalpine fir (*Abies lasiocarpa*) following fire: Effects of climate and other factors. Canadian Journal of Forest Research **24**:934–944.

Logan, J. A., P. V. Bolstad, B. J. Bentz, and D. L. Perkins. 1995. Assessing the effects of changing climate on mountain pine beetle dynamics. Pages 86–108 *in* F. P. Hain, S. M. Salom, W. F. Ravlin, T. L. Payne, and K. F. Raffa, editors. *Scolytid* Bark Beetles: Behavior, Population Dynamics and Control and Its Rationale, February 6–11, 1995, Maui, Hawaii. International Union of Forest Researchers Organizations, U.S. Department of Agriculture, Forest Service General Technical Report GTR-RM-92. Ft. Collins, Colorado.

Logan, J. A., and J. A. Powell. 2001. Ghost forests, global warming, and the mountain pine beetle. American Entomologist **47**:160–173.

Losensky, B. J. 1990. Historical uses of whitebark pine. Pages 191–197 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Luckman, B. H. 1994. Glacier fluctuation and tree-ring records for the last millennium in the Canadian Rockies. Quaternary Science Reviews **12**:441–450.

Luckman, B. H. 1995. Calendar-dated, early Little Ice Age glacier advance at Robson Glacier, British Columbia, Canada. The Holocene **5**:149–159.

Luckman, B. H. 2000. The Little Ice Age in the Canadian Rockies. Geomorphology **32**:357–384.

Luckman, B. H., L. A. Jozsa, and P. J. Murphy. 1984. Living seven-hundred-year-old *Picea engelmannii* and *Pinus albicaulis* in the Canadian Rockies. Arctic and Alpine Research **16**:419–422.

Luckman, B. H., and R. Villalba. 2001. Assessing the synchroneity of glacier fluctuations in the western cordillera of the Americas during the last millennium. Pages 119–140 *in* V. Markgraf, editor. Interhemispheric Climate Linkages. Academic Press, New York, New York.

Luckman, B. H., and R. J. S. Wilson. 2005. Summer temperatures in the Canadian Rockies during the last millennium: a revised record. Climate Dynamics **24**:131–144.

Luckman, B. H., and D. Youngblut. 1999. Millennial-aged trees from Banff National Park. Research Links **7**:15–17.

MacDonald, G. M., L. C. Cwynar, and C. Whitlock. 1989. Late Quaternary dynamics of pines: Northern North America. Pages 122–136 *in* D. M. Richardson, editor. Ecology and Biogeography of Pinus. Cambridge University Press, New York.

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 the American Meteorological Society **78**:1069–1079.

Mast, J. N., T. T. Veblen, and Y. B. Linhart. 1998. Disturbance and climatic influences on age structure of ponderosa pine at the pine/grassland ecotone, Colorado Front Range. Journal of Biogeography **25**:743–755.

Mattson, D. J., B. M. Blanchard, and R. R. Knight. 1991. Food habits of Yellowstone grizzly bears. Canadian Journal of Zoology **69**:1619–1629.

Mattson, D. J., and C. Jonkel. 1990. Stone pines and bears. Pages 223–236 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Mattson, D. J., K. C. Kendall, and D. P. Reinhart. 2001. Whitebark pine, grizzly bears, and red squirrels. Pages 121–136 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

Mattson, D. J., and E. D. Reinhardt. 1990. Whitebark pine on the Mount Washburn Massif, Yellowstone National Park. Pages 106–117 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Mattson, D. J., and D. P. Reinhart. 1997. Excavation of red squirrel middens by grizzly bears in the whitebark pine zone. Journal of Applied Ecology **34**:926–941.

McCaughey, W. W., and W. C. Schmidt. 2001. Taxonomy, distribution, and history. Pages 29–40 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

McCaughey, W. W., and D. F. Tomback. 2001. The natural regeneration process. Pages 105–120 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

McCool, S. F., and W. A. Freimund. 2001. Threatened landscapes and fragile experiences: Conflict in whitebark pine restoration. Pages 263–284 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

McDonald, G. I., and R. J. Hoff. 2001. Blister rust: An introduced plague. Pages 193–220 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

McNeil, R. C., and D. B. Zobel. 1980. Vegetation and fire history of a ponderosa pine-white fir forest in Crater Lake National Park. Northwest Science **54**:30–46.

McWhorter, L. V. 1984. Hear Me, My Chiefs! Nez Perce Legend and History. Caxton Press, Caldwell, Idaho. 640 pp.

Merrell, C., and J. T. Clark. 2001. Peeled lodgepole pines: A disappearing cultural resource and archaeological record. Northwest Anthropological Research Notes **35**:27–43.

Mills, T. J., and R. N. Clark. 2001. Roles of research scientists in natural resource decision-making. Forest Ecology and Management **153**:189–198.

Morgan, P., G. H. Aplet, J. B. Haufler, H. C. Humphries, M. M. Moore, and W. D. Wilson. 1994a. Historical range of variability: A useful tool for evaluating ecosystem change. Journal of Sustainable Forestry **2**:87–111.

Morgan, P., and S. C. Bunting. 1990. Fire effects in whitebark pine forests. Pages 166–170 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Morgan, P., S. C. Bunting, R. E. Keane, and S. F. Arno. 1994b. Fire ecology of whitebark pine forests of the Northern Rocky Mountains, U.S.A. Pages 136–141 *in* International Workshop on Subalpine Stone Pines and Their Environment: The Status of Our Knowledge, September 5–11, 1992, St. Moritz, Switzerland. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-309, Intermountain Research Station, Ogden, Utah.

Morrison, P. H., and F. J. Swanson. 1990. Fire history and pattern in a Cascade Range landscape. U.S. Department of Agriculture, Forest Service General Technical Report PNW-GTR-254, Pacific Northwest Research Station, Portland, Oregon. 77 pp.

Murray, M. P., S. C. Bunting, and P. Morgan. 1995. Whitebark pine and fire suppression in small wilderness areas. Pages 237–240 *in* J. K. Brown, R. W. Mutch, C. W. Spoon, and R. H. Wakimoto, editors. Proceedings: Symposium on Fire in Wilderness and Park Management, March 30–April 1, 1993, Missoula, Montana. U.S. Department of Agriculture, Forest Service General Technical Report INT-GTR-320, Intermountain Research Station, Ogden, Utah.

Murray, M. P., S. C. Bunting, and P. Morgan. 1998. Fire history of an isolated subalpine mountain range of the Intermountain Region, United States. Journal of Biogeography **25**:1071–1080.

Murray, M. P., S. C. Bunting, and P. Morgan. 2000. Landscape trends (1753–1993) of whitebark pine (Pinus albicaulis) forests in the West Big Hole Range of Idaho/Montana, U.S.A. Arctic, Antarctic, and Alpine Research **32**:412–418.

NCDC. 2005. National Climatic Data Center. Available: [http://www.ncdc.noaa.gov].

NHLR. 2005. National Historic Lookout Register. Available: [http://www.firetower.org/index.html].

NIFC. 2005. National Interagency Fire Center. Available: [http://www.nifc.gov/].

Norman, S. P., and A. H. Taylor. 2003. Tropical and north Pacific teleconnections influence fire regimes in pine-dominated forests of north-eastern California, USA. Journal of Biogeography **30**:1081–1092.

NPS. 1986. Fire Management Guidelines. U.S. National Park Service, NPS-18, Washington, D.C.

NWCD. 1995. Federal wildland fire management policy and program review, final report. National Interagency Fire Center, National Wildfire Coordinating Group, Boise, Idaho.

NWCD. 2001. Review and update of the 1995 Federal Wildland Fire Management policy. National Interagency Fire Center, National Wildfire Coordinating Group, Boise, Idaho.

Orvis, K. H., and H. D. Grissino-Mayer. 2002. Standardizing the reporting of abrasive papers used to surface tree-ring samples. Tree-Ring Research **58**:47–50.

Owenby, J., R. Heim, Jr., M. Burgin, and D. Ezell. 1991. Climatography of the United States No. 81, supplement #3: Maps of annual 1961–90 normal temperature, precipitation, and degree days. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, North Carolina.

Peet, R. K. 1988. Forests of the Rocky Mountains. Pages 63–102 *in* M. G. Barbour and W. D. Billings, editors. North American Vegetation. Cambridge University Press, New York, New York.

Perkins, D. L., and T. W. Swetnam. 1996. A dendroecological assessment of whitebark pine in the Sawtooth-Salmon River region, Idaho. Canadian Journal of Forest Research **26**:2123–2133.

Peterson, D. L., M. J. Arbaugh, L. J. Robinson, and B. R. Derderian. 1990. Growth trends of whitebark pine and lodgepole pine in a subalpine Sierra Nevada forest, California, U.S.A. Arctic and Alpine Research **22**:233–243.

Peterson, J. A. 1986. Paleotectonics and sedimentation in the Rocky Mountain Region, United States. The American Association of Petroleum Geologists, Tulsa, Oklahoma. 693 pp.

Pfister, R. D., and S. F. Arno. 1980. Classifying forest habitat types based on potential climax vegetation. Forest Science **26**:52–70.

Pfister, R. P., B. L. Kovalchik, S. F. Arno, and R. Presby. 1977. Forest habitat types of Montana. U.S. Department of Agriculture, Forest Service General Technical Report INT-GTR-34, Intermountain Forest and Range Experiment Station, Ogden, Utah. 174 pp.

Pilcher, J. R., M. G. L. Baillie, B. Schmidt, and B. Becker. 1984. A 7,272-year tree-ring chronology for western Europe. Nature **312**:150–152.

Pohl, K. A., K. S. Hadley, and K. B. Arabas. 2003. A 545-year drought reconstruction for central Oregon. Physical Geography **23**:302–320.

Pyne, S. J. 1982. Fire in America: A Cultural History of Wildland and Rural Fire. Princeton University Press, Princeton, New Jersey. 654 pp.

Pyne, S. J. 2002. Year of the Fires: The Story of the Great Fires of 1910. Penguin, New York, New York. 322 pp.

Pyne, S. J. 2003. Fire, native peoples, and the natural landscape: A review. Restoration Ecology **11**:257–259.

Raines, G. L., and B. R. Johnson. 1996. Digital representation of the Montana state geologic map: A contribution to the Interior Columbia River Basin Ecosystem Management Project. U.S. Department of the Interior, U.S. Geological Survey in cooperation with the U.S. Forest Service and Bureau of Land Management, Open File Report 95-691. 21 pp.

Reed, R. A., J. Johnson Barnard, and W. L. Baker. 1996. Contribution of roads to forest fragmentation in the Rocky Mountains. Conservation Biology **10**:1098–1106.

Romme, W. H. 1980. Fire history terminology - report of the ad hoc committee. Pages 135–137 *in* M. A. Stokes and J. H. Dieterich, editors. Proceedings of the Fire History Workshop, October 20–24, 1980, Tucson, Arizona. U.S. Department of Agriculture, Forest Service General Technical Report RM-81, Rocky Mountain Research Station, Ogden, Utah.

Romme, W. H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park, Wyoming. Ecological Monographs **52**:199–221.

Romme, W. H., and D. G. Despain. 1989. Historical perspective on the Yellowstone fires of 1988. Bioscience **39**:695–699.

Ross, C. P., D. A. Andres, and I. J. Witkind. 1955. Geological map of Montana: Plate 2, scale 1:500,000. U.S. Department of the Interior, U.S. Geological Survey and the Montana Bureau of Mines and Geology.

Ryan, K. C. 2002. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fennica **36**:13–39.

Safford, J. J. 2004. The Mechanics of Optimism: Mining Companies, Technology, and the Hot Spring Gold Rush, Montana Territory, 1864–1868. University Press of Colorado, Boulder, Colorado. 185 pp.

Safranyik, L., and D. A. Linton. 1998. Mortality of mountain pine beetle larvae, *Dendroctonus ponderosae* (*Coleoptera*: *Scolytidae*) in logs of lodgepole pine (*Pinus contorta* var. *latifolia*) at constant low temperatures. Journal of the Entomological Society of British Columbia **95**:81–87.

Salwasser, H., and D. E. Huff. 2001. Social and environmental challenges to restoring white pine ecosystems. Pages 401–415 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

Savage, M., and T. W. Swetnam. 1990. Early 19th-century fire decline following sheep pasturing in a Navajo ponderosa pine forest. Ecology: a publication of the Ecological Society of America **71**:2374–2378.

Schmidt, K. M., J. P. Menakis, C. C. Hardy, W. J. Hann, and D. L. Bunnell. 2002. Development of coarse-scale spatial data for wildland fire and fuel management. U.S. Department of Agriculture, Forest Service General Technical Report RMRS-GTR-87, Rocky Mountain Research Center, Fort Collins, Colorado. 41 pp.

Schmidt, W. C., and J. E. Lotan. 1980. Phenology of common forest flora of the northern Rockies: 1928–1937. U.S. Department of Agriculture, Forest Service Research Paper INT-259, Intermountain Forest and Range Experiment Station, Ogden, Utah. 20 pp.

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, W. H. Romme, J. S. Sibold, and E. R. Cook. 2005. ENSO and PDO interactions affect drought-induced fire occurrence in Rocky Mountain subalpine forests. Fire History and Climate Synthesis in Western North America Meeting, Northern Arizona University, April 30–May 3, 2005, Flagstaff, Arizona.

Schweingruber, F. H. 1996. Tree Rings and Environment - Dendroecology. Swiss Federal Institute for Forest, Snow and Landscape Research, Paul Haupt, Berne. 609 pp.

Seklecki, M. T., H. D. Grissino-Mayer, and T. W. Swetnam. 1996. Fire history and the possible role of Apache-set fires in the Chiricahua Mountains of Southeastern Arizona. Pages 238–246 *in* P. F. Ffolliott, L. F. DeBano, M. B. Maker, Jr., G. J. Gottfried, G. Solis-Garza, C. B. Edminster, D. G. Neary, L. S. Allen, and R. H. Hamre, editors. Effects of Fire on Madrean Province Ecosystems: A Symposium Proceedings, March 11–15, 1996, Tucson, Arizona. U.S. Department of

Agriculture, Forest Service General Technical Report RM-289, Rocky Mountain Forest and Range Experiment Station. Ft. Collins, Colorado.

Sherriff, R. L., T. T. Veblen, and J. S. Sibold. 2001. Fire history in high elevation subalpine forests in the Colorado Front Range. Ecoscience **8**:369–380.

Shumway, D. L., M. D. Abrams, and C. M. Ruffner. 2001. A 400-year history of fire and oak recruitment in an old-growth oak forest in western Maryland, U.S.A. Canadian Journal of Forest Research **31**:1437–1443.

Sibold, J. S., and T. T. Veblen. 2005. Influences of Pacific (ENSO and PDO) and Atlantic (AMO) Ocean climate drivers on subalpine zone fire occurrence in the Colorado Front Range. Annual Meeting of the Association of American Geographers, April 5–9, Denver, Colorado.

Smith, D. A. 1992. Rocky Mountain West: Colorado, Wyoming, and Montana, 1859–1915. University of New Mexico Press, Albuquerque, New Mexico. 290 pp.

Solheim, H. 1995. Early stages of blue-stain fungus invasion of lodgepole pine sapwood following mountain pine beetle attack. Canadian Journal of Botany **73**:70–74.

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.

Space, R. S. 2001. The Lolo Trail: A History and a Guide to the Trail of Lewis and Clark, 2nd edition. Historic Montana Publishing, Missoula, Montana. 136 pp.

Stahle, D. W., R. D'Arrigo, P. J. Krusic, M. K. Cleaveland, E. Cook, R. J. Allan, J. E. Cole, R. B. Dunbar, M. D. Therrell, D. A. Gay, M. D. Moore, M. A. Stokes, B. T. Burns, J. Villanueva-Diaz, and L. G. Thompson. 1998. Experimental dendroclimatic reconstruction of the Southern Oscillation. Bulletin of the American Meteorological Society **79**:2137–2152.

Stankey, G., and S. F. McCool. 1995. Evolving conceptions of wilderness: Implications for the management of fire. Pages 9–14 *in* J. K. Brown, R. W. Mutch, C. W. Spoon, and R. H. Wakimoto, editors. Proceedings: Symposium on Fire in Wilderness and Park Management, March 30–April 1, 1993, Missoula, Montana. U.S. Department of Agriculture, Forest Service General Technical Report INT-GTR-320, Intermountain Research Station, Ogden, Utah.

Steele, R. 1994. The role of succession in forest health. Journal of Sustainable Management **2**:183–189.

Stokes, M. A., and T. L. Smiley. 1996. An Introduction to Tree-Ring Dating. University of Arizona Press, Tucson, Arizona. 73 pp.

Stuart, J. D. 1984. Hazard rating of lodgepole pine stands to mountain pine beetle outbreaks in southcentral Oregon. Canadian Journal of Forest Research **14**:666–671.

Stuart, J. D., D. R. Geiszler, R. I. Gara, and J. K. Agee. 1983. Mountain pine beetle scarring of lodgepole pine in south-central Oregon. Forest Ecology and Management **5**:207–214.

Sutton, M. Q. 2000. An Introduction to Native North America. Allyn and Bacon, Boston, Massachusetts. 404 pp.

