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Separating the Effects of Wildfires from Climate in Growth of Ponderosa Pine (Pinus ponderosa Douglas ex. C. Lawson), Central Idaho, U.S.A.

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To the Graduate Council:

I am submitting herewith a thesis written by Jessica Dominique Slayton entitled "Separating the Effects of Wildfires from Climate in Growth of Ponderosa Pine (Pinus ponderosa Douglas ex. C. Lawson), Central Idaho, U.S.A.." 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:

Sally P. Horn, Carol P. Harden

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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

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

Jessica Dominique Slayton
December 2010

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Abstract

Scientists use climate proxies, such as tree rings, to extend the climate record back in time, adding to the growing body of knowledge of past climate change. Tree rings provide a high-resolution proxy of climate. Many of the reconstructed climate records for the western U.S. use ponderosa pine (*Pinus ponderosa* Douglas ex. C. Lawson), a fire-adapted species that grows in areas prone to frequent fires. Such a disturbance as fire can introduce noise to climate reconstructions by causing growth releases or suppression following a fire event. My objective was to determine whether fire damage causes a quantifiable change in growth patterns of affected trees and whether the affected trees experience the changes in the same way.

Increment cores and cross-sections were collected from living and dead ponderosa pine trees in Payette National Forest, central Idaho, U.S.A. One chronology was developed from a stand of ponderosa pine showing no evidence of frequent fire while two chronologies, one from cores collected mostly from trees without visible fire damage and one from cross-sections of fire-scarred trees, snags, and stumps, were developed from a separate cluster of three subsites affected by frequent fire.

The mean fire-free interval for all fire subsites was 7.38 years. The mid-1600s to mid-1900s were characterized by nearly continuous fire activity at the fire subsites. The results from superposed epoch analysis (SEA) showed that tree growth is significantly lower than average the year of a fire event. The fire site chronologies showed slightly suppressed growth for 3 years after a fire. Significantly ($p < 0.05$) below average growth occurred after large fires in the fire site cross-section chronology. The difference chronologies indicated that fire does not cause a systematic change in tree growth and any added signal is comparable to other noise in the chronologies. Analyses using the computer program OUTBREAK showed that some fire years appeared to be followed by growth suppressions while others are not, regardless of fire size. Analyses of the chronologies and the fire history of the subsites indicated that no statistically significant systematic signal is introduced into the tree-growth patterns by fire events.

Table of Contents

Chapter 1
Why disentangle wildfire and climate?

Chapter 2
Ecology of Ponderosa Pine (*Pinus ponderosa* Douglas ex. P. Lawson & C. Lawson)

Chapter 3
Study Sites

Chapter 4
Methods

Chapter 5
Results

Chapter 6
Discussion, Conclusions, and Future Research

Appendices

List of Tables

List of Figures

List of Figures - Continued

Chapter 1

Why Disentangle Wildfire and Climate?

1.1 Introduction

Climate change is of increasing concern to scientists, politicians, and policy-makers because of the serious ramifications involved. Future climate variability will affect humans in varying degrees and at various scales as populations become more vulnerable to climate change (e.g., Bohle *et al.* 1994, Messerli *et al.* 2000, Parry *et al.* 2001, Patz *et al.* 2005). Important insights to advance understanding the possibilities for future climate change can be gained through the study of past climate change. Climate proxies, such as tree rings, corals, ice cores, and lake sediments, are used to extend historical climate records back in time, providing a more comprehensive overview of trends in past climate (e.g., Cook 1995, Gray *et al.* 2004). In many ways, the past may be the key to the future.

Tree rings have long been shown to be high-resolution (subannual to annual) proxies of past climate. The field of dendroclimatology relies on the premise that the width of each annual ring is governed by limiting factors in the environment (Fritts 2001). To reconstruct climate history, the influence of climate on radial tree growth must first be determined statistically and separated from any other confounding factor, such as competition or local disturbance (e.g., windthrow or wildfires). Tree growth can often be related to one dominant environmental variable through principal components analysis or correlations with climatic factors (e.g., Perkins and Swetnam 1996, Fritts 1999).

Paramount to finding trees that are sensitive to changes in climate is selecting a site where the climate signal of interest would be enhanced over other potential limiting factors to tree growth (Fritts 2001).

One example of a climate factor that has been reconstructed on a large temporal and spatial scale is the occurrence of drought in the western U.S. Water resources are essential for human and wildlife populations in the arid west, especially because availability of water has fluctuated in the past and will continue to do so (Mote *et al*. 2003). To better understand these past fluctuations, ponderosa pine (*Pinus ponderosa* Douglas ex. P. Lawson & C. Lawson) trees have been used in the creation of a network of tree-ring chronologies throughout the western U.S. (Stockton and Meko 1975, Meko 1982, Earle 1993, Grissino-Mayer 1996, Grissino-Mayer *et al*. 1997, Woodhouse and Brown 2001, Benson *et al*. 2002, Pohl *et al*. 2002). The tree-ring network was developed to reconstruct regional rainfall and drought conditions over many centuries. Ponderosa pine is a popular species for these reconstructions because it is long-lived, broadly distributed (Figure 1.1), and climatically sensitive (Oliver and Ryker 1990).

In addition to being excellent recorders of climate, ponderosa pines are excellent recorders of past wildfires. Disturbance events (such as fire) may also affect tree growth by causing changes in growth rates because of release from competing vegetation, release of nutrients to the soil, cambial damage, damage to roots, or fire-induced defoliation (Fritts 2001). Direct evidence of wildfire is preserved within the tree rings as fire scars and trauma rings. Growth suppression and growth release can be indirect indicators of fire occurrence or other disturbance (Brown and Swetnam 1994, Fritts 2001). This

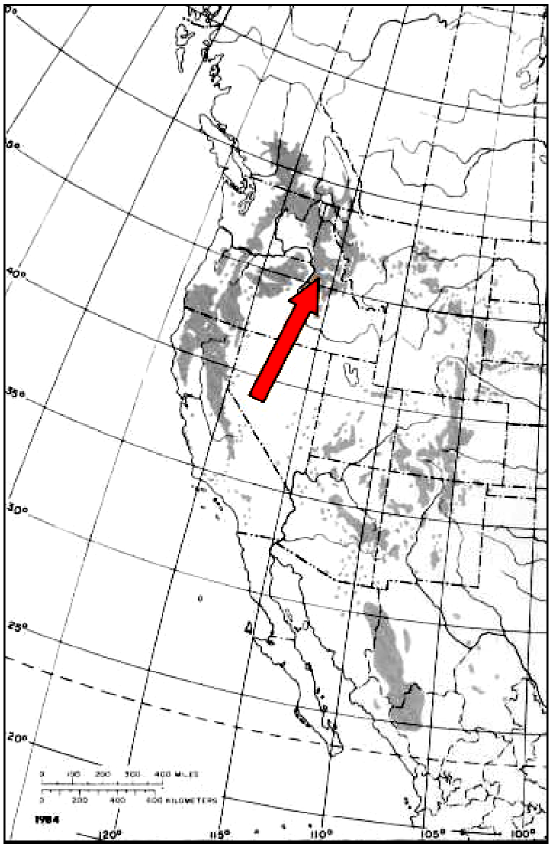


Figure 1.1 The native range of ponderosa pine (adapted from Oliver and Ryker 1990). The study area is indicated by an arrow.

indirect effect of fire on ring width could introduce noise into a climate reconstruction that uses fire-affected trees. Trees selected for climate reconstruction should not contain visible evidence of past fire on the tree trunks, but low-severity wildfires could cause changes in growth rates within the tree without leaving external evidence.