Swetnam, T. W. 1983. Fire history of the Gila Wilderness, New Mexico. M.S. Thesis. University of Arizona, Tucson, Arizona. 140 pp.

Swetnam, T. W. 1984. Peeled ponderosa pine trees: A record of inner bark utilization by native Americans. Journal of Ethnobiology **4**:177–190.

Swetnam, T. W. 1990. Fire history and climate in the southwestern United States. Pages 6–17 *in* J. S. Krammes, editor. Effects of Fire Management of Southwestern Natural Resources. U.S. Department of Agriculture, Forest Service General Technical Report RM-191, Rocky Mountain Forest and Range Experiment Station, Ogden, Utah.

Swetnam, T. W. 1996. Fire and climate history in the Central Yenisey region, Siberia. Pages 90–104 *in* J. G. Goldhammer and V. V. Furyaev, editors. Fire in Ecosystems of Boreal Siberia. Kluwer Academic Publishers, The Hague, The Netherlands.

Swetnam, T. W., C. D. Allen, and J. L. Betancourt. 1999. Applied historical ecology: Using the past to manage for the future. Ecological Applications **9**:1189–1206.

Swetnam, T. W., and C. H. Baisan. 1996. Historical fire regime patterns in the Southwestern United States since AD 1700. Pages 11–32 *in* C. D. Allen, editor. Fire Effects in Southwestern Forests: Proceedings of the Second La Mesa Fire Symposium, March 29–31, 1994, Los Alamos, New Mexico. U.S. Department of Agriculture, Forest Service General Technical Report GTR-RM-286, Rocky Mountain Forest and Range Experiment Station. Ft. Collins, Colorado.

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.

Tande, G. F. 1979. Fire history and vegetation pattern of coniferous forests in Jasper National Park, Alberta. Canadian Journal of Botany **57**:1912–1931.

Teensma, P. D. 1996. Integrating fire management into land management planning for westside forests. Pages 81–82 *in* C. C. Hardy and S. F. Arno, editors. The Use of Fire in Forest Restoration, September 14–16, 1995, Seattle, Washington. U.S. Department of Agriculture, Forest Service General Technical Report INT-GTR-341, Intermountain Research Station. Ogden, Utah.

Thouret, J. C., and J. Dávila. 1999. Largest explosive eruption in historical times in the Andes at Huaynaputina volcano, A.D. 1600. Geology **27**:435–438.

Thouret, J. C., E. Juvigné, A. Gourgaud, P. Boivin, and J. Dávila. 2002. Reconstruction of the AD 1600 Huaynaputina eruption based on the correlation of geologic evidence with early Spanish chronicles. Journal of Volcanology and Geothermal Research **115**:529–571.

Tinker, D. B., C. A. C. Resor, G. P. Beauvais, K. F. Kipfmueller, C. I. Fernandes, and W. L. Baker. 1998. Watershed analysis of forest fragmentation by clearcuts and roads in a Wyoming forest. Landscape Ecology **13**:149–165.

Tomback, D. F. 1982. Dispersal of whitebark pine seeds by Clark's nutcracker: A mutualism hypothesis. The Journal of Animal Ecology **51**:451–467.

Tomback, D. F. 1994a. Ecological relationship between Clark's nutcracker and four wingless-seed *Strobus* pine of western North America. Pages 221–224 *in* W. C. Schmidt and F. K. Holtmeier, editors. International Workshop on Subalpine Stone Pines and Their Environment: The Status of Our Knowledge, September 5–11, 1992, St. Moritz, Switzerland. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-309, Intermountain Research Station, Ogden, Utah.

Tomback, D. F. 1994b. Effects of seed dispersal by Clark's nutcracker on early post-fire regeneration of whitebark pine. Pages 193–198 *in* W. C. Schmidt and F. K. Holtmeier, editors. International Workshop on Subalpine Stone Pines and Their Environment: The Status of Our Knowledge, September 5–11, 1992, St. Moritz, Switzerland. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-309, Intermountain Research Station, Ogden, Utah.

Tomback, D. F. 2001. Clark's nutcracker: Agent of regeneration. Pages 89–104 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

Tomback, D. F., S. F. Arno, and R. E. Keane. 2001a. The compelling case for management intervention. Pages 3–28 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

Tomback, D. F., S. F. Arno, and R. E. Keane. 2001b. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC. 440 pp.

Tomback, D. F., L. A. Hoffman, and S. K. Sund. 1990. Coevolution of whitebark pine and nutcrackers: Implications for forest regeneration. Pages 118–129 *in* W. C. Schmidt and K. J. McDonald, editors. Symposium on Whitebark Pine Ecosystems: Ecology and Management of a High-Mountain Resource, March 29–31, 1989, Bozeman, Montana. U.S. Department of Agriculture, Forest Service General Technical Report GTR-INT-270, Intermountain Forest and Range Research Station, Ogden, Utah.

Tomback, D. F., S. K. Sund, and L. A. Hoffmann. 1993. Post-fire regeneration of *Pinus albicaulis*: Height-age relationships, age structure, and microsite characteristics. Canadian Journal of Forest Research **23**:113–119.

Touchan, R., T. W. Swetnam, and H. D. Grissino-Mayer. 1995. Effects of livestock grazing on pre-settlement fire regimes in New Mexico. Pages 268–272 *in* J. K. Brown, R. W. Mutch, C. W. Spoon, and R. H. Wakimoto, editors. Proceedings: Symposium on Fire in Wilderness and Park Management, March 30–April 1, 1993, Missoula, Montana. U.S. Department of Agriculture, Forest Service General Technical Report INT-GTR-320, Intermountain Research Station, Ogden, Utah.

United States Congress. 2000. The Consolidated Appropriations Act FY2001. Congressional Record **146**:12100–12428.

United States Congress, H. C. o. R. 2003. The President's healthy forests initiative and H.R. 5214, H.R. 5309 and H.R. 5319: Hearing before the Committee on Resources, U.S. House of Representatives, One Hundred Seventh Congress, second session, September 5, 2002. U.S. Government Printing Office, Washington, D.C. 105 pp.

USBM. 1992. Mineral Information Location System. U.S. Department of the Interior, Bureau of Mines, Washington, D.C.

USDA Soil Conservation Service. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. U.S. Department of Agriculture Handbook 436, Washington, D.C. 754 pp.

USFS. 1968. History of Smokejumping. U.S. Department of Agriculture, Forest Service Northern Region, Division of Fire Control, Missoula, Montana. 22 pp.

USFS. 1986. The Lolo National Forest Plan. U.S. Department of Agriculture, Forest Service, Northern Region, Kalispell, Montana. 416 pp.

USFS. 1998. Land areas of the national forest system. U.S. Department of Agriculture, Forest Service FS-383, Washington, D.C. 115 pp.

Vale, T. R. 1981. Ages of invasive trees in Dana Meadows, Yosemite National Park, California. Madroño **28**:45–47.

Vale, T. R. 2002. Fire, Native Peoples, and the Natural Landscape. Island Press, Washington, D.C. 315 pp.

van der Plank, J. E. 1963. Plant Diseases: Epidemics and Control. Academic Press, New York, New York. 349 pp.

van Wagtendonk, J. W. 1991. The evolution of National Park Service fire policy. Pages 328–332 *in* S. C. Nodvin and T. A. Waldrop, editors. Fire and the Environment: Ecological and Cultural Perspectives. U.S. Department of Agriculture, Forest Service General Technical Report GTR-SE-69 Southeastern Forest Experiment Station, Asheville, North Carolina.

Vandygriff, J. C., L. A. Rasmussen, and J. F. Rineholt. 2000. A novel approach to managing fuel wood harvest using bark beetle pheromones. Western Journal of Applied Forestry **15**:1–6.

Veblen, T. T. 2003. Key issues in fire regime research for fuels management and ecological restoration. Pages 259–276 *in* P. N. Omi and L. A. Joyce, editors. Fire, Fuel Treatments, and Ecological Restoration, April 16–18, 2002, Ft. Collins, Colorado. U.S. Department of Agriculture, Forest Service RMRS-P-29, Rocky Mountain Research Station. Ft. Collins, Colorado.

Veblen, T. T., K. S. Hadley, M. S. Reid, and A. J. Rebertus. 1991. Methods of detecting past spruce beetle outbreaks in Rocky Mountain subalpine forests. Canadian Journal of Forest Research **21**:242–254.

Veblen, T. T., and T. Kitzberger. 2002. Inter-hemispheric comparison of fire history: The Colorado Front Range, U.S.A., and the Northern Patagonian Andes, Argentina. Plant Ecology **163**:187–207.

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.

Viereck, L. A. 1973. Wildfire in the taiga of Alaska. Journal of Quaternary Research **3**:465–495.

Villalba, R., and T. T. Veblen. 1997. Improving estimates of total tree ages based on increment core samples. Ecoscience **4**:534–542.

Weaver, H. 1959. Ecological changes in the ponderosa pine forest of the Warm Springs Indian Reservation in Oregon. Journal of Forestry **57**:15–20.

Weaver, H. 1961. Ecological changes in the ponderosa pine forest of Cedar Valley in southern Washington. Ecology **42**:416–420.

Weaver, T. 2001. Whitebark pine and its environment. Pages 41–73 *in* D. F. Tomback, S. F. Arno, and R. E. Keane, editors. Whitebark Pine Communities: Ecology and Restoration. Island Press, Washington, DC.

Weaver, T., and D. Dale. 1974. *Pinus albicaulis* in central Montana: Environment, vegetation, and production. American Midland Naturalist **92**:222–230.

Weibull, W. 1951. A statistical distribution function of wide applicability. Journal of Applied Mechanics **18**:293–297.

Welch, N. T., and T. A. Waldrop. 2001. Restoring table mountain pine (*Pinus pungens* Lamb.) communities with prescribed fire: An overview of current research. Castanea **66**:42–49.

Wellner, C. A. 1970. Fire history in the northern Rocky Mountains. Pages 42–64 *in* The role of fire in the Intermountain West: Symposium Proceedings, October 27–29, 1970, Missoula, Montana. Intermountain Fire Research Council, in cooperation with the University of Montana, School of Forestry.

West, N. E. 1969. Successional changes in the montane forests of the central Oregon Cascades. American Midland Naturalist **81**:265–271.

Westerling, A. L., and T. W. Swetnam. 2004. A long term perspective on decadal variability in climate and wildfire in the western United States. EOS Transnational American Geophysical Union **84**:Abstract B43E-04.

Whitlock, C., S. L. Shafer, and J. Marlon. 2003. The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. Forest Ecology and Management **178**:5–21.

Williams, J. T., and R. C. Rothermal. 1992. Fire dynamics in Northern Rocky Mountain stand types. U.S. Department of Agriculture, Forest Service Research Note INT-405, Intermountain Forest and Range Experiment Station, Ogden, Utah. 4 pp.

WLFC. 2002. A collaborative approach for reducing wildland fire risks to communities and the environment: 10-year comprehensive strategy implementation plan. Wildland Fire Leadership Council, Conference Report for the Fiscal Year 2001 Interior and Related Agencies Appropriations Act, Public Law 106-291, Washington, D.C. 27 pp.

Wright, H. A., and A. W. Bailey. 1982. Fire Ecology: United States and Southern Canada. John Wiley and Sons, Inc., New York, New York. 501 pp.

Zimmerman, G. T. 2003. Fire, fuel treatments, and ecological restoration - Proper place, appropriate time. Pages 435–442 *in* P. N. Omi and L. A. Joyce, editors. Fire, Fuel Treatments, and Ecological Restoration, April 16–18, 2002, Ft. Collins, Colorado. U.S. Department of Agriculture, Forest Service RMRS-P-29, Rocky Mountain Research Station. Ft. Collins, Colorado.

Appendices

Appendix A. Statistical descriptions for the 214 measurement series from fire-scarred cross-sections collected on three mountains in the Lolo National Forest. MOR, ML: Morrell Mountain; PS: Point Six; MP: Mineral Peak.

Seq	Series	Interval		No. Years	Correl. w/ Maste	Std dev	Auto corr	Mean sens	AR ()
1	ml2002a	1488	1974	487	0.336	0.193	0.807	0.202	1
2	ml2002b	1488	1976	489	0.420	0.174	0.679	0.262	1
3	ml2003a	1599	1764	166	0.450	0.301	0.648	0.259	1
4	ml2003b	1599	1899	301	0.378	0.245	0.801	0.234	1
5	ML2006a	1643	1950	308	0.375	0.416	0.829	0.282	2
6	ML2006b	1652	1857	206	0.520	0.502	0.812	0.257	1
7	ML2007a	1625	1800	176	0.338	0.429	0.838	0.212	1
8	ML2007b	1584	1825	242	0.369	0.329	0.838	0.201	1
9	ML2007c	1659	1914	256	0.406	0.431	0.885	0.249	1
10	ML2008a	1678	1900	223	0.342	0.481	0.897	0.210	1
11	ML2008b	1678	1843	166	0.405	0.372	0.839	0.187	1
12	ML2009a	1685	1865	181	0.570	0.322	0.758	0.202	1
13	ML2009b	1705	1875	171	0.561	0.399	0.798	0.203	1
14	ml2013a	1726	1975	250	0.311	0.528	0.918	0.269	1
15	ml2013b	1780	1960	181	0.457	0.377	0.901	0.258	1
16	ml2014a	1743	1965	223	0.286	0.343	0.880	0.261	1
17	ml2014b	1743	1900	158	0.445	0.243	0.691	0.255	1
18	ml2016b	1770	1852	83	0.338	0.286	0.635	0.291	1
19	ml3004a	1725	1875	151	0.368	0.400	0.802	0.210	1
20	ml3004b	1701	1882	182	0.503	0.530	0.698	0.220	1
21	ml3006a	1624	1840	217	0.520	0.174	0.745	0.200	2
22	ml3008a	1732	1969	238	0.557	0.138	0.633	0.261	1
23	ml3008b	1697	1968	272	0.542	0.183	0.768	0.307	1
24	mor001a	1540	1947	408	0.389	0.157	0.862	0.246	1
25	mor001b	1518	1965	448	0.376	0.163	0.769	0.258	1
26	mor003a	1567	1885	319	0.443	0.202	0.773	0.210	1
27	mor003b	1591	1887	297	0.526	0.174	0.714	0.248	1
28	mor004a	1520	1880	361	0.456	0.192	0.856	0.224	1
29	mor004b	1600	1900	301	0.486	0.097	0.690	0.204	1
30	mor006	1526	1956	431	0.434	0.191	0.791	0.248	1
31	mor007	1564	1809	246	0.380	0.167	0.676	0.254	1
32	mor008a	1646	1820	175	0.574	0.128	0.598	0.325	1
33	mor008b	1628	1851	224	0.493	0.167	0.777	0.339	1

Appendix A. *continued.*

Seq	Series	Interval		No. Years	Correl. w/ Maste	Std dev	Auto corr	Mean sens	AR ()
34	mor010a	1694	1977	284	0.315	0.216	0.784	0.293	1
35	mor011a	1801	1946	146	0.497	0.175	0.461	0.220	2
36	mor011b	1802	1946	145	0.498	0.234	0.592	0.211	3
37	mor012a	1518	1916	399	0.544	0.219	0.835	0.227	1
38	mor012b	1520	1697	178	0.496	0.308	0.910	0.191	1
39	mor012b	1790	1900	111	0.502	0.068	0.482	0.289	1
40	mor013a	1515	1930	416	0.471	0.246	0.898	0.272	1
41	mor013b	1519	1839	321	0.502	0.291	0.888	0.237	1
42	mor014a	1587	1917	331	0.527	0.246	0.858	0.290	2
43	mor014b	1549	1831	283	0.436	0.276	0.839	0.262	1
44	mor015a	1514	1865	352	0.491	0.325	0.850	0.255	1
45	mor015b	1520	1930	411	0.512	0.362	0.776	0.231	1
46	mor016a	1520	1982	463	0.499	0.188	0.786	0.234	1
47	mor016b	1600	1983	384	0.522	0.200	0.839	0.220	1
48	mor017a	1572	1958	387	0.495	0.270	0.854	0.224	1
49	mor017b	1562	1946	385	0.488	0.262	0.803	0.282	1
50	mor018a	1513	1713	201	0.458	0.560	0.878	0.237	1
51	mor018b	1514	1680	167	0.544	0.525	0.923	0.199	1
52	mor019a	1603	1879	277	0.464	0.206	0.797	0.175	1
53	mor019b	1556	1843	288	0.415	0.239	0.813	0.169	1
54	mor020a	1517	1976	460	0.567	0.220	0.884	0.194	1
55	mor020b	1508	1825	318	0.475	0.336	0.913	0.215	1
56	mor021a	1520	1760	241	0.504	0.252	0.817	0.234	1
57	mor021b	1567	1954	388	0.433	0.181	0.740	0.229	1
58	mor022a	1466	1960	495	0.368	0.291	0.910	0.211	1
59	mor022b	1480	1925	446	0.426	0.318	0.880	0.221	1
60	mp1001fa	1510	1696	187	0.351	0.363	0.896	0.148	1
61	mp1001fb	1521	1733	213	0.429	0.406	0.932	0.146	1
62	mp1002fa	1603	1776	174	0.366	0.140	0.648	0.203	1
63	mp1002fb	1603	1989	387	0.333	0.168	0.748	0.213	1
64	mp1003fa	1670	1962	293	0.386	0.255	0.869	0.188	1
65	mp1003fb	1670	1962	293	0.345	0.225	0.875	0.203	1
66	mp1004fa	1351	1867	517	0.445	0.223	0.879	0.188	1
67	mp1004fb	1344	1957	614	0.434	0.210	0.876	0.184	2
68	mp1004fc	1331	1590	260	0.297	0.250	0.854	0.236	1
69	mp1008fa	1541	1673	133	0.450	0.353	0.768	0.206	1
70	mp1008fb	1531	1686	156	0.415	0.338	0.825	0.164	2