1.2 Science of Dendrochronology

Dendrochronology is the science that uses tree rings dated to their exact year of formation to analyze temporal and spatial patterns of processes in the physical and cultural sciences (Kaennel and Schweingruber 1995). It is founded on seven principles: uniformitarianism, limiting factors, ecological amplitude, site selection, sensitivity, crossdating, replication (Fritts 2001). While all seven principles are fundamental to dendrochronology, my thesis research could affect conventional interpretations related to the principles of limiting factors and site selection.

The principle of limiting factors, borrowed from the biological sciences, is concerned with which environmental factors are limiting the growth of trees (Fritts 2001). The variation in width of annual growth rings is a record of the environmental factor or factors that most limit tree growth. Dendrochronological reconstruction of environmental factors can become complicated if the most limiting factor changes throughout a tree’s life. For example, if fire occurs in a stand of trees for which growth is normally limited by soil moisture, any damaged trees may not have soil moisture as their most limiting factor in the years immediately following the fire event. They are limited in their photosynthetic capacity by the physiological damage caused by the fire. After recovery from the damage, tree growth will once again be limited by climate.

Dendrochronologists select trees whose growth is most limited by the factor they are most interested in studying. Such targeting is known as the principle of site selection. Sampling from stressed trees maximizes the signal recorded in the tree-rings. A researcher seeking trees for a climate reconstruction may unknowingly sample from trees whose growth is also affected by fire, but which do not display evidence of fire injury. Disturbances such as fire can diminish the strength of the sought-after climate signal.

Before any proper dendrochronological analysis can be performed on any tree-ring data, all rings must be dated to the year of formation. Simple ring counting results in dating errors because of the occurrence of locally absent rings and false rings in addition to the possibility of miscounting. To combat such problems, dendrochronologists have available the principle and technique of crossdating. Crossdating is achieved by matching patterns of wide and narrow rings found on the radii within one tree and matching that pattern with other trees in that stand or region (Douglass 1941, Stokes and Smiley 1996). The pattern is common to trees within an area because of the common climate experienced by those trees. Wide rings represent years with favorable growing conditions (i.e., wet or cool) while narrow rings represent years with unfavorable growing conditions (i.e., dry or hot) (Fritts 2001). Without crossdating, there is no assurance of the annual precision which is required for studying high-resolution climate and fire occurrence.

1.2.1 Dendropyrochronology

The principles and techniques of dendrochronology are particularly useful for studying characteristics of the historic fire regime in an area. The western United States has received most of the attention on fire history. Throughout the West, human-induced effects, such as intensive grazing and fire suppression, have altered historic fire regimes and disrupted the relationship between fire and climate.

Grassy areas in the American West have been invaded by woody vegetation since the arrival of Euro-American settlers. In southwest Idaho, Burkhardt and Tisdale (1976) found that the expansion of Western juniper (*Juniperus occidentalis* Hook. var. occidentalis) into sagebrush-grass dominated areas was primarily the result of the precipitous decline in fire frequency since Euro-American settlement. Besides fire suppression, grazing and climate change have also contributed to the decline in fire through a slower accumulation of fuels.

Baisan and Swetnam (1990) reconstructed fire history for the Rincon Mountains of southern Arizona from modern records, historical accounts, and through analysis of fire scars collected from living trees and remnant wood. They determined fire intervals, seasonality, and size, and compared their record with a reconstruction of regional drought. The stands consist of mixed-conifer or open pine forest. Lightning-ignited fires occurred throughout the summer months until the heavy rains of the monsoon moistened fuels so that they were no longer readily ignitable. Some large fires occurred during regional droughts, but many occurred during years of average moisture conditions that had been preceded by two wet years, spurring fuel production. The authors found that after Euro-American settlement large fires did not occur because of removal of the Apache, heavy grazing, and eventually, active fire suppression.

1.2.2 Dendroclimatology

This section provides two examples of how tree rings have been used in reconstructions of climate. Dendrochronological reconstructions of climate rely on the principles of dendrochronology. Any possible fire damage-caused alteration of the climate signal as contained in tree rings could add uncertainty to climate reconstructions.

Perkins and Swetnam (1996) evaluated whitebark pine (*Pinus albicaulis* Engelm.) as a candidate for dendrochronological studies. Relatively few chronologies of whitebark pine exist and only a few tree-ring chronologies exist from the study area in central Idaho. The authors compared the four master chronologies from their four study sites with other tree-ring chronologies in the area and found no crossdating among the sites except with a whitebark pine chronology from Oregon. The four chronologies themselves were moderately to strongly correlated with each other. Divisional monthly mean temperature and total monthly precipitation data for a 14 month period (July–August) and three years of prior growth were used to analyze the climate-tree growth relationship. Simple correlation analysis and response function analysis revealed similar responses in all the sites, but only two chronologies showed significant correlations. For these two sites, 54% and 56% of the variance was explained by a combination of the climate variables and prior growth. Year 2 of prior growth was significant at both sites but did not contribute as much as prior growth does in other chronologies. Winter and spring precipitation were positively correlated with tree growth while temperatures during May and July were negatively correlated with tree growth. The trees preferred plenty of snowpack and cool early growing season temperatures for optimum growth.

Gray *et al.* (2004) reconstructed the Atlantic Multidecadal Oscillation (AMO) with tree rings to extend the record of low-frequency sea surface temperature (SST) variability back in time past the instrumental record. The AMO is a pattern of variability in North Atlantic SSTs with a multidecadal 65–80 year cycle. The instrumental record contains only two full cycles of the AMO, so the extension of the record greatly adds to current knowledge. Tree-ring chronologies obtained from the International Tree-Ring Data Bank (ITRDB) included records from areas most affected by variability in Atlantic SSTs.

To preserve the low-frequency signal, raw measurements were detrended conservatively. Records with a high correlation with North Atlantic SSTs then went through principal components analysis and multiple regression. The regression model was calibrated with the first half of the instrumental record and then checked against the second half. The model had a good correlation with the instrumental data (Gray *et al.* 2004). Regime shifts of the AMO were identified through intervention analysis, while changes in the strength and duration of modes throughout the reconstruction were examined through wavelet analysis.

Gray *et al.* (2004) were able to extend the record to A.D. 1567 and captured 13 climate regimes longer than a decade. Between modes, the North Atlantic SSTs usually went into a neutral phase for 5–10 years before entering a warm or cold phase. For most of the 1700s, the AMO index remained near the series mean. That is the longest period of neutrality in the record. Throughout the rest of the record, AMO behaved in a multidecadal time scale with little decadal or bidecadal signal.

The authors were able to create a proxy for the AMO signal through the use of tree rings (Gray *et al.* 2004). Strong, regular occurrences of warm and cool phases of the AMO occur throughout the record spanning the last four and a half centuries. Because the AMO consistently occurs at a longer timescale than the North Atlantic Oscillation and the Arctic Oscillation, it is a separate but intimately related climate signal. AMO affects a wide geographic area and has shown up in dendroclimatic reconstructions in western North America.

1.2.3 Fire-climate relationships

Climate plays a role in forcing fire activity. Surface fires often tend to occur during drought years that have been preceded by wetter years, allowing for a build-up of fine fuels. Several studies have investigated this relationship.

Swetnam (1993) developed fire histories for five giant sequoia (*Sequoiadendron giganteum* (Lindl.) J. Buchholz) groves in California. Each grove was spaced sufficiently far apart to make fire spread between them unlikely. The oldest fire scar dated to 1125 B.C., while most samples contained recorded fires by A.D. 500. Fire years were consistently recorded within trees and among trees within a stand. Additionally, the fire record matched the historic record of fire from the late 1800s to the present. This gave Swetnam (1993) a very long fire history to analyze for regional climate-fire relationships.