Appendix A. *continued.*

Seq	Series	Interval		No. Years	Correl. w/ Maste	Std dev	Auto corr	Mean sens	AR ()
71	mp1009fa	1610	1780	171	0.312	0.295	0.672	0.293	1
72	mp1009fb	1621	1778	158	0.298	0.293	0.696	0.238	1
73	mp1009fc	1791	1983	193	0.393	0.375	0.820	0.222	1
74	mp1010fa	1623	1971	349	0.512	0.354	0.744	0.230	1
75	mp1010fb	1622	1785	164	0.507	0.307	0.554	0.216	1
76	mp1010fc	1812	1974	163	0.493	0.355	0.808	0.209	1
77	mp1011fa	1566	1712	147	0.388	0.675	0.892	0.154	1
78	mp1011fb	1587	1771	185	0.430	0.494	0.799	0.189	2
79	mp1012fa	1171	1396	226	0.543	0.658	0.838	0.243	3
80	mp1012fb	1179	1383	205	0.476	0.505	0.825	0.232	1
81	mp1013fa	1687	1922	236	0.403	0.470	0.813	0.288	1
82	mp1013fb	1678	1922	245	0.423	0.424	0.763	0.258	1
83	mp1014fa	1613	1742	130	0.638	0.435	0.716	0.197	2
84	mp1014fb	1619	1738	120	0.630	0.467	0.740	0.157	1
85	mp1017fa	1467	1736	270	0.393	0.178	0.785	0.234	1
86	mp1017fb	1441	1690	250	0.373	0.259	0.702	0.235	1
87	mp2001fa	1589	1825	237	0.410	0.703	0.846	0.229	1
88	mp2002fa	1562	1786	225	0.468	0.577	0.901	0.213	1
89	mp2002fb	1562	1970	409	0.350	0.444	0.920	0.200	1
90	mp2004fa	1664	1892	229	0.420	0.189	0.828	0.227	1
91	mp2004fb	1658	1967	310	0.346	0.286	0.893	0.235	1
92	mp2005fa	1320	1910	591	0.309	0.494	0.928	0.244	1
93	mp2008fa	1631	1829	199	0.373	0.363	0.864	0.248	3
94	mp2008fb	1638	1981	344	0.344	0.350	0.835	0.288	1
95	mp2009fa	1522	1792	271	0.345	0.288	0.794	0.247	1
96	mp2009fb	1522	1834	313	0.321	0.259	0.844	0.272	1
97	mp2009fc	1785	1962	178	0.421	0.325	0.880	0.228	1
98	mp2010fa	1554	1823	270	0.437	0.441	0.851	0.208	1
99	mp2010fb	1555	1790	236	0.519	0.428	0.875	0.226	2
100	mp2011fa	1558	1964	407	0.339	0.126	0.733	0.233	1
101	mp2011fb	1558	2000	443	0.338	0.159	0.813	0.254	1
102	mp2012fa	1404	1497	94	0.532	0.241	0.576	0.237	1
103	mp2012fb	1419	1976	558	0.560	0.225	0.820	0.208	2
104	mp2012fc	1508	1976	469	0.621	0.303	0.860	0.194	1
105	mp2013fa	1537	1952	416	0.459	0.273	0.853	0.176	1
106	mp2013fb	1588	1952	365	0.469	0.242	0.898	0.170	1
107	mp3001fa	1660	1834	175	0.418	0.290	0.883	0.203	3

Appendix A. *continued.*

Seq	Series	Interval		No. Years	Correl. w/ Maste	Std dev	Auto corr	Mean sens	AR ()
108	mp3001fb	1841	1978	138	0.320	0.363	0.915	0.197	1
109	mp3001fc	1891	1997	107	0.508	0.542	0.889	0.221	1
110	mp3002fa	1087	1812	726	0.343	0.190	0.923	0.249	2
111	mp3002fb	1087	1725	639	0.376	0.163	0.828	0.212	2
112	mp3003fa	1522	1984	463	0.327	0.280	0.899	0.169	2
113	mp3003fb	1526	1816	291	0.302	0.305	0.887	0.169	1
114	mp3004fa	1506	1816	311	0.451	0.154	0.703	0.193	1
115	mp3004fb	1464	1679	216	0.453	0.198	0.816	0.233	1
116	mp3005fa	1561	1979	419	0.292	0.397	0.903	0.272	1
117	mp3005fb	1561	1834	274	0.379	0.125	0.514	0.310	1
118	mp3006fa	1434	1951	518	0.394	0.145	0.732	0.206	1
119	mp3006fb	1434	1853	420	0.410	0.190	0.826	0.200	1
120	mp3007fa	1265	1409	145	0.445	0.215	0.682	0.180	1
121	mp3007fb	1263	1805	543	0.372	0.213	0.836	0.179	1
122	mp3007fc	1421	1809	389	0.349	0.123	0.657	0.168	1
123	mp3009fa	1591	1832	242	0.449	0.267	0.869	0.186	1
124	mp3009fb	1597	1964	368	0.409	0.265	0.873	0.218	1
125	mp3010fa	1550	1992	443	0.341	0.172	0.783	0.243	1
126	mp3010fb	1550	1801	252	0.405	0.289	0.789	0.293	1
127	mp3011fa	1579	1828	250	0.451	0.304	0.740	0.246	1
128	mp3011fb	1579	1832	254	0.549	0.552	0.861	0.242	1
129	mp3011fc	1845	1998	154	0.435	0.412	0.821	0.255	1
130	mp3012fa	1635	1956	322	0.332	0.297	0.806	0.278	1
131	mp3012fb	1638	1828	191	0.399	0.190	0.672	0.250	1
132	mp3013fa	1268	1762	495	0.374	0.273	0.911	0.239	2
133	mp3013fb	1268	1801	534	0.394	0.285	0.892	0.224	2
134	mp3015fa	1630	1964	335	0.495	0.436	0.891	0.186	1
135	mp3015fb	1628	1830	203	0.432	0.463	0.892	0.183	1
136	mp3016fa	1601	1982	382	0.419	0.140	0.652	0.283	2
137	mp3016fa	1596	1981	386	0.473	0.157	0.720	0.276	1
138	ps1001fa	1753	1950	198	0.456	0.605	0.836	0.218	1
139	ps1001fc	1753	1957	205	0.417	0.670	0.879	0.201	1
140	ps1002fa	1735	1898	164	0.485	0.341	0.604	0.194	1
141	ps1002fb	1735	1949	215	0.380	0.503	0.843	0.231	1
142	ps1003fa	1764	1878	115	0.399	0.317	0.575	0.173	1
143	ps1003fb	1764	1926	163	0.531	0.507	0.778	0.204	1
144	ps1003fc	1764	1923	160	0.487	0.444	0.787	0.189	2

Appendix A. *continued.*

Seq	Series	Interval		No. Years	Correl. w/ Maste	Std dev	Auto corr	Mean sens	AR ()
145	ps1004fa	1759	2003	245	0.394	0.689	0.909	0.202	1
146	ps1004fb	1818	1996	179	0.509	0.587	0.920	0.180	1
147	ps1005fa	1760	2002	243	0.439	0.759	0.851	0.207	1
148	ps1005fb	1830	2003	174	0.369	0.852	0.884	0.202	2
149	ps1006fa	1757	1952	196	0.427	0.526	0.835	0.216	1
150	ps1006fb	1757	1816	60	0.555	0.300	0.756	0.135	4
151	ps1007fa	1761	1977	217	0.348	0.712	0.910	0.236	1
152	ps1007fb	1761	1976	216	0.408	0.722	0.904	0.233	1
153	ps1008fa	1617	2003	387	0.447	0.575	0.900	0.290	2
154	ps1008fb	1617	1808	192	0.389	0.186	0.773	0.311	1
155	ps1008fc	1824	2003	180	0.484	0.526	0.802	0.246	1
156	ps1009fa	1645	1724	80	0.327	0.416	0.758	0.226	1
157	ps1009fb	1650	1812	163	0.432	0.253	0.734	0.240	1
158	ps1009fc	1828	1985	158	0.391	0.499	0.882	0.210	1
159	ps1009fd	1828	1985	158	0.398	0.534	0.849	0.222	1
160	ps1010fb	1647	1926	280	0.402	0.365	0.903	0.197	1
161	ps1011fb	1840	1969	130	0.415	0.272	0.653	0.174	1
162	ps1012fa	1835	2002	168	0.340	0.591	0.871	0.233	1
163	ps1013fa	1633	1811	179	0.385	0.190	0.838	0.237	1
164	ps1013fb	1633	1929	297	0.375	0.297	0.788	0.238	2
165	ps1014fa	1608	1897	290	0.312	0.369	0.665	0.213	3
166	ps1014fb	1608	1846	239	0.341	0.342	0.770	0.217	1
167	ps1015fa	1581	1928	348	0.380	0.260	0.701	0.229	1
168	ps1016fa	1618	1976	359	0.451	0.350	0.905	0.222	1
169	ps1016fb	1618	1816	199	0.440	0.412	0.870	0.236	1
170	ps2001fa	1629	1913	285	0.456	0.266	0.791	0.250	1
171	ps2001fb	1643	1906	264	0.420	0.294	0.799	0.221	1
172	ps2002fa	1662	1926	265	0.448	0.309	0.785	0.184	2
173	ps2002fb	1671	1814	144	0.446	0.351	0.802	0.185	1
174	ps2003fa	1615	1975	361	0.413	0.308	0.372	0.273	1
175	ps2003fb	1615	1866	252	0.382	0.186	0.818	0.266	1
176	ps2003fc	1882	1973	92	0.461	0.145	0.852	0.248	4
177	ps2004fa	1655	1926	272	0.440	0.297	0.845	0.294	1
178	ps2004fb	1654	1816	163	0.468	0.292	0.846	0.231	1
179	ps2005fa	1614	1930	317	0.401	0.279	0.838	0.245	1
180	ps2005fb	1614	1917	304	0.475	0.240	0.801	0.258	1
181	ps2007fa	1612	1983	372	0.344	0.372	0.860	0.222	1

Appendix A. *continued.*

Seq	Series	Interval		No. Years	Correl. w/ Maste	Std dev	Auto corr	Mean sens	AR ()
182	ps2007fb	1612	1980	369	0.392	0.406	0.861	0.218	1
183	ps2010fa	1626	1993	368	0.382	0.429	0.898	0.243	2
184	ps2010fb	1626	1815	190	0.399	0.483	0.857	0.232	1
185	ps2011fa	1621	1731	111	0.359	0.189	0.584	0.256	1
186	ps2011fc	1867	1985	119	0.361	0.196	0.541	0.272	2
187	ps2012fa	1762	1972	211	0.528	0.216	0.793	0.182	1
188	ps2012fb	1643	1813	171	0.388	0.310	0.805	0.231	1
189	ps2013a	1606	1816	211	0.373	0.278	0.782	0.228	1
190	ps2013b	1606	1980	375	0.451	0.273	0.855	0.226	1
191	ps2014a	1621	1979	359	0.549	0.377	0.850	0.205	1
192	ps2014b	1621	1979	359	0.509	0.350	0.830	0.190	1
193	ps2015a	1684	1961	278	0.354	0.297	0.843	0.234	1
194	ps2015b	1652	1960	309	0.312	0.292	0.843	0.232	1
195	ps2016a	1659	1776	118	0.422	0.427	0.823	0.177	2
196	ps2016b	1672	1929	258	0.484	0.353	0.770	0.186	1
197	ps2016c	1671	1897	227	0.568	0.413	0.799	0.195	1
198	ps2extra	1689	1814	126	0.316	0.260	0.747	0.252	1
199	ps3001fa	1821	1949	129	0.380	0.686	0.809	0.297	1
200	ps3001fb	1756	1938	183	0.370	0.717	0.905	0.255	1
201	ps3002fa	1734	1907	174	0.345	0.553	0.896	0.230	1
202	ps3002fb	1734	1852	119	0.402	0.444	0.849	0.195	1
203	ps3003fc	1763	1885	123	0.373	0.340	0.828	0.208	3
204	ps3004fa	1742	1877	136	0.380	0.597	0.876	0.218	2
205	ps3004fb	1742	1889	148	0.383	0.385	0.808	0.225	1
206	ps3006fb	1737	1837	101	0.395	0.573	0.838	0.181	1
207	ps3007fa	1768	1925	158	0.372	0.423	0.850	0.216	1
208	ps3007fb	1768	1924	157	0.393	0.481	0.852	0.184	1
209	ps3008fa	1757	1929	173	0.415	0.509	0.861	0.239	2
210	ps3008fb	1757	1929	173	0.430	0.493	0.804	0.291	1
211	ps3009fa	1762	1929	168	0.364	0.544	0.884	0.192	1
212	ps3009fb	1762	1901	140	0.360	0.523	0.859	0.158	2
213	ps3010fa	1750	1930	181	0.494	0.583	0.801	0.239	1
214	ps3010fb	1750	1929	180	0.483	0.721	0.775	0.241	1
Total or mean:				56652	0.423	0.318	0.814	0.227	

Appendix B. Fire-scar data from 111 fire-scarred cross sections collected from three mountains in the Lolo National Forest.

MOR, ML: Morrell Mountain; PS: Point Six; MP: Mineral Peak.

Series 1 : ML2002
Pith Date : 1489
Outer Ring : 1976
Length of sample : 488
Number in final analysis : 78
Information on fire history :
1601 M injury
1900 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 78.0

Series 2 : ML2003
Pith Date : 1599
Outer Ring : 1899
Length of sample : 301
Number in final analysis : 172
Information on fire history :
1728 D fire scar
1769 U fire scar FI = 41
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire : 86.0
Sample mean fire interval : 41.0

Series 3 : ML2006
Inner Ring : 1643
Outer Ring : 1952
Length of sample : 310
Number in final analysis : 203
Information on fire history :
1655 U injury
1751 M fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 203.0

Series 4 : ML2007
Inner Ring : 1571
Outer Ring : 1914
Length of sample : 344
Number in final analysis : 260
Information on fire history :
1655 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 260.0

Series 5 : ML2008
Pith Date : 1678
Outer Ring : 1915
Length of sample : 238
Number in final analysis : 37
Information on fire history :
1734 D fire scar
1739 U injury
1751 D fire scar FI = 17
Total number of fire scars : 2
Total number all indicators : 3
Average number years per fire : 18.5
Sample mean fire interval : 17.0

Series 6 : ML2009
Pith Date : 1685
Outer Ring : 1875
Length of sample : 191
Number in final analysis : 24
Information on fire history :
1694 D fire scar
1711 D fire scar FI = 17
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire : 12.0
Sample mean fire interval : 17.0

Series 7 : ML2013
Pith Date : 1726
Outer Ring : 1976
Length of sample : 251
Number in final analysis : 134
Information on fire history :
1843 D fire scar
Total number of fire scars : 1
Average number years per fire : 134.0

Appendix B. *continued.*

Series 8 : ML2014
Pith Date : 1743
Outer Ring : 1965
Length of sample : 223
Number in final analysis : 6
Information on fire history :
  1754 D fire scar
Total number of fire scars : 1
Average number years per fire : 6.0

Series 9 : ML2016
Pith Date : 1704
Outer Ring : 1932
Length of sample : 229
Number in final analysis : 82
Information on fire history :
  1851 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 82.0

Series 10 : ML3004
Inner Ring : 1593
Outer Ring : 1882
Length of sample : 290
Number in final analysis : 55
Information on fire history :
  1601 M injury
  1640 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 55.0

Series 11 : ML3006
Pith Date : 1500
Outer Ring : 1840
Length of sample : 341
Number in final analysis : 1
Information on fire history :
  1601 M injury
Total number all indicators : 1

Series 12 : ML3008
Inner Ring : 1697
Outer Ring : 1969
Length of sample : 273
Number in final analysis : 203
Information on fire history :
  1767 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 203.0

Series 13 : MOR001
Pith Date : 1519
Bark Date : 1965
Length of sample : 447
Number in final analysis : 89
Information on fire history :
  1531 D fire scar
  1544 D fire scar FI = 9
  1588 E injury
  1601 M injury
  1868 U injury
  1898 D fire scar FI = 7
Total number of fire scars : 3
Total number all indicators : 6
Average number years per fire : 29.7
Sample mean fire interval : 8.0

Series 14 : MOR003
Inner Ring : 1567
Outer Ring : 1915
Length of sample : 349
Number in final analysis : 164
Information on fire history :
  1601 M injury
  1642 L injury
  1754 E fire scar
Total number of fire scars : 1
Total number all indicators : 3
Average number years per fire : 164.0

Series 15 : MOR004
Inner Ring : 1521
Bark Date : 1999
Length of sample : 479
Number in final analysis : 248

Appendix B. *continued.*

Information on fire history :
1562 E injury
1701 U injury
1754 U fire scar
1796 E fire scar FI = 42
1836 D fire scar FI = 40
1919 U fire scar FI = 83
1974 E fire scar FI = 55
Total number of fire scars : 5
Total number all indicators : 7
Average number years per fire : 49.6
Sample mean fire interval : 55.0

Series 16 : MOR006
Inner Ring : 1513
Outer Ring : 1987
Length of sample : 475
Number in final analysis : 315
Information on fire history :
1560 E injury
1585 E injury
1675 E injury
1706 D injury
1754 U fire scar
1762 D injury
1806 D fire scar FI = 52
1829 U injury
Total number of fire scars : 2
Total number all indicators : 8
Average number years per fire : 157.5
Sample mean fire interval : 52.0

Series 17 : MOR007
Inner Ring : 1565
Outer Ring : 1966
Length of sample : 402
Number in final analysis : 128
Information on fire history :
1601 M injury
1613 E fire scar
1624 D injury
1644 E injury
1681 D injury
1754 D fire scar FI = 97
1804 E injury
1963 U injury
Total number of fire scars : 2
Total number all indicators : 8
Average number years per fire : 64.0
Sample mean fire interval : 97.0
Series 18 : MOR008
Inner Ring : 1628
Outer Ring : 1959
Length of sample : 332
Number in final analysis : 65
Information on fire history :
1684 D injury
1692 D injury
1787 D injury
1898 U fire scar
Total number of fire scars : 1
Total number all indicators : 4
Average number years per fire : 65.0

Series 19 : MOR010
Pith Date : 1694
Outer Ring : 1977
Length of sample : 284
Number in final analysis : 95
Information on fire history :
1883 D fire scar
1889 U fire scar FI = 6
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire : 47.5
Sample mean fire interval : 6.0

Series 20 : MOR012
Inner Ring : 1519
Outer Ring : 1981
Length of sample : 463
Number in final analysis : 188
Information on fire history :
1537 U injury
1601 D injury
1796 E fire scar
1830 E fire scar FI = 34
1848 E injury

Appendix B. *continued.*

Total number of fire scars : 2
Total number all indicators : 5
Average number years per fire : 94.0
Sample mean fire interval : 34.0

Series 21 : MOR013
Inner Ring : 1516
Outer Ring : 1956
Length of sample : 441
Number in final analysis : 20
Information on fire history :
  1531 E injury
  1601 M injury
  1768 D fire scar
Total number of fire scars : 1
Total number all indicators : 3
Average number years per fire : 20.0

Series 22 : MOR014
Inner Ring : 1537
Outer Ring : 1967
Length of sample : 431
Number in final analysis : 304
Information on fire history :
  1555 D injury
  1573 E injury
  1601 D injury
  1667 D fire scar
  1675 E fire scar FI = 8
  1694 U injury
  1698 U injury
  1724 U fire scar FI = 49
Total number of fire scars : 3
Total number all indicators : 8
Average number years per fire : 101.3
Sample mean fire interval : 28.5
Series 23 : MOR015
Pith Date : 1515
Outer Ring : 1865
Length of sample : 351
Number in final analysis : 77
Information on fire history :
  1562 E injury
  1601 D injury
  1643 L injury
  1700 U injury
  1748 U fire scar
  1754 U fire scar FI = 6
  1782 U injury
  1788 U injury
  1836 E fire scar FI = 54
Total number of fire scars : 3
Total number all indicators : 9
Average number years per fire : 25.7
Sample mean fire interval : 30.0

Series 24 : MOR016
Pith Date : 1562
Bark Date : 1982
Length of sample : 421
Number in final analysis : 273
Information on fire history :
  1601 E injury
  1711 U fire scar
  1754 D injury
  1796 D injury
Total number of fire scars : 1
Total number all indicators : 4
Average number years per fire : 273.0

Series 25 : MOR017
Inner Ring : 1561
Outer Ring : 1964
Length of sample : 404
Number in final analysis : 168
Information on fire history :
  1562 U injury
  1601 D injury
  1754 U fire scar
  1789 U injury
  1830 U fire scar FI = 28
  1843 U fire scar FI = 13
  1867 U injury
  1898 U fire scar FI = 55
Total number of fire scars : 4
Total number all indicators : 8
Average number years per fire : 42.0
Sample mean fire interval : 32.0

Appendix B. *continued.*

Series 26 : MOR018
Pith Date : 1514
Outer Ring : 1820
Length of sample : 307
Number in final analysis : 10
Information on fire history :
  1531 E injury
  1566 D injury
  1601 M injury
  1642 L injury
  1660 D fire scar
Total number of fire scars : 1
Total number all indicators : 5
Average number years per fire : 10.0

Series 27 : MOR019
Inner Ring : 1600
Outer Ring : 1891
Length of sample : 292
Number in final analysis : 160
Information on fire history :
  1601 M injury
  1658 D injury
  1698 D injury
  1736 U injury
  1796 U fire scar
  1811 U injury
  1843 U fire scar FI = 47
Total number of fire scars : 2
Total number all indicators : 7
Average number years per fire : 80.0
Sample mean fire interval : 47.0

Series 28 : MOR020
Pith Date : 1509
Outer Ring : 1963
Length of sample : 455
Number in final analysis : 26
Information on fire history :
  1601 M injury
  1632 D injury
  1639 D fire scar
  1669 D injury
  1733 E injury
  1843 E fire scar FI = 11
Total number of fire scars : 2
Total number all indicators : 6
Average number years per fire : 13.0
Sample mean fire interval : 11.0

Series 29 : MOR021
Pith Date : 1520
Outer Ring : 1954
Length of sample : 435
Number in final analysis : 24
Information on fire history :
  1562 E injury
  1573 L injury
  1601 D injury
  1699 U injury
  1754 U injury
  1830 D fire scar
  1836 D fire scar FI = 6
  1849 U injury
  1903 U injury
  1919 U fire scar FI = 9
Total number of fire scars : 3
Total number all indicators : 10
Average number years per fire : 8.0
Sample mean fire interval : 7.5

Series 30 : MOR022
Pith Date : 1467
Outer Ring : 1960
Length of sample : 494
Number in final analysis : 132
Information on fire history :
  1564 D fire scar
  1601 M injury
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 132.0

Series 31 : LP3009
Inner Ring : 1591
Bark Date : 1964
Length of sample : 374
Number in final analysis : 131

Appendix B. *continued.*

Information on fire history :
  1834 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 131.0

Series 32 : MP1001
Inner Ring : 1508
Outer Ring : 1733
Length of sample : 226
Number in final analysis : 4
Information on fire history :
  1509 L injury
  1520 E injury
  1601 U injury
No information in this range.
Total number all indicators : 3

Series 33 : MP1002
Pith Date : 1603
Bark Date : 1989
Length of sample : 387
Number in final analysis : 210
Information on fire history :
  1712 M injury
  1781 U fire scar
  1802 U injury
  1804 U injury
  1837 D injury
  1841 D injury
  1866 U injury
  1897 U injury
  1907 U injury
  1935 L injury
Total number of fire scars : 1
Total number all indicators : 10
Average number years per fire : 210.0

Series 34 : MP1003
Inner Ring : 1664
Bark Date : 1962
Length of sample : 299
Number in final analysis : 299
Information on fire history :
  1665 U fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 299.0

Series 35 : MP1004
Inner Ring : 1331
Outer Ring : 1957
Length of sample : 627
Number in final analysis : 471
Information on fire history :
  1406 U injury
  1488 U fire scar
  1497 U injury
  1502 U injury
  1518 U fire scar FI = 30
  1529 U injury
  1542 U injury
  1547 U injury
  1601 U injury
  1661 U injury
  1675 L injury
  1679 L injury
  1682 D fire scar FI = 164
  1745 D fire scar FI = 63
  1756 U injury
  1781 U fire scar FI = 36
  1822 U fire scar FI = 41
  1834 U fire scar FI = 12
Total number of fire scars : 7
Total number all indicators : 18
Average number years per fire : 67.3
Sample mean fire interval : 57.7

Series 36 : MP1007
Inner Ring : 1780
Bark Date : 1922
Length of sample : 143
Number in final analysis : 89
Information on fire history :
  1834 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 89.0

Appendix B. *continued.*

Series 37 : MP1008
Inner Ring : 1531
Outer Ring : 1686
Length of sample : 156
Number in final analysis : 96
Information on fire history :
  1591 M fire scar
  1601 M injury
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 96.0

Series 38 : MP1009
Inner Ring : 1610
Bark Date : 1983
Length of sample : 374
Number in final analysis : 203
Information on fire history :
  1781 U fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 203.0

Series 39 : MP1010
Inner Ring : 1622
Bark Date : 1974
Length of sample : 353
Number in final analysis : 2
Information on fire history :
  1791 U injury
  1803 U injury
No information in this range.
Total number all indicators : 2

Series 40 : MP1011
Inner Ring : 1566
Outer Ring : 1771
Length of sample : 206
Number in final analysis : 2
Information on fire history :
  1601 L injury
  1669 L injury
No information in this range.
Total number all indicators : 2

Series 41 : MP1012
Inner Ring : 1171
Outer Ring : 1396
Length of sample : 226
Number in final analysis : 1
Information on fire history :
  1347 U injury
No information in this range.
Total number all indicators : 1

Series 42 : MP1013
Inner Ring : 1678
Bark Date : 1922
Length of sample : 245
Number in final analysis : 142
Information on fire history :
  1781 U fire scar
  1839 L injury
  1882 D injury
  1885 D injury
Total number of fire scars : 1
Total number all indicators : 4
Average number years per fire : 142.0

Series 43 : MP1014
Inner Ring : 1613
Outer Ring : 1742
Length of sample : 130
Number in final analysis : 1
Information on fire history :
  1637 D injury
Total number all indicators : 1

Series 44 : MP1017
Inner Ring : 1441
Outer Ring : 1736
Length of sample : 296
Number in final analysis : 0
Information on fire history :
No information in this range.

Series 45 : MP2001
Inner Ring : 1589
Bark Date : 1975

Appendix B. *continued.*

Length of sample : 387
Number in final analysis : 143
Information on fire history :
  1601 U injury
  1834 U injury
  1845 U injury
  1938 U injury
No information in this range.
Total number all indicators : 4

Series 46 : MP2002
Inner Ring : 1562
Bark Date : 1970
Length of sample : 409
Number in final analysis : 83
Information on fire history :
  1576 U injury
  1889 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 83.0

Series 47 : MP2003
Inner Ring : 1569
Bark Date : 1974
Length of sample : 406
Number in final analysis : 90
Information on fire history :
  1591 E injury
  1593 E injury
  1596 E injury
  1795 U injury
  1889 L fire scar
  1934 D injury
Total number of fire scars : 1
Total number all indicators : 6
Average number years per fire : 90.0

Series 48 : MP2004
Inner Ring : 1658
Bark Date : 1967
Length of sample : 310
Number in final analysis : 79
Information on fire history :
  1889 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 79.0

Series 49 : MP2005
Pith Date : 1320
Outer Ring : 1951
Length of sample : 632
Number in final analysis : 475
Information on fire history :
  1323 U injury
  1344 U injury
  1351 U injury
  1369 U injury
  1481 D injury
  1489 D injury
  1585 D fire scar
  1705 U fire scar FI = 120
Total number of fire scars : 2
Total number all indicators : 8
Average number years per fire : 237.5
Sample mean fire interval : 120.0

Series 50 : MP2007
Pith Date : 1657
Bark Date : 1919
Length of sample : 263
Number in final analysis : 43
Information on fire history :
  1668 E injury
  1670 U injury
  1738 E injury
  1880 U fire scar
Total number of fire scars : 1
Total number all indicators : 4
Average number years per fire : 43.0

Series 51 : MP2008
Inner Ring : 1631
Bark Date : 1981
Length of sample : 351
Number in final analysis : 148

Appendix B. *continued.*

Information on fire history :
  1834 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 148.0

Series 52 : MP2009
Pith Date : 1522
Bark Date : 1962
Length of sample : 441
Number in final analysis : 133
Information on fire history :
  1529 U injury
  1534 U injury
  1601 U injury
  1812 U injury
  1834 U fire scar
Total number of fire scars : 1
Total number all indicators : 5
Average number years per fire : 133.0

Series 53 : MP2010
Inner Ring : 1554
Outer Ring : 1823
Length of sample : 270
Number in final analysis : 1
Information on fire history :
  1601 U injury
No information in this range.
Total number all indicators : 1

Series 54 : MP2011
Pith Date : 1558
Bark Date : 2000
Length of sample : 443
Number in final analysis : 105
Information on fire history :
  1561 U injury
  1591 U injury
  1601 U injury
  1625 U injury
  1836 U injury
  1901 U fire scar
  1907 U injury
  1965 U fire scar FI = 64
Total number of fire scars : 2
Total number all indicators : 8
Average number years per fire : 52.5
Sample mean fire interval : 64.0

Series 55 : MP2012
Inner Ring : 1404
Bark Date : 1976
Length of sample : 573
Number in final analysis : 480
Information on fire history :
No information in this range.

Series 56 : MP2013
Inner Ring : 1470
Bark Date : 1952
Length of sample : 483
Number in final analysis : 456
Information on fire history :
  1497 U fire scar
  1555 L injury
  1568 U injury
  1601 U injury
  1668 U injury
Total number of fire scars : 1
Total number all indicators : 5
Average number years per fire : 456.0

Series 57 : MP3001
Pith Date : 1660
Bark Date : 1997
Length of sample : 338
Number in final analysis : 166
Information on fire history :
  1705 E injury
  1757 D injury
  1834 D fire scar
Total number of fire scars : 1
Total number all indicators : 3
Average number years per fire : 166.0

Series 58 : MP3002
Inner Ring : 1087

Appendix B. *continued.*

Outer Ring : 1812
Length of sample : 726
Number in final analysis : 1
Information on fire history :
  1601 U injury
Total number all indicators : 1

Series 59 : MP3003
Inner Ring : 1520
Bark Date : 1984
Length of sample : 465
Number in final analysis : 152
Information on fire history :
  1522 U injury
  1834 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 152.0

Series 60 : MP3004
Inner Ring : 1464
Outer Ring : 1816
Length of sample : 353
Number in final analysis : 14
Information on fire history :
  1497 D injury
  1601 U injury
  1805 D fire scar
Total number of fire scars : 1
Total number all indicators : 3
Average number years per fire : 14.0

Series 61 : MP3005
Pith Date : 1561
Bark Date : 1979
Length of sample : 419
Number in final analysis : 148
Information on fire history :
  1582 U injury
  1731 U injury
  1834 D fire scar
Total number of fire scars : 1
Total number all indicators : 3
Average number years per fire : 148.0

Series 62 : MP3006
Inner Ring : 1434
Bark Date : 1951
Length of sample : 518
Number in final analysis : 119
Information on fire history :
  1601 U injury
  1834 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 119.0

Series 63 : MP3007
Inner Ring : 1263
Outer Ring : 1805
Length of sample : 543
Number in final analysis : 0

Series 64 : MP3010
Pith Date : 1550
Bark Date : 1992
Length of sample : 443
Number in final analysis : 286
Information on fire history :
  1562 M injury
  1580 D injury
  1609 D injury
  1627 D fire scar
  1642 D injury
  1645 D injury
  1647 D injury
  1648 D injury
  1658 D injury
  1834 D fire scar FI = 123
  1893 D injury
Total number of fire scars : 2
Total number all indicators : 11
Average number years per fire : 143.0
Sample mean fire interval : 123.0

Series 65 : MP3011
Pith Date : 1579
Bark Date : 1998
Length of sample : 420

Appendix B. *continued.*

Number in final analysis : 166
Information on fire history :
  1601 U injury
  1834 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 166.0

Series 66 : MP3012
Inner Ring : 1635
Bark Date : 1956
Length of sample : 322
Number in final analysis : 296
Information on fire history :
  1647 D fire scar
  1834 D fire scar FI = 172
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire : 148.0
Sample mean fire interval : 172.0

Series 67 : MP3013
Pith Date : 1268
Outer Ring : 1801
Length of sample : 534
Number in final analysis : 472
Information on fire history :
  1330 D injury
  1410 D injury
  1498 D injury
  1518 E injury
  1520 E injury
  1571 D injury
No information in this range.
Total number all indicators : 6

Series 68 : MP3015
Inner Ring : 1628
Bark Date : 1964
Length of sample : 337
Number in final analysis : 131
Information on fire history :
  1834 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 131.0

Series 69 : MP3016
Inner Ring : 1596
Bark Date : 1982
Length of sample : 387
Number in final analysis : 175
Information on fire history :
  1601 U injury
  1774 D injury
  1810 D fire scar
  1834 D fire scar FI = 24
Total number of fire scars : 2
Total number all indicators : 4
Average number years per fire : 87.5
Sample mean fire interval : 24.0