The period A.D. 500 to 800 was marked by lower fire frequency in all the sites. Fire frequency increased after this period, reaching a high point in the years 1000 to 1300. Fire frequency again decreased after 1300. In some of the sites, fire frequency increased again in the 1600s and 1700s before declining again. After the late 1800s, fire was less frequent than ever as grazing, less Native American activity, and fire suppression set in (Swetnam 1993).

Fires were recorded in the same years (or no fires recorded in the same years) in two or more of the sites more often than would be expected by chance. Because the sites are not likely to be recording one fire in a given year, Swetnam (1993) stated the fires are probably driven by regional climate.

Precipitation significantly affected the likelihood of fire on an annual basis. The drier a year was, the more sites recorded a fire. Temperature did not have a significant relationship with year-to-year fire occurrences. The relationships were reversed on longer (decade to century) time scales (Swetnam 1993). Increases in growing season temperature are associated with increases in fires. At this time scale, precipitation is not significantly related to fire. In the short term, fuel moisture is most important, but in the long term, fuel production is more important for fire regimes.

Swetnam (1993) found that the spatial pattern of fire was related to length of fire-free intervals. With a longer fire-free period, fires were exponentially larger in area. Fires were also more likely to occur in more of the sites when they did occur, as fire became less frequent. The opposite was true in times of higher fire frequency. Swetnam (1993) extended his findings to the current conditions of climate change and the creation of a more homogenous fuels landscape through fire suppression. Fires can be expected to be more spatially extensive, occur in many locations at the same time, and have a greater intensity.

Swetnam and Betancourt (1998) examined the complex relationship between climate variability and mesoscale disturbances and ecosystems in the American Southwest as a region. The authors’ reasons for choosing a larger, regional spatial scale and a decadal time scale for the study concern the population dynamics of the plants in this area, which occur over decadal time scales. Furthermore, climate in the area behaves on decadal scales as demonstrated by the instrumental record and tree-ring records, and few studies have focused on these scales. Regional climate trends are most readily obtained by observing an entire region. Isolation of trends is necessary before other factors can be attributed to causing changes in ecosystem responses.

Events of recruitment of new individuals and mortality events are often tied to extreme seasonal variations in climate. Young plants cannot tolerate dry soil during the growing season due to an unusually dry winter or a summer during which the monsoonal rains fail. If a drought occurs for one growing season or several, a gap in the population age structure occurs. The opposite occurs during more favorable wet conditions in which a large group will enter the population at that time, creating a cluster of individuals reflecting that year or group of years.

The examples of these plant demographic-climate relationships given by Swetnam and Betancourt (1998) were the 1950s drought in the Southwest and the post-1976 wet period. The 1950s drought was unrivaled in severity in the Southwest for the last few centuries. Plants died off in great numbers, unable to tolerate the stress. The plant deaths may have been caused by root mortality through drier, hotter soils. Strong El Nino-Southern Oscillation (ENSO) events occurred on both ends of the drought period. From 1976 to the present, the American Southwest has been experiencing relatively wet conditions. These conditions may be related to increasing tree growth observed in some Southwestern tree-ring records, in addition to the effects of global warming. Assessment of whether recruitment is occurring during this wet period is difficult because of a lack of information on mortality and many human-caused effects on the landscape. The authors did note a period of recruitment in the wet early 1600s after a severe drought.

Regional insect outbreaks were tied to climatic factors (Swetnam and Betancourt 1998). Growth of affected trees was compared to nearby non-host trees to develop a history of insect outbreaks. Insects that consume the leaves or buds of trees are favored by periods favorable to the host trees, not droughts. Insects feeding on the cambium rely on a breakdown of defenses during the stress of drought. Once an insect outbreak occurs, the fuel load is increased, affecting fire activity.