Series 70 : PS1001
Pith Date : 1753
Bark Date : 1957
Length of sample : 205
Number in final analysis : 142
Information on fire history :
  1816 D fire scar
  1861 D fire scar FI = 45
  1934 D injury
Total number of fire scars : 2
Total number all indicators : 3
Average number years per fire : 71.0
Sample mean fire interval : 45.0

Series 71 : PS1002
Pith Date : 1735
Bark Date : 1949
Length of sample : 215
Number in final analysis : 135
Information on fire history :
  1751 E injury
  1816 D fire scar
  1835 D injury
  1848 L fire scar FI = 32
  1861 D fire scar FI = 13
  1872 D fire scar FI = 11

Appendix B. *continued.*

1874 D injury
1879 D injury
Total number of fire scars : 4
Total number all indicators : 8
Average number years per fire : 33.8
Sample mean fire interval : 18.7

Series 72 : PS1003
Pith Date : 1764
Bark Date : 1926
Length of sample : 163
Number in final analysis : 114
Information on fire history :
1772 M injury
1778 E injury
1783 E injury
1816 D fire scar
1843 D fire scar FI = 27
Total number of fire scars : 2
Total number all indicators : 5
Average number years per fire : 57.0
Sample mean fire interval : 27.0

Series 73 : PS1004
Pith Date : 1759
Bark Date : 2003
Length of sample : 245
Number in final analysis : 188
Information on fire history :
1816 D fire scar
Total number of fire scars : 1
Average number years per fire : 188.0

Series 74 : PS1005
Pith Date : 1760
Bark Date : 2003
Length of sample : 244
Number in final analysis : 189
Information on fire history :
1772 E injury
1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 189.0

Series 75 : PS1006
Pith Date : 1757
Bark Date : 1952
Length of sample : 196
Number in final analysis : 137
Information on fire history :
1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 137.0

Series 76 : PS1007
Pith Date : 1761
Bark Date : 1977
Length of sample : 217
Number in final analysis : 162
Information on fire history :
1816 D fire scar
1967 D injury
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 162.0

Series 77 : PS1008
Pith Date : 1617
Bark Date : 2003
Length of sample : 387
Number in final analysis : 189
Information on fire history :
1794 U injury
1816 D fire scar
1969 D injury
Total number of fire scars : 1
Total number all indicators : 3
Average number years per fire : 189.0

Series 78 : PS1009
Inner Ring : 1645
Bark Date : 1985
Length of sample : 341
Number in final analysis : 170
Information on fire history :
1816 U fire scar
Total number of fire scars : 1

Appendix B. *continued.*

Total number all indicators : 1
Average number years per fire : 170.0

Series 79 : PS1010
Pith Date : 1647
Outer Ring : 1926
Length of sample : 280
Number in final analysis : 114
Information on fire history :
  1649 E injury
  1665 U injury
  1684 D injury
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 4
Average number years per fire : 114.0

Series 80 : PS1011
Pith Date : 1840
Bark Date : 1969
Length of sample : 130
Number in final analysis : 41
Information on fire history :
  1858 E injury
  1930 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 41.0

Series 81 : PS1012
Inner Ring : 1835
Bark Date : 2003
Length of sample : 169
Number in final analysis : 73
Information on fire history :
  1931 D injury
  1963 D injury
No information in this range.
Total number all indicators : 2

Series 82 : PS1013
Pith Date : 1633
Bark Date : 1929
Length of sample : 297
Number in final analysis : 116
Information on fire history :
  1642 E injury
  1671 U injury
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 3
Average number years per fire : 116.0

Series 83 : PS1014
Pith Date : 1608
Bark Date : 1897
Length of sample : 290
Number in final analysis : 180
Information on fire history :
  1625 E injury
  1719 D fire scar
  1816 D fire scar FI = 97
Total number of fire scars : 2
Total number all indicators : 3
Average number years per fire : 90.0
Sample mean fire interval : 97.0

Series 84 : PS1015
Pith Date : 1581
Bark Date : 1928
Length of sample : 348
Number in final analysis : 215
Information on fire history :
  1583 E injury
  1584 E injury
  1601 U injury
  1625 E injury
  1679 D injury
  1719 D fire scar
  1750 U injury
  1816 D fire scar FI = 97
Total number of fire scars : 2
Total number all indicators : 8
Average number years per fire : 107.5
Sample mean fire interval : 97.0

Series 85 : PS1016
Inner Ring : 1618

Appendix B. *continued.*

Bark Date : 1976
Length of sample : 359
Number in final analysis : 260
Information on fire history :
  1640 U injury
  1691 U injury
  1719 D fire scar
  1723 D injury
  1751 U injury
  1816 D fire scar FI = 97
Total number of fire scars : 2
Total number all indicators : 6
Average number years per fire : 130.0
Sample mean fire interval : 97.0

Series 86 : PS2001
Inner Ring : 1629
Outer Ring : 1913
Length of sample : 285
Number in final analysis : 101
Information on fire history :
  1745 U injury
  1774 U injury
  1781 D injury
  1816 D fire scar
  1880 D injury
Total number of fire scars : 1
Total number all indicators : 5
Average number years per fire : 101.0

Series 87 : PS2002
Inner Ring : 1662
Bark Date : 1926
Length of sample : 265
Number in final analysis : 111
Information on fire history :
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 111.0
Series 88 : PS2003
Pith Date : 1615
Bark Date : 1975
Length of sample : 361
Number in final analysis : 162
Information on fire history :
  1653 M injury
  1752 D injury
  1816 D fire scar
  1931 D injury
  1932 D injury
Total number of fire scars : 1
Total number all indicators : 5
Average number years per fire : 162.0

Series 89 : PS2004
Inner Ring : 1654
Bark Date : 1926
Length of sample : 273
Number in final analysis : 112
Information on fire history :
  1752 D injury
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 112.0

Series 90 : PS2005
Pith Date : 1614
Bark Date : 1930
Length of sample : 317
Number in final analysis : 117
Information on fire history :
  1625 E injury
  1752 U injury
  1816 U fire scar
  1882 D injury
Total number of fire scars : 1
Total number all indicators : 4
Average number years per fire : 117.0

Series 91 : PS2007
Pith Date : 1612
Bark Date : 1983
Length of sample : 372
Number in final analysis : 170
Information on fire history :
  1625 E injury

Appendix B. *continued.*

1637 E injury
1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 3
Average number years per fire : 170.0

Series 92 : PS2008
Pith Date : 1778
Bark Date : 1891
Length of sample : 114
Number in final analysis : 42
Information on fire history :
1789 E injury
1816 U injury
1852 D fire scar
1865 U fire scar FI = 13
Total number of fire scars : 2
Total number all indicators : 4
Average number years per fire : 21.0
Sample mean fire interval : 13.0

Series 93 : PS2009
Pith Date : 1861
Bark Date : 1994
Length of sample : 134
Number in final analysis : 66
Information on fire history :
1866 E injury
1930 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 66.0

Series 94 : PS2010
Inner Ring : 1624
Outer Ring : 1993
Length of sample : 370
Number in final analysis : 183
Information on fire history :
1625 U injury
1633 D injury
1651 E injury
1758 D injury
1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 5
Average number years per fire : 183.0

Series 95 : PS2011
Pith Date : 1621
Bark Date : 1985
Length of sample : 365
Number in final analysis : 176
Information on fire history :
1625 E injury
1629 L injury
1637 E injury
1640 E injury
1671 M injury
1752 U injury
1816 D fire scar
1967 D injury
Total number of fire scars : 1
Total number all indicators : 8
Average number years per fire : 176.0

Series 96 : PS2012
Inner Ring : 1643
Bark Date : 1972
Length of sample : 330
Number in final analysis : 163
Information on fire history :
1651 E injury
1671 E injury
1708 D injury
1710 M injury
1752 U injury
1801 D injury
1816 D fire scar
1841 U injury
Total number of fire scars : 1
Total number all indicators : 8
Average number years per fire : 163.0

Series 97 : PS2013
Pith Date : 1606
Bark Date : 1980
Length of sample : 375

Appendix B. *continued.*

Number in final analysis : 169
Information on fire history :
  1612 E injury
  1613 E injury
  1625 E injury
  1637 M injury
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 5
Average number years per fire : 169.0

Series 98 : PS2014
Pith Date : 1621
Bark Date : 1979
Length of sample : 359
Number in final analysis : 6
Information on fire history :
  1625 E injury
  1632 E injury
  1640 D injury
  1649 E injury
  1653 E injury
  1771 D injury
No information in this range.
Total number all indicators : 6

Series 99 : PS2015
Inner Ring : 1652
Bark Date : 1961
Length of sample : 310
Number in final analysis : 301
Information on fire history :
  1661 D fire scar
  1719 D fire scar FI = 58
  1749 D fire scar FI = 30
  1816 D fire scar FI = 67
  1827 U injury
  1855 D injury
  1879 U injury
  1891 D fire scar FI = 75
  1901 U injury
  1904 D fire scar FI = 13
  1913 D fire scar FI = 9
  1921 D injury
Total number of fire scars : 7
Total number all indicators : 12
Average number years per fire : 43.0
Sample mean fire interval : 42.0
Series 100 : PS2016
Inner Ring : 1659
Bark Date : 1929
Length of sample : 271
Number in final analysis : 211
Information on fire history :
  1719 D fire scar
  1776 U injury
  1816 D fire scar FI = 97
Total number of fire scars : 2
Total number all indicators : 3
Average number years per fire : 105.5
Sample mean fire interval : 97.0

Series 101 : PS2EX
Inner Ring : 1689
Outer Ring :1816
Length of sample : 128
Number in final analysis : 98
Information on fire history :
  1719 D fire scar
  1752 U injury
  1774 U injury
  1816 D fire scar FI = 97
Total number of fire scars : 2
Total number all indicators : 4
Average number years per fire : 49.0
Sample mean fire interval : 97.0

Series 102 : PS3001
Pith Date : 1756
Bark Date : 1949
Length of sample : 194
Number in final analysis : 135
Information on fire history :
  1768 E injury
  1816 D fire scar
  1829 D fire scar FI = 13
  1904 U injury
Total number of fire scars : 2

Appendix B. *continued.*

Total number all indicators : 4
Average number years per fire : 67.5
Sample mean fire interval : 13.0

Series 103 : PS3002
Pith Date : 1734
Outer Ring : 1938
Length of sample : 205
Number in final analysis : 123
Information on fire history :
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 123.0

Series 104 : PS3003
Pith Date : 1763
Bark Date : 1984
Length of sample : 222
Number in final analysis : 169
Information on fire history :
  1816 D fire scar
  1940 U injury
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 169.0

Series 105 : PS3004
Pith Date : 1742
Outer Ring : 1889
Length of sample : 148
Number in final analysis : 75
Information on fire history :
  1794 E injury
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 75.0

Series 106 : PS3005
Pith Date : 1743
Outer Ring : 1858
Length of sample : 116
Number in final analysis : 43
Information on fire history :
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 43.0

Series 107 : PS3006
Pith Date : 1737
Bark Date : 1897
Length of sample : 161
Number in final analysis : 85
Information on fire history :
  1739 D injury
  1741 D injury
  1750 D injury
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 4
Average number years per fire : 85.0

Series 108 : PS3007
Pith Date : 1768
Bark Date : 1925
Length of sample : 158
Number in final analysis : 112
Information on fire history :
  1772 E injury
  1780 E injury
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 3
Average number years per fire : 112.0

Series 109 : PS3008
Pith Date : 1757
Bark Date : 1929
Length of sample : 173
Number in final analysis : 114
Information on fire history :
  1816 D fire scar
  1831 D fire scar FI = 15
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire : 57.0

Appendix B. *continued.*

Sample mean fire interval : 15.0

Series 110 : PS3009
Pith Date : 1762
Bark Date : 1929
Length of sample : 168
Number in final analysis : 115
Information on fire history :
  1772 E injury
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 2
Average number years per fire : 115.0

Series 111 : PS3010
Inner Ring : 1750
Bark Date : 1830
Length of sample : 81
Number in final analysis : 15
Information on fire history :
  1816 D fire scar
Total number of fire scars : 1
Total number all indicators : 1
Average number years per fire : 15.0

Summary Information:

Beginning year : 1092
Last year : 2003
Length of fire chronology : 1004
Total number of samples : 111
Total number of recorder years : 15353
Total number of fire scars : 150
Total number of all indicators : 409

Avg number of years per fire : 102.4
Avg number of years per all injuries : 37.5
Avg all sample mean fire intervals : 15.3
Total number of years with fire : 68
Percentage of years with fire : 6.8
Percentage of years without fire : 93.2
Percentage of years MFI : 14.8

Appendix C1. Fire-tree establishment MDSEA output for annual tree establishment.

Index	Yr	Mean	n	Std dev	Limits +/-1.96 SD		Limits +/-2.575 SD		Limits +/-3.294 SD		Min	Max
0	0	0.625	8	0.9161	-1.1706	2.4206	-1.734	2.984	-2.3927	3.6427	0	2
1	1	0.625	8	0.744	-0.8333	2.0833	-1.2909	2.5409	-1.8258	3.0758	0	2
2	2	0.375	8	0.5175	-0.6394	1.3894	-0.9577	1.7077	-1.3298	2.0798	0	1
3	3	0.75	8	1.165	-1.5333	3.0333	-2.2498	3.7498	-3.0874	4.5874	0	3
4	4	0.125	8	0.3536	-0.568	0.818	-0.7854	1.0354	-1.0396	1.2896	0	1
5	5	0.375	8	0.744	-1.0833	1.8333	-1.5409	2.2909	-2.0758	2.8258	0	2
6	6	1.125	8	0.991	-0.8174	3.0674	-1.4269	3.6769	-2.1395	4.3895	0	3
7	7	0.25	8	0.4629	-0.6573	1.1573	-0.942	1.442	-1.2748	1.7748	0	1
8	8	0.25	8	0.4629	-0.6573	1.1573	-0.942	1.442	-1.2748	1.7748	0	1
9	9	0.75	8	0.7071	-0.6359	2.1359	-1.0708	2.5708	-1.5792	3.0792	0	2
10	10	1	8	0.7559	-0.4816	2.4816	-0.9465	2.9465	-1.49	3.49	0	2
11	11	0.5	8	0.5345	-0.5477	1.5477	-0.8764	1.8764	-1.2607	2.2607	0	1
12	12	0.5	8	0.5345	-0.5477	1.5477	-0.8764	1.8764	-1.2607	2.2607	0	1
13	13	0.375	8	0.744	-1.0833	1.8333	-1.5409	2.2909	-2.0758	2.8258	0	2
14	14	0.625	8	0.744	-0.8333	2.0833	-1.2909	2.5409	-1.8258	3.0758	0	2
15	15	1	8	0.9258	-0.8146	2.8146	-1.384	3.384	-2.0497	4.0497	0	3
16	16	0.5	8	0.7559	-0.9816	1.9816	-1.4465	2.4465	-1.99	2.99	0	2
17	17	0.625	8	0.9161	-1.1706	2.4206	-1.734	2.984	-2.3927	3.6427	0	2
18	18	0.875	8	0.8345	-0.7607	2.5107	-1.2739	3.0239	-1.8739	3.6239	0	2
19	19	1.25	8	1.7525	-2.185	4.685	-3.2628	5.7628	-4.5229	7.0229	0	5
20	20	0.75	8	0.7071	-0.6359	2.1359	-1.0708	2.5708	-1.5792	3.0792	0	2
21	21	0.875	8	1.3562	-1.7832	3.5332	-2.6172	4.3672	-3.5923	5.3423	0	4
22	22	0.5	8	1.069	-1.5953	2.5953	-2.2528	3.2528	-3.0214	4.0214	0	3
23	23	0.75	8	0.7071	-0.6359	2.1359	-1.0708	2.5708	-1.5792	3.0792	0	2
24	24	1.625	8	1.685	-1.6776	4.9276	-2.7139	5.9639	-3.9254	7.1754	0	5
25	25	0.75	8	1.3887	-1.9719	3.4719	-2.826	4.326	-3.8245	5.3245	0	4
26	26	0.75	8	0.7071	-0.6359	2.1359	-1.0708	2.5708	-1.5792	3.0792	0	2
27	27	0.75	8	0.8864	-0.9874	2.4874	-1.5325	3.0325	-2.1698	3.6698	0	2
28	28	0.75	8	0.8864	-0.9874	2.4874	-1.5325	3.0325	-2.1698	3.6698	0	2
29	29	0.375	8	0.744	-1.0833	1.8333	-1.5409	2.2909	-2.0758	2.8258	0	2
30	30	0.75	8	1.0351	-1.2788	2.7788	-1.9154	3.4154	-2.6596	4.1596	0	3
31	31	1	8	0.7559	-0.4816	2.4816	-0.9465	2.9465	-1.49	3.49	0	2
32	32	0.5	8	0.7559	-0.9816	1.9816	-1.4465	2.4465	-1.99	2.99	0	2
33	33	0.75	8	1.0351	-1.2788	2.7788	-1.9154	3.4154	-2.6596	4.1596	0	3
34	34	1.125	8	1.4577	-1.7322	3.9822	-2.6287	4.8787	-3.6768	5.9268	0	4
35	35	0.25	8	0.4629	-0.6573	1.1573	-0.942	1.442	-1.2748	1.7748	0	1
36	36	1.125	8	0.991	-0.8174	3.0674	-1.4269	3.6769	-2.1395	4.3895	0	3
37	37	1.375	8	1.7678	-2.0898	4.8398	-3.177	5.927	-4.448	7.198	0	5
38	38	1.375	8	0.9161	-0.4206	3.1706	-0.984	3.734	-1.6427	4.3927	0	3
39	-1	0.875	8	1.4577	-1.9822	3.7322	-2.8787	4.6287	-3.9268	5.6768	0	4
40	0	1	8	1.069	-1.0953	3.0953	-1.7528	3.7528	-2.5214	4.5214	0	3
41	1	0.875	8	0.8345	-0.7607	2.5107	-1.2739	3.0239	-1.8739	3.6239	0	2
42	2	0.75	8	0.8864	-0.9874	2.4874	-1.5325	3.0325	-2.1698	3.6698	0	2
43	3	0.625	8	1.0607	-1.4539	2.7039	-2.1062	3.3562	-2.8688	4.1188	0	3
44	4	1	8	1.1952	-1.3426	3.3426	-2.0777	4.0777	-2.9371	4.9371	0	3
45	5	0.875	8	0.991	-1.0674	2.8174	-1.6769	3.4269	-2.3895	4.1395	0	2
46	6	1.25	8	1.3887	-1.4719	3.9719	-2.326	4.826	-3.3245	5.8245	0	4
47	7	0.75	8	0.7071	-0.6359	2.1359	-1.0708	2.5708	-1.5792	3.0792	0	2
48	8	1.125	8	1.126	-1.0819	3.3319	-1.7744	4.0244	-2.584	4.834	0	3
49	9	0.875	8	1.126	-1.3319	3.0819	-2.0244	3.7744	-2.834	4.584	0	3
50	10	0.625	8	0.744	-0.8333	2.0833	-1.2909	2.5409	-1.8258	3.0758	0	2

Appendix C1. *Continued.*

					Limits		Limits		Limits			
Index	Yr	Mean	n	Std dev	+/-1.96 SD		+/-2.575 SD		+/-3.294 SD		Min	Max
51	11	1	8	0.7559	-0.4816	2.4816	-0.9465	2.9465	-1.49	3.49	0	2
52	12	1.625	8	1.1877	-0.703	3.953	-1.4334	4.6834	-2.2874	5.5374	0	4
53	13	1.625	8	1.1877	-0.703	3.953	-1.4334	4.6834	-2.2874	5.5374	0	3
54	14	1.125	8	1.126	-1.0819	3.3319	-1.7744	4.0244	-2.584	4.834	0	3
55	15	1.125	8	1.126	-1.0819	3.3319	-1.7744	4.0244	-2.584	4.834	0	3
56	16	1	8	1.1952	-1.3426	3.3426	-2.0777	4.0777	-2.9371	4.9371	0	3
57	17	1	8	1.6903	-2.313	4.313	-3.3525	5.3525	-4.5679	6.5679	0	5
58	18	0.75	8	1.0351	-1.2788	2.7788	-1.9154	3.4154	-2.6596	4.1596	0	3
59	19	1.75	8	1.669	-1.5213	5.0213	-2.5478	6.0478	-3.7478	7.2478	0	4
60	20	0.625	8	0.744	-0.8333	2.0833	-1.2909	2.5409	-1.8258	3.0758	0	2
61	21	1.25	8	1.0351	-0.7788	3.2788	-1.4154	3.9154	-2.1596	4.6596	0	3
62	22	1.5	8	1.3093	-1.0662	4.0662	-1.8715	4.8715	-2.8129	5.8129	0	4
63	23	1.125	8	0.8345	-0.5107	2.7607	-1.0239	3.2739	-1.6239	3.8739	0	2
64	24	0.875	8	1.3562	-1.7832	3.5332	-2.6172	4.3672	-3.5923	5.3423	0	4
65	25	1.375	8	1.1877	-0.953	3.703	-1.6834	4.4334	-2.5374	5.2874	0	3
66	26	1.5	8	1.3093	-1.0662	4.0662	-1.8715	4.8715	-2.8129	5.8129	0	3
67	27	1	8	1.069	-1.0953	3.0953	-1.7528	3.7528	-2.5214	4.5214	0	3
68	28	0.75	8	1.0351	-1.2788	2.7788	-1.9154	3.4154	-2.6596	4.1596	0	3
69	29	1.75	8	1.5811	-1.349	4.849	-2.3214	5.8214	-3.4583	6.9583	0	5
70	30	0.875	8	0.8345	-0.7607	2.5107	-1.2739	3.0239	-1.8739	3.6239	0	2
71	31	1.125	8	0.991	-0.8174	3.0674	-1.4269	3.6769	-2.1395	4.3895	0	3
72	32	1.625	8	1.8468	-1.9948	5.2448	-3.1305	6.3805	-4.4584	7.7084	0	5
73	33	1.125	8	0.991	-0.8174	3.0674	-1.4269	3.6769	-2.1395	4.3895	0	3
74	34	1.25	8	1.5811	-1.849	4.349	-2.8214	5.3214	-3.9583	6.4583	0	4
75	35	0.75	8	1.0351	-1.2788	2.7788	-1.9154	3.4154	-2.6596	4.1596	0	3
76	36	0.875	8	1.126	-1.3319	3.0819	-2.0244	3.7744	-2.834	4.584	0	3
77	37	1	8	1.4142	-1.7719	3.7719	-2.6416	4.6416	-3.6584	5.6584	0	4
78	38	0.75	8	1.0351	-1.2788	2.7788	-1.9154	3.4154	-2.6596	4.1596	0	3
79	19	0.875	8	0.8345	-0.7607	2.5107	-1.2739	3.0239	-1.8739	3.6239	0	2
80	20	1.25	8	1.3887	-1.4719	3.9719	-2.326	4.826	-3.3245	5.8245	0	4
81	21	1	8	1.1952	-1.3426	3.3426	-2.0777	4.0777	-2.9371	4.9371	0	3
82	22	0.875	8	0.8345	-0.7607	2.5107	-1.2739	3.0239	-1.8739	3.6239	0	2
83	23	1.25	8	1.0351	-0.7788	3.2788	-1.4154	3.9154	-2.1596	4.6596	0	3
84	24	1.5	8	1.4142	-1.2719	4.2719	-2.1416	5.1416	-3.1584	6.1584	0	4
85	25	0.5	8	0.7559	-0.9816	1.9816	-1.4465	2.4465	-1.99	2.99	0	2
86	26	1.25	8	1.488	-1.6666	4.1666	-2.5817	5.0817	-3.6516	6.1516	0	3
87	27	2	8	1.8516	-1.6292	5.6292	-2.768	6.768	-4.0993	8.0993	0	5
88	28	0.375	8	0.5175	-0.6394	1.3894	-0.9577	1.7077	-1.3298	2.0798	0	1
89	29	1	8	1.069	-1.0953	3.0953	-1.7528	3.7528	-2.5214	4.5214	0	3
90	30	1	8	1.069	-1.0953	3.0953	-1.7528	3.7528	-2.5214	4.5214	0	3
91	31	1.125	8	1.2464	-1.318	3.568	-2.0845	4.3345	-2.9807	5.2307	0	3
92	32	0.5	8	0.5345	-0.5477	1.5477	-0.8764	1.8764	-1.2607	2.2607	0	1
93	33	1.125	8	1.126	-1.0819	3.3319	-1.7744	4.0244	-2.584	4.834	0	3
94	34	0.625	8	0.744	-0.8333	2.0833	-1.2909	2.5409	-1.8258	3.0758	0	2
95	35	1	8	0.9258	-0.8146	2.8146	-1.384	3.384	-2.0497	4.0497	0	3
96	36	1	8	1.069	-1.0953	3.0953	-1.7528	3.7528	-2.5214	4.5214	0	3
97	37	1.375	8	1.3025	-1.1778	3.9278	-1.9789	4.7289	-2.9153	5.6653	0	4
98	38	0.625	8	0.9161	-1.1706	2.4206	-1.734	2.984	-2.3927	3.6427	0	2

Appendix C2. Fire-tree establishment MDSEA bootstrapped confidence intervals for annual tree establishment.

					Limits		Limits		Limits			
Index	Yr	Mean	n	Std dev	+/-1.96 SD		+/-2.575 SD		+/-3.294 SD		Min	Max
0	0	0.6346	1000	0.373	-0.0965	1.3658	-0.3259	1.5952	-0.5942	1.8634	0	2.5
1	1	0.638	1000	0.3717	-0.0905	1.3665	-0.3191	1.5951	-0.5864	1.8624	0	2.25
2	2	0.6231	1000	0.3568	-0.0763	1.3225	-0.2957	1.542	-0.5523	1.7985	0	2
3	3	0.6369	1000	0.3796	-0.1071	1.3809	-0.3405	1.6143	-0.6135	1.8872	0	2.25
4	4	0.658	1000	0.3783	-0.0834	1.3994	-0.316	1.632	-0.588	1.904	0	2.25
5	5	0.6436	1000	0.3743	-0.0901	1.3773	-0.3203	1.6075	-0.5894	1.8767	0	2
6	6	0.6304	1000	0.3557	-0.0669	1.3276	-0.2857	1.5464	-0.5414	1.8022	0	2
7	7	0.6516	1000	0.3713	-0.0761	1.3793	-0.3044	1.6077	-0.5714	1.8746	0	2.125
8	8	0.645	1000	0.366	-0.0724	1.3624	-0.2974	1.5874	-0.5606	1.8506	0	2
9	9	0.6521	1000	0.3641	-0.0614	1.3657	-0.2853	1.5896	-0.5471	1.8513	0	2.25
10	10	0.6635	1000	0.365	-0.052	1.379	-0.2764	1.6034	-0.5389	1.8659	0	1.875
11	11	0.6594	1000	0.3763	-0.0781	1.3968	-0.3095	1.6282	-0.58	1.8988	0	2.375
12	12	0.676	1000	0.3774	-0.0637	1.4157	-0.2959	1.6479	-0.5672	1.9192	0	2.375
13	13	0.6774	1000	0.3776	-0.0628	1.4175	-0.295	1.6498	-0.5665	1.9213	0	2.25
14	14	0.6593	1000	0.3808	-0.0871	1.4056	-0.3213	1.6398	-0.5951	1.9136	0	2.125
15	15	0.676	1000	0.3854	-0.0793	1.4313	-0.3163	1.6683	-0.5934	1.9454	0	2.25
16	16	0.6901	1000	0.3677	-0.0306	1.4109	-0.2568	1.637	-0.5212	1.9014	0	2
17	17	0.6691	1000	0.3741	-0.064	1.4023	-0.2941	1.6324	-0.5631	1.9013	0	2
18	18	0.6766	1000	0.3746	-0.0576	1.4109	-0.288	1.6413	-0.5573	1.9106	0	2.125
19	19	0.7011	1000	0.3811	-0.0459	1.4482	-0.2803	1.6826	-0.5544	1.9566	0	2.375
20	20	0.6854	1000	0.3765	-0.0526	1.4233	-0.2841	1.6549	-0.5549	1.9256	0	2.375
21	21	0.691	1000	0.3795	-0.0528	1.4348	-0.2862	1.6682	-0.559	1.941	0	2.25
22	22	0.7021	1000	0.3749	-0.0327	1.4369	-0.2632	1.6675	-0.5328	1.9371	0	1.875
23	23	0.6801	1000	0.3774	-0.0596	1.4198	-0.2917	1.6519	-0.563	1.9233	0	2.125
24	24	0.7185	1000	0.3849	-0.0359	1.4729	-0.2726	1.7096	-0.5494	1.9864	0	2
25	25	0.7069	1000	0.3682	-0.0149	1.4286	-0.2414	1.6551	-0.5061	1.9199	0	2.375
26	26	0.7097	1000	0.3951	-0.0647	1.4842	-0.3077	1.7272	-0.5918	2.0113	0	2.5
27	27	0.6934	1000	0.3751	-0.0417	1.4285	-0.2724	1.6591	-0.5421	1.9288	0	2.375
28	28	0.6971	1000	0.3861	-0.0597	1.4539	-0.2971	1.6914	-0.5748	1.969	0	2.5
29	29	0.724	1000	0.3913	-0.043	1.491	-0.2837	1.7317	-0.565	2.013	0	2.125
30	30	0.7124	1000	0.3807	-0.0337	1.4585	-0.2678	1.6926	-0.5415	1.9663	0	2.375
31	31	0.7013	1000	0.3692	-0.0224	1.4249	-0.2495	1.652	-0.515	1.9175	0	2.25
32	32	0.7309	1000	0.3885	-0.0306	1.4923	-0.2695	1.7312	-0.5488	2.0106	0	2.125
33	33	0.6841	1000	0.3668	-0.0348	1.403	-0.2603	1.6286	-0.5241	1.8923	0	2
34	34	0.7153	1000	0.3756	-0.0209	1.4514	-0.2519	1.6824	-0.5219	1.9524	0	2.125
35	35	0.7003	1000	0.3806	-0.0456	1.4461	-0.2797	1.6802	-0.5533	1.9538	0	2.375
36	36	0.7064	1000	0.3807	-0.0397	1.4525	-0.2739	1.6866	-0.5476	1.9603	0	2.375
37	37	0.7314	1000	0.3783	-0.0101	1.4729	-0.2428	1.7055	-0.5148	1.9776	0	2.25
38	38	0.726	1000	0.383	-0.0247	1.4767	-0.2602	1.7122	-0.5356	1.9876	0	2.625
39	-1	0.7111	1000	0.3478	0.0295	1.3927	-0.1844	1.6065	-0.4344	1.8566	0	2
40	0	0.7167	1000	0.3828	-0.0335	1.467	-0.2689	1.7024	-0.5442	1.9777	0	2.5714
41	1	0.7211	1000	0.3796	-0.023	1.4652	-0.2564	1.6987	-0.5294	1.9717	0	2.125
42	2	0.7493	1000	0.3667	0.0305	1.468	-0.195	1.6936	-0.4587	1.9572	0	2.625
43	3	0.733	1000	0.3695	0.0088	1.4572	-0.2184	1.6845	-0.4841	1.9501	0	2.125
44	4	0.746	1000	0.3947	-0.0277	1.5196	-0.2705	1.7624	-0.5543	2.0462	0	2.375
45	5	0.7344	1000	0.3692	0.0107	1.458	-0.2164	1.6851	-0.4818	1.9506	0	2.25
46	6	0.7324	1000	0.3683	0.0106	1.4543	-0.2159	1.6807	-0.4807	1.9455	0	2.25
47	7	0.727	1000	0.3715	-0.0011	1.455	-0.2295	1.6835	-0.4966	1.9505	0	2.125
48	8	0.7304	1000	0.3767	-0.0078	1.4687	-0.2395	1.7004	-0.5103	1.9712	0	2.125
49	9	0.7455	1000	0.3774	0.0058	1.4851	-0.2262	1.7172	-0.4975	1.9885	0	2

Appendix C2. *Continued.*

					Limits		Limits		Limits			
Index	Yr	Mean	n	Std dev	+/-1.96 SD		+/-2.575 SD		+/-3.294 SD		Min	Max
50	10	0.7554	1000	0.3757	0.0191	1.4917	-0.2119	1.7227	-0.482	1.9928	0	2.25
51	11	0.769	1000	0.3976	-0.0104	1.5484	-0.255	1.7929	-0.5409	2.0788	0	2.625
52	12	0.7517	1000	0.3793	0.0082	1.4951	-0.2251	1.7284	-0.4978	2.0011	0	2.375
53	13	0.757	1000	0.3749	0.0222	1.4918	-0.2084	1.7224	-0.4779	1.992	0	2.5714
54	14	0.7599	1000	0.3755	0.024	1.4959	-0.2069	1.7268	-0.4768	1.9967	0	2.125
55	15	0.7556	1000	0.3828	0.0053	1.5059	-0.2301	1.7413	-0.5053	2.0165	0	2.375
56	16	0.7358	1000	0.3662	0.0181	1.4535	-0.2071	1.6787	-0.4703	1.942	0	2
57	17	0.7345	1000	0.3816	-0.0135	1.4824	-0.2482	1.7171	-0.5225	1.9915	0	2.125
58	18	0.7434	1000	0.3759	0.0067	1.4802	-0.2245	1.7114	-0.4948	1.9817	0	2.375
59	19	0.7543	1000	0.3743	0.0206	1.488	-0.2097	1.7182	-0.4788	1.9874	0	2.25
60	20	0.7544	1000	0.3775	0.0146	1.4943	-0.2176	1.7264	-0.489	1.9979	0	2.25
61	21	0.7642	1000	0.3737	0.0318	1.4965	-0.198	1.7263	-0.4667	1.995	0	2
62	22	0.7533	1000	0.3704	0.0273	1.4793	-0.2005	1.7071	-0.4668	1.9734	0	2.375
63	23	0.7585	1000	0.3824	0.009	1.508	-0.2261	1.7431	-0.5011	2.0181	0	2.2857
64	24	0.7614	1000	0.3762	0.024	1.4989	-0.2074	1.7302	-0.4779	2.0008	0	2.125
65	25	0.7303	1000	0.3615	0.0218	1.4387	-0.2005	1.661	-0.4604	1.9209	0	1.875
66	26	0.7487	1000	0.3831	-0.0021	1.4995	-0.2376	1.7351	-0.5131	2.0105	0	2.25
67	27	0.7562	1000	0.3724	0.0263	1.4861	-0.2028	1.7152	-0.4705	1.983	0	2
68	28	0.7723	1000	0.3797	0.0281	1.5165	-0.2054	1.75	-0.4784	2.023	0	2.5
69	29	0.7788	1000	0.3856	0.0231	1.5345	-0.214	1.7716	-0.4912	2.0488	0	2.375
70	30	0.7552	1000	0.3673	0.0353	1.475	-0.1906	1.7009	-0.4546	1.965	0	2.25
71	31	0.7564	1000	0.3798	0.0119	1.5009	-0.2217	1.7345	-0.4948	2.0076	0	2.125
72	32	0.7791	1000	0.3837	0.027	1.5312	-0.209	1.7672	-0.4849	2.0431	0	2.125
73	33	0.7489	1000	0.3751	0.0137	1.4842	-0.217	1.7149	-0.4867	1.9846	0	2.125
74	34	0.7619	1000	0.3888	-0.0002	1.524	-0.2394	1.7632	-0.5189	2.0428	0	2.375
75	35	0.7486	1000	0.3812	0.0015	1.4957	-0.2329	1.7301	-0.507	2.0042	0	2.125
76	36	0.7787	1000	0.3861	0.0219	1.5355	-0.2155	1.773	-0.4932	2.0506	0	2.375
77	37	0.7636	1000	0.3847	0.0096	1.5176	-0.227	1.7542	-0.5036	2.0308	0	2.25
78	38	0.7649	1000	0.384	0.0122	1.5176	-0.224	1.7538	-0.5001	2.03	0	2.875
79	19	0.7814	1000	0.4008	-0.0042	1.5669	-0.2507	1.8134	-0.5389	2.1016	0	2.25
80	20	0.7791	1000	0.3625	0.0685	1.4896	-0.1545	1.7126	-0.4152	1.9733	0	2.25
81	21	0.799	1000	0.3996	0.0158	1.5822	-0.2299	1.828	-0.5172	2.1153	0	2.375
82	22	0.7892	1000	0.3934	0.018	1.5603	-0.224	1.8023	-0.5068	2.0852	0	2.125
83	23	0.7839	1000	0.3857	0.0279	1.5398	-0.2093	1.777	-0.4866	2.0543	0	2.5
84	24	0.7747	1000	0.3878	0.0146	1.5347	-0.2238	1.7732	-0.5026	2.052	0	2.375
85	25	0.7785	1000	0.3855	0.023	1.5341	-0.2141	1.7712	-0.4912	2.0483	0	2.25
86	26	0.8002	1000	0.406	0.0045	1.596	-0.2451	1.8456	-0.537	2.1375	0	2.5
87	27	0.7744	1000	0.3841	0.0216	1.5271	-0.2146	1.7633	-0.4907	2.0395	0	2.25
88	28	0.805	1000	0.3828	0.0547	1.5554	-0.1808	1.7908	-0.456	2.0661	0	2
89	29	0.7866	1000	0.3751	0.0513	1.5219	-0.1794	1.7526	-0.4491	2.0224	0	2.125
90	30	0.7587	1000	0.3735	0.0267	1.4907	-0.203	1.7204	-0.4715	1.989	0	2.25
91	31	0.7811	1000	0.3813	0.0338	1.5284	-0.2007	1.7629	-0.4748	2.037	0	2.5
92	32	0.7725	1000	0.3834	0.0211	1.524	-0.2147	1.7597	-0.4904	2.0354	0	2.125
93	33	0.7619	1000	0.3662	0.0441	1.4797	-0.1812	1.7049	-0.4445	1.9683	0	2.5
94	34	0.7836	1000	0.3749	0.0488	1.5184	-0.1817	1.749	-0.4513	2.0185	0	2.375
95	35	0.7786	1000	0.3799	0.0341	1.5232	-0.1995	1.7568	-0.4727	2.0299	0	2.375
96	36	0.8078	1000	0.3904	0.0427	1.573	-0.1974	1.8131	-0.4781	2.0937	0	2.125
97	37	0.7753	1000	0.379	0.0324	1.5182	-0.2007	1.7513	-0.4733	2.0238	0	2.25
98	38	0.7678	1000	0.3806	0.0218	1.5138	-0.2122	1.7479	-0.4859	2.0215	0	2.375

Appendix D1. Fire-tree establishment MDSEA for 5-yr mean tree establishment.

					Limits		Limits		Limits			
Index	Yr	Mean	n	Std dev	+/-1.96 SD		+/-2.575 SD		+/-3.294 SD		Min	Max
0	0	0.55	8	0.3964	-0.227	1.327	-0.4708	1.5708	-0.7558	1.8558	0.2	1.2
1	1	0.65	8	0.5099	-0.3494	1.6494	-0.663	1.963	-1.0296	2.3296	0.2	1.6
2	2	0.5	8	0.4408	-0.3639	1.3639	-0.635	1.635	-0.9519	1.9519	0	1.2
3	3	0.45	8	0.3338	-0.2043	1.1043	-0.4096	1.3096	-0.6496	1.5496	0	1
4	4	0.55	8	0.4504	-0.3328	1.4328	-0.6098	1.7098	-0.9336	2.0336	0	1.4
5	5	0.525	8	0.44	-0.3373	1.3873	-0.6079	1.6579	-0.9243	1.9743	0	1.4
6	6	0.425	8	0.42	-0.3983	1.2483	-0.6566	1.5066	-0.9586	1.8086	0	1.2
7	7	0.55	8	0.5318	-0.4924	1.5924	-0.8195	1.9195	-1.2019	2.3019	0	1.6
8	8	0.675	8	0.5651	-0.4325	1.7825	-0.78	2.13	-1.1863	2.5363	0	1.6
9	9	0.55	8	0.3665	-0.1682	1.2682	-0.3936	1.4936	-0.6571	1.7571	0.2	1.2
10	10	0.6	8	0.3024	0.0074	1.1926	-0.1786	1.3786	-0.396	1.596	0.2	1.2
11	11	0.625	8	0.2712	0.0934	1.1566	-0.0734	1.3234	-0.2685	1.5185	0.2	1
12	12	0.6	8	0.2619	0.0868	1.1132	-0.0743	1.2743	-0.2626	1.4626	0.2	1
13	13	0.6	8	0.2619	0.0868	1.1132	-0.0743	1.2743	-0.2626	1.4626	0.4	1.2
14	14	0.6	8	0.4276	-0.2381	1.4381	-0.5011	1.7011	-0.8086	2.0086	0.2	1.6
15	15	0.625	8	0.4713	-0.2988	1.5488	-0.5886	1.8386	-0.9275	2.1775	0	1.6
16	16	0.725	8	0.4528	-0.1624	1.6124	-0.4409	1.8909	-0.7664	2.2164	0	1.6
17	17	0.85	8	0.7764	-0.6718	2.3718	-1.1493	2.8493	-1.7076	3.4076	0	2.4
18	18	0.8	8	0.6047	-0.3853	1.9853	-0.7572	2.3572	-1.192	2.792	0.2	2
19	19	0.875	8	0.6923	-0.4819	2.2319	-0.9077	2.6577	-1.4055	3.1555	0.2	2.4
20	20	0.85	8	0.7838	-0.6862	2.3862	-1.1682	2.8682	-1.7317	3.4317	0.2	2.6
21	21	0.825	8	0.6882	-0.5238	2.1738	-0.947	2.597	-1.4418	3.0918	0.4	2.4
22	22	0.9	8	0.5757	-0.2284	2.0284	-0.5824	2.3824	-0.9964	2.7964	0.4	1.8
23	23	0.9	8	0.835	-0.7365	2.5365	-1.25	3.05	-1.8503	3.6503	0.4	2.6
24	24	0.875	8	0.7555	-0.6057	2.3557	-1.0703	2.8203	-1.6135	3.3635	0.2	2.6
25	5	0.925	8	0.5651	-0.1825	2.0325	-0.53	2.38	-0.9363	2.7863	0.2	2
26	6	0.925	8	0.6585	-0.3656	2.2156	-0.7705	2.6205	-1.244	3.094	0	1.8
27	7	0.675	8	0.5007	-0.3064	1.6564	-0.6143	1.9643	-0.9744	2.3244	0	1.6
28	8	0.675	8	0.6228	-0.5457	1.8957	-0.9287	2.2787	-1.3764	2.7264	0	1.6
29	9	0.725	8	0.512	-0.2785	1.7285	-0.5934	2.0434	-0.9615	2.4115	0.2	1.6
30	10	0.675	8	0.5007	-0.3064	1.6564	-0.6143	1.9643	-0.9744	2.3244	0	1.6
31	11	0.675	8	0.4773	-0.2606	1.6106	-0.5542	1.9042	-0.8974	2.2474	0	1.4
32	12	0.825	8	0.6274	-0.4046	2.0546	-0.7904	2.4404	-1.2415	2.8915	0	1.8
33	13	0.725	8	0.5751	-0.4022	1.8522	-0.7558	2.2058	-1.1693	2.6193	0.2	1.6
34	14	0.75	8	0.6655	-0.5543	2.0543	-0.9636	2.4636	-1.4421	2.9421	0.2	2
35	15	0.925	8	0.8681	-0.7764	2.6264	-1.3103	3.1603	-1.9345	3.7845	0.2	2.4
36	16	1.05	8	0.8194	-0.556	2.656	-1.06	3.16	-1.6491	3.7491	0.2	2.6
37	17	1	8	0.7709	-0.511	2.511	-0.9851	2.9851	-1.5393	3.5393	0	2.4
38	18	1.15	8	0.8928	-0.5999	2.8999	-1.149	3.449	-1.791	4.091	0.2	2.6
39	19	1.1	8	0.7928	-0.4539	2.6539	-0.9415	3.1415	-1.5116	3.7116	0.2	2.4
40	20	0.975	8	0.6089	-0.2184	2.1684	-0.5928	2.5428	-1.0306	2.9806	0.2	1.8
41	21	0.825	8	0.6541	-0.4571	2.1071	-0.8593	2.5093	-1.3296	2.9796	0	1.8
42	22	0.85	8	0.699	-0.52	2.22	-0.9499	2.6499	-1.4524	3.1524	0	2
43	23	0.825	8	0.7046	-0.556	2.206	-0.9893	2.6393	-1.4959	3.1459	0	1.8
44	24	0.9	8	0.8418	-0.7499	2.5499	-1.2675	3.0675	-1.8728	3.6728	0	2.4
45	5	0.9	8	0.8211	-0.7095	2.5095	-1.2145	3.0145	-1.8049	3.6049	0	2.4
46	6	1	8	0.8	-0.568	2.568	-1.06	3.06	-1.6352	3.6352	0	2.4
47	7	0.975	8	0.8582	-0.707	2.657	-1.2347	3.1847	-1.8518	3.8018	0	2.6
48	8	0.925	8	0.7402	-0.5257	2.3757	-0.9809	2.8309	-1.5131	3.3631	0	2.2
49	9	0.875	8	0.5651	-0.2325	1.9825	-0.58	2.33	-0.9863	2.7363	0.2	1.8

Appendix D1. *Continued.*

					Limits		Limits		Limits			
Index	Yr	Mean	n	Std dev	+/-1.96 SD		+/-2.575 SD		+/-3.294 SD		Min	Max
50	10	1.05	8	0.6024	-0.1307	2.2307	-0.5011	2.6011	-0.9342	3.0342	0.4	1.8
51	11	1.15	8	0.487	0.1955	2.1045	-0.104	2.404	-0.4541	2.7541	0.4	1.8
52	12	1.2	8	0.4781	0.2629	2.1371	-0.0311	2.4311	-0.3748	2.7748	0.6	2
53	13	1.3	8	0.5345	0.2523	2.3477	-0.0764	2.6764	-0.4607	3.0607	0.6	2.2
54	14	1.3	8	0.659	0.0084	2.5916	-0.3969	2.9969	-0.8708	3.4708	0.6	2.6
55	15	1.175	8	0.7285	-0.2529	2.6029	-0.7009	3.0509	-1.2247	3.5747	0.4	2.4
56	16	1	8	0.8	-0.568	2.568	-1.06	3.06	-1.6352	3.6352	0.2	2.4
57	17	1.125	8	0.8345	-0.5107	2.7607	-1.0239	3.2739	-1.6239	3.8739	0	2.4
58	18	1.025	8	0.8172	-0.5768	2.6268	-1.0794	3.1294	-1.6669	3.7169	0	2.6
59	19	1.075	8	0.7246	-0.3452	2.4952	-0.7908	2.9408	-1.3117	3.4617	0	2.4
60	20	1.175	8	0.6798	-0.1574	2.5074	-0.5755	2.9255	-1.0643	3.4143	0.2	2
61	21	1.25	8	0.6024	0.0693	2.4307	-0.3011	2.8011	-0.7342	3.2342	0.4	2
62	22	1.075	8	0.6042	-0.1091	2.2591	-0.4807	2.6307	-0.9151	3.0651	0.4	2.4
63	23	1.225	8	0.6798	-0.1074	2.5574	-0.5255	2.9755	-1.0143	3.4643	0.6	2.4
64	24	1.275	8	0.6671	-0.0325	2.5825	-0.4427	2.9927	-0.9224	3.4724	0.6	2.4
65	5	1.175	8	0.6882	-0.1738	2.5238	-0.597	2.947	-1.0918	3.4418	0.4	2.6
66	6	1.1	8	0.6503	-0.1745	2.3745	-0.5745	2.7745	-1.042	3.242	0.2	2.2
67	7	1.275	8	0.7166	-0.1296	2.6796	-0.5703	3.1203	-1.0856	3.6356	0.2	2.4
68	8	1.175	8	0.7363	-0.2682	2.6182	-0.721	3.071	-1.2504	3.6004	0	2
69	9	1.1	8	0.6414	-0.1572	2.3572	-0.5517	2.7517	-1.0129	3.2129	0	1.8
70	10	1.225	8	0.744	-0.2333	2.6833	-0.6909	3.1409	-1.2258	3.6758	0	2.4
71	11	1.3	8	0.6676	-0.0085	2.6085	-0.4191	3.0191	-0.8991	3.4991	0.2	2
72	12	1.2	8	0.8	-0.368	2.768	-0.86	3.26	-1.4352	3.8352	0.2	2.4
73	13	1.175	8	0.9161	-0.6206	2.9706	-1.184	3.534	-1.8427	4.1927	0.2	2.6
74	14	1.125	8	0.913	-0.6645	2.9145	-1.226	3.476	-1.8824	4.1324	0.2	2.6
75	15	1	8	0.7091	-0.3899	2.3899	-0.826	2.826	-1.3359	3.3359	0	1.8
76	16	0.925	8	0.8548	-0.7504	2.6004	-1.2762	3.1262	-1.8908	3.7408	0	2.4
77	17	0.85	8	0.6655	-0.4543	2.1543	-0.8636	2.5636	-1.3421	3.0421	0	2
78	18	0.95	8	0.6655	-0.3543	2.2543	-0.7636	2.6636	-1.2421	3.1421	0	2
79	19	0.975	8	0.7517	-0.4983	2.4483	-0.9605	2.9105	-1.501	3.451	0	2
80	20	0.95	8	0.6568	-0.3374	2.2374	-0.7413	2.6413	-1.2136	3.1136	0.2	2
81	21	1.05	8	0.6024	-0.1307	2.2307	-0.5011	2.6011	-0.9342	3.0342	0.4	1.8
82	22	1.175	8	0.7363	-0.2682	2.6182	-0.721	3.071	-1.2504	3.6004	0.4	2.4
83	23	1.025	8	0.7046	-0.356	2.406	-0.7893	2.8393	-1.2959	3.3459	0.4	2.4
84	24	1.075	8	0.6756	-0.2492	2.3992	-0.6647	2.8147	-1.1504	3.3004	0.4	2.4
85	25	1.3	8	0.9134	-0.4902	3.0902	-1.052	3.652	-1.7087	4.3087	0.4	2.6
86	26	1.125	8	0.7402	-0.3257	2.5757	-0.7809	3.0309	-1.3131	3.5631	0.4	2.2
87	27	1.025	8	0.7363	-0.4182	2.4682	-0.871	2.921	-1.4004	3.4504	0	2
88	28	1.125	8	0.7479	-0.3408	2.5908	-0.8007	3.0507	-1.3384	3.5884	0.2	2.2
89	29	1.1	8	0.8552	-0.5763	2.7763	-1.1022	3.3022	-1.7171	3.9171	0.2	2.6
90	30	0.8	8	0.5657	-0.3087	1.9087	-0.6566	2.2566	-1.0634	2.6634	0.2	1.8
91	31	0.95	8	0.7838	-0.5862	2.4862	-1.0682	2.9682	-1.6317	3.5317	0.2	2.4
92	32	0.875	8	0.7005	-0.498	2.248	-0.9288	2.6788	-1.4325	3.1825	0	2
93	33	0.875	8	0.6135	-0.3275	2.0775	-0.7049	2.4549	-1.146	2.896	0	1.8
94	34	0.85	8	0.5732	-0.2735	1.9735	-0.626	2.326	-1.0382	2.7382	0	1.6
95	35	1.025	8	0.6882	-0.3238	2.3738	-0.747	2.797	-1.2418	3.2918	0.2	2
96	36	0.925	8	0.5946	-0.2405	2.0905	-0.6061	2.4561	-1.0337	2.8837	0.2	1.8
97	37	1.1	8	0.8751	-0.6151	2.8151	-1.1533	3.3533	-1.7824	3.9824	0.2	2.4
98	38	1.075	8	0.894	-0.6773	2.8273	-1.2271	3.3771	-1.8699	4.0199	0.2	2.4

Appendix D2. Fire-tree establishment MDSEA bootstrapped confidence intervals for 5-yr mean tree establishment.

Index	Yr	Mean	n	Std dev	Limits +/-1.96 SD		Limits +/-2.575 SD		Limits +/-3.294 SD		Min	Max
0	0	0.6267	1000	0.2684	0.1005	1.1528	-0.0646	1.3179	-0.2576	1.5109	0.1	1.5
1	1	0.6296	1000	0.2669	0.1065	1.1527	-0.0576	1.3168	-0.2495	1.5087	0.1	1.5
2	2	0.6342	1000	0.2677	0.1096	1.1589	-0.055	1.3235	-0.2474	1.5159	0.1	1.4
3	3	0.6374	1000	0.2652	0.1176	1.1572	-0.0455	1.3203	-0.2362	1.511	0.1	1.4
4	4	0.6434	1000	0.2658	0.1224	1.1644	-0.0411	1.3278	-0.2322	1.519	0.1	1.3
5	5	0.6435	1000	0.2612	0.1315	1.1555	-0.0292	1.3162	-0.217	1.504	0.1	1.3
6	6	0.6465	1000	0.2635	0.13	1.1631	-0.0321	1.3252	-0.2216	1.5147	0.1	1.4
7	7	0.6469	1000	0.2672	0.1231	1.1706	-0.0412	1.3349	-0.2333	1.527	0.1	1.3
8	8	0.6513	1000	0.27	0.122	1.1806	-0.044	1.3467	-0.2382	1.5408	0.1	1.4
9	9	0.652	1000	0.2649	0.1328	1.1712	-0.0301	1.3341	-0.2206	1.5246	0.2	1.5
10	10	0.6523	1000	0.2692	0.1246	1.18	-0.041	1.3456	-0.2345	1.5392	0.2	1.4
11	11	0.6552	1000	0.2642	0.1373	1.1732	-0.0252	1.3357	-0.2152	1.5257	0.2	1.5
12	12	0.6587	1000	0.2619	0.1455	1.172	-0.0156	1.333	-0.2038	1.5213	0.2	1.4
13	13	0.6602	1000	0.2617	0.1472	1.1732	-0.0138	1.3341	-0.2019	1.5223	0.2	1.4
14	14	0.662	1000	0.2628	0.147	1.177	-0.0146	1.3386	-0.2035	1.5275	0.1	1.4
15	15	0.6677	1000	0.2618	0.1545	1.1809	-0.0065	1.3419	-0.1947	1.5301	0.2	1.5
16	16	0.672	1000	0.2611	0.1602	1.1838	-0.0004	1.3443	-0.1881	1.5321	0.1	1.4
17	17	0.6753	1000	0.2633	0.1594	1.1913	-0.0025	1.3532	-0.1918	1.5425	0.2	1.5
18	18	0.6799	1000	0.2655	0.1595	1.2003	-0.0038	1.3636	-0.1947	1.5545	0.2	1.4
19	19	0.681	1000	0.2651	0.1614	1.2006	-0.0017	1.3637	-0.1923	1.5543	0.2	1.6
20	20	0.6853	1000	0.2648	0.1663	1.2042	0.0035	1.367	-0.1869	1.5574	0.2	1.5
21	21	0.6905	1000	0.2704	0.1605	1.2206	-0.0058	1.3869	-0.2003	1.5813	0.2	1.5
22	22	0.6898	1000	0.2679	0.1647	1.2149	-0.0001	1.3797	-0.1927	1.5723	0.2	1.4
23	23	0.6897	1000	0.2648	0.1707	1.2086	0.0079	1.3714	-0.1825	1.5618	0.2	1.5
24	24	0.6947	1000	0.2658	0.1738	1.2157	0.0103	1.3792	-0.1808	1.5703	0.2	1.5
25	5	0.7094	1000	0.2591	0.2015	1.2172	0.0421	1.3766	-0.1442	1.5629	0.2	1.5
26	6	0.7114	1000	0.2587	0.2044	1.2185	0.0453	1.3776	-0.1407	1.5636	0.1	1.5
27	7	0.7146	1000	0.2581	0.2087	1.2206	0.0499	1.3793	-0.1357	1.5649	0.1	1.4
28	8	0.7182	1000	0.2617	0.2052	1.2311	0.0443	1.392	-0.1439	1.5802	0.2	1.5
29	9	0.7204	1000	0.2631	0.2046	1.2361	0.0428	1.398	-0.1464	1.5872	0.2	1.5
30	10	0.718	1000	0.2619	0.2046	1.2314	0.0435	1.3925	-0.1448	1.5808	0.2	1.4
31	11	0.7236	1000	0.2636	0.2069	1.2402	0.0448	1.4023	-0.1447	1.5919	0.2	1.5
32	12	0.7272	1000	0.2663	0.2052	1.2492	0.0414	1.413	-0.15	1.6044	0.2	1.4
33	13	0.7269	1000	0.2615	0.2143	1.2394	0.0535	1.4002	-0.1345	1.5882	0.2	1.5
34	14	0.7262	1000	0.2549	0.2265	1.2259	0.0697	1.3827	-0.1136	1.566	0.2	1.4
35	15	0.7303	1000	0.2574	0.2258	1.2347	0.0675	1.393	-0.1176	1.5781	0.2	1.4
36	16	0.7287	1000	0.2582	0.2226	1.2348	0.0638	1.3936	-0.1219	1.5792	0.2	1.5
37	17	0.73	1000	0.2579	0.2244	1.2355	0.0658	1.3941	-0.1196	1.5795	0.2	1.5
38	18	0.734	1000	0.2582	0.228	1.24	0.0692	1.3988	-0.1165	1.5845	0.2	1.5
39	19	0.7391	1000	0.2613	0.2269	1.2512	0.0662	1.4119	-0.1216	1.5998	0.2	1.5
40	20	0.7403	1000	0.2619	0.2269	1.2537	0.0658	1.4148	-0.1225	1.6032	0.2	1.5
41	21	0.7439	1000	0.2632	0.228	1.2598	0.0661	1.4217	-0.1231	1.611	0.2	1.5
42	22	0.7463	1000	0.2632	0.2304	1.2622	0.0685	1.4241	-0.1208	1.6134	0.1	1.5
43	23	0.7475	1000	0.2625	0.233	1.262	0.0716	1.4235	-0.1172	1.6122	0.1	1.5
44	24	0.7451	1000	0.2593	0.2368	1.2534	0.0773	1.4128	-0.1091	1.5993	0.2	1.5
45	5	0.7329	1000	0.2567	0.2297	1.2361	0.0718	1.394	-0.1128	1.5786	0.2	1.6
46	6	0.7361	1000	0.2636	0.2194	1.2527	0.0573	1.4148	-0.1322	1.6043	0.2	1.5
47	7	0.7367	1000	0.2632	0.2209	1.2525	0.059	1.4144	-0.1302	1.6036	0.2	1.6
48	8	0.7404	1000	0.263	0.225	1.2559	0.0632	1.4177	-0.1259	1.6067	0.2	1.5
49	9	0.7402	1000	0.258	0.2344	1.2459	0.0758	1.4046	-0.1098	1.5901	0.2	1.5

Appendix D2. *Continued.*

Index	Yr	Mean	n	Std dev	Limits +/-1.96 SD		Limits +/-2.575 SD		Limits +/-3.294 SD		Min	Max
50	10	0.7469	1000	0.2619	0.2335	1.2603	0.0724	1.4213	-0.1159	1.6097	0.2	1.5
51	11	0.7464	1000	0.2616	0.2337	1.2592	0.0728	1.4201	-0.1153	1.6082	0.3	1.5
52	12	0.748	1000	0.2579	0.2425	1.2536	0.0839	1.4122	-0.1016	1.5976	0.2	1.5
53	13	0.7489	1000	0.2566	0.2461	1.2518	0.0883	1.4096	-0.0962	1.594	0.2	1.5
54	14	0.7544	1000	0.2559	0.2527	1.256	0.0954	1.4134	-0.0887	1.5974	0.2	1.5
55	15	0.7525	1000	0.2533	0.256	1.2489	0.1002	1.4047	-0.0819	1.5868	0.2	1.5
56	16	0.7588	1000	0.2543	0.2604	1.2571	0.104	1.4135	-0.0788	1.5963	0.2	1.6
57	17	0.7615	1000	0.2565	0.2588	1.2642	0.101	1.4219	-0.0834	1.6063	0.2	1.5
58	18	0.7656	1000	0.2575	0.2608	1.2704	0.1024	1.4288	-0.0828	1.6139	0.2	1.5
59	19	0.7635	1000	0.2587	0.2564	1.2706	0.0973	1.4297	-0.0887	1.6157	0.3	1.7
60	20	0.7668	1000	0.2614	0.2544	1.2791	0.0937	1.4398	-0.0943	1.6278	0.2	1.5
61	21	0.766	1000	0.2588	0.2588	1.2733	0.0996	1.4325	-0.0865	1.6185	0.3	1.5
62	22	0.7668	1000	0.2569	0.2633	1.2703	0.1053	1.4283	-0.0794	1.613	0.2	1.5
63	23	0.7647	1000	0.2562	0.2626	1.2668	0.105	1.4244	-0.0792	1.6086	0.2	1.5
64	24	0.7653	1000	0.2548	0.266	1.2646	0.1093	1.4213	-0.0739	1.6045	0.2	1.6
65	5	0.7635	1000	0.2592	0.2554	1.2716	0.096	1.431	-0.0904	1.6174	0.2	1.5
66	6	0.7675	1000	0.2601	0.2577	1.2773	0.0978	1.4373	-0.0892	1.6243	0.2	1.5
67	7	0.7734	1000	0.2558	0.272	1.2747	0.1147	1.432	-0.0692	1.6159	0.2	1.4
68	8	0.7746	1000	0.2601	0.2649	1.2844	0.1049	1.4443	-0.082	1.6313	0.2	1.6
69	9	0.7781	1000	0.2609	0.2668	1.2894	0.1064	1.4499	-0.0812	1.6375	0.2	1.5
70	10	0.7758	1000	0.2633	0.2597	1.292	0.0978	1.4539	-0.0916	1.6432	0.2	1.6
71	11	0.777	1000	0.2586	0.2701	1.2839	0.111	1.4429	-0.0749	1.6289	0.3	1.5
72	12	0.7748	1000	0.2626	0.26	1.2895	0.0985	1.451	-0.0903	1.6398	0.2	1.5
73	13	0.7752	1000	0.2645	0.2568	1.2937	0.0942	1.4563	-0.096	1.6465	0.2	1.5
74	14	0.7772	1000	0.2637	0.2604	1.294	0.0982	1.4562	-0.0914	1.6458	0.2	1.6
75	15	0.7795	1000	0.2603	0.2692	1.2897	0.1091	1.4498	-0.0781	1.637	0.2	1.5
76	16	0.7807	1000	0.2579	0.2753	1.2861	0.1167	1.4447	-0.0687	1.6301	0.3	1.5
77	17	0.783	1000	0.2624	0.2686	1.2974	0.1072	1.4588	-0.0815	1.6475	0.2	1.7
78	18	0.7836	1000	0.259	0.2759	1.2913	0.1166	1.4507	-0.0697	1.6369	0.2	1.6
79	19	0.7841	1000	0.2577	0.2791	1.2892	0.1206	1.4477	-0.0647	1.633	0.3	1.5
80	20	0.7864	1000	0.2561	0.2845	1.2884	0.1269	1.4459	-0.0572	1.6301	0.2	1.6
81	21	0.7861	1000	0.2586	0.2792	1.293	0.1201	1.4521	-0.0658	1.638	0.2	1.5
82	22	0.7836	1000	0.2586	0.2767	1.2906	0.1176	1.4496	-0.0683	1.6356	0.2	1.5
83	23	0.7865	1000	0.2561	0.2846	1.2885	0.1271	1.446	-0.0571	1.6301	0.2	1.5
84	24	0.7884	1000	0.2512	0.2962	1.2807	0.1417	1.4351	-0.0389	1.6157	0.2	1.4
85	25	0.7886	1000	0.2488	0.301	1.2762	0.148	1.4292	-0.0309	1.6081	0.2	1.5
86	26	0.7915	1000	0.2487	0.3041	1.2789	0.1512	1.4319	-0.0276	1.6107	0.2	1.5
87	27	0.794	1000	0.249	0.3059	1.2821	0.1528	1.4353	-0.0263	1.6143	0.2	1.4
88	28	0.7908	1000	0.249	0.3027	1.2789	0.1496	1.432	-0.0295	1.6111	0.2	1.5
89	29	0.7882	1000	0.2477	0.3027	1.2736	0.1504	1.4259	-0.0276	1.604	0.3	1.5
90	30	0.7864	1000	0.2478	0.3006	1.2721	0.1482	1.4245	-0.0299	1.6026	0.2	1.5
91	31	0.7833	1000	0.247	0.2991	1.2675	0.1472	1.4195	-0.0304	1.5971	0.2	1.6
92	32	0.7828	1000	0.2473	0.2981	1.2675	0.1461	1.4196	-0.0317	1.5974	0.2	1.5
93	33	0.7799	1000	0.2453	0.2991	1.2607	0.1482	1.4115	-0.0282	1.5879	0.2	1.5
94	34	0.7816	1000	0.2502	0.2913	1.272	0.1375	1.4258	-0.0424	1.6057	0.2	1.5
95	35	0.78	1000	0.2514	0.2873	1.2727	0.1327	1.4273	-0.0481	1.608	0.2	1.4
96	36	0.7797	1000	0.2541	0.2817	1.2776	0.1255	1.4339	-0.0572	1.6165	0.2	1.6
97	37	0.777	1000	0.2493	0.2885	1.2656	0.1352	1.4189	-0.044	1.5981	0.2	1.5
98	38	0.7811	1000	0.2512	0.2888	1.2734	0.1343	1.4278	-0.0462	1.6084	0.2	1.5

Vitae

Evan Larson was born in Princeton, Minnesota on September 5, 1979, to Eric and Shelley Larson. He grew up running the woods of his parent's land and the neighboring 32,000-hectare Rum River State Forest 22 kilometers outside of the town of Milaca, Minnesota, as well as spending a good deal of time camping in the north woods and the Boundary Waters Canoe Area. Evan traveled with his family extensively, and saw much of the United States by the time he graduated from Milaca High School in 1998. Following high school, he enrolled at Willamette University in Salem, Oregon, where he earned a Bachelor of Arts in Environmental and Earth Sciences. During his years as an undergraduate, Evan spent a semester on the island of South Caicos in the British West Indies conducting research with the School for Field Studies, was awarded a Morris K. Udall scholarship for Excellence in Environmental Policy, and was introduced to the science of dendrochronology as a participant in Willamette University's Science Collaborative Research Program.

Under the mentorship of Dr. Karen Arabas and Dr. Keith Hadley, Evan spent the summer of 2001 and his senior year reconstructing the fire history of the old-growth ponderosa pine forests on the kipuka of the Lava Cast Forest in central Oregon. He presented his findings at several professional meetings, including the 2002 Association of American Geographers meeting in Los Angeles, California, where he first met Dr. Henri Grissino-Mayer. Following his graduation from Willamette University, Evan worked as a research technician with Dr. Arabas for the summer before returning to Minnesota to spend a year as a substitute teacher for several public school districts and eventually the Nay Ah Shing Tribal School System on the reservation of the Mille Lacs Band of

Ojibwe. After a year of work, Evan enrolled as a Master's Student in the Department of Geography at the University of Tennessee, Knoxville, to continue his studies under the guidance of Dr. Grissino-Mayer.

During the two years of his Master's Program, Evan was introduced to several new lines of dendrochronological and biogeographical research, while developing his comprehension of the natural world and the political realm that revolves around it. He is a member of the Association of American Geographers and the Biogeography Specialty Group, and was awarded the 2003 Biogeography Specialty Group Graduate Research Grant. He is a member of the Whitebark Pine Ecosystem Foundation, participated in the 2004 Monitoring Whitebark Pine for Blister Rust: A Methods Workshop, and presented his research at the 2004 Whitebark Pine Ecosystem Foundation Annual Meeting in Waterton National Park, Alberta, Canada. Evan is also a member of the Tree-Ring Society and the American Geophysical Union.

Evan is continuing his research on whitebark pine as a Ph.D. Fellow in the Department of Geography at the University of Minnesota, with additional funding from an EPA Science To Achieve Results (STAR) Graduate Fellowship. Evan plans to teach and conduct research at the collegiate level.