Fires occurring throughout a region in a particular year are caused by regional climate (Swetnam and Betancourt 1998). Extreme drought occurring in a region for one or more years is reflected by the recording of fires over the affected area. The authors used superposed epoch analysis (SEA) to compare the largest and smallest fire years and to find any lag effects. The largest fire years had extreme drought conditions while the smallest fire years were wet. In open ponderosa pine forests, the buildup of fine fuels during wet years was a precursor to large fire years. Swetnam and Betancourt (1998) found that climate and fire also interact based on the strength of the relationship. An extreme El Niño event in 1747 was followed by the largest fire year in the Southwest. The fire regimes of the late 1700s to early 1800s were less influenced by climate variability and fires were less frequent. Despite the recent wet conditions, annual area burned in the Southwest is increasing perhaps due to drier summers, increasing human ignitions, and fuel accumulation due to fire suppression.

Grissino-Mayer and Swetnam (2000) also investigated the longer-term associations of climate and fire in addition to the interannual relationship between the two. Their study area in El Malpais National Monument in northwestern New Mexico contained trees of sufficient age for long-term climate history and the area has experienced less human impact on fire regimes than many other places in the southwestern United States because of its challenging terrain.

Grissino-Mayer and Swetnam (2000) found significant changes in fire regimes in the late 1700s. The changes in fire regimes at that time were unlikely to have been related to humans because few were in the area and grazing was not intense. During most of the 1700s, climate was in a dry phase and fires occurred frequently. Climate shifted to a wet phase in the late 1700s and fire became less frequent but more spatially extensive. This new fire regime lasted through most of the 1800s until heavy grazing and then more effective fire suppression greatly reduced fire occurrence. The seasonality of fires also changed from mostly occurring in July in the 1700s to occurring in April, May, and June after the 1700s. Superposed epoch analysis showed a change in the way fires responded to precipitation (Grissino-Mayer and Swetnam 2000). Before the late 1700s climate shift, fires occurred in extreme drought years preceded by somewhat wet years. After the shift, fires occurred in slightly dry years preceded by extremely wet years.

Norman and Taylor (2003) explored relationships between fire regimes in northeastern California and tree-ring based reconstructions of the Pacific Decadal Oscillation (PDO) and El Nino-Southern Oscillation (ENSO) climate teleconnections. While the authors found little relationship between ENSO and fire in their study, fire appeared to be sensitive to the transitional periods of PDO. Climatic factors appeared most important to widespread fires during the most severe drought years. Less widespread fires showed no apparent relationship to climate. Norman and Taylor (2003) concluded that the factors responsible for the less widespread fires were related to individual site characteristics. Fuels and vegetation dynamics were a result of both climate-fire interaction and individual site properties that affect the fire regime.

Hessl *et al.* (2004) also found no clear relationship between regional fire and ENSO in ponderosa pine forests of central and eastern Washington. As in the findings of Grissino-Mayer and Swetnam (2000) in New Mexico, fire became less frequent in the late 1700s at the study sites in central and eastern Washington (Hessl *et al.* 2004). The authors found that most large fires occurred during the positive phase of the PDO. Regional fires occurred during dry years and did not seem to have a pattern of preconditioning. The relationship between drought and fire changed once grazing and fire suppression began to affect the fire regime. Since 1900, fire and climate have been out of phase in the region (Hessl *et al.* 2004).

1.3 Problem Statement

Fire can have a confounding effect fire on tree growth which can then introduce noise into a climate reconstruction. It is therefore important to separate the effects of climate and wildfire disturbance on tree growth because these two factors are often operating on similar time scales (Swetnam and Betancourt 1998, Norman and Taylor 2003), and previous research has not investigated the possibility of a “fire signature.” Because fire is such an important factor in ponderosa pine forests, it would be necessary to remove the signature of fire events from chronologies before they could be used for climate reconstruction if this signature does exist systematically. My research aims to identify whether a “fire signature” exists in pine trees that would normally be selected for climate reconstruction, and to characterize its properties if it does exist. The location of my study sites in central Idaho fills a gap in the network of tree-ring studies in the western United States.

1.4 Objectives

My thesis research characterizes the effect fire has on the climate signal as expressed in tree growth. My research objectives are to:

- Develop a control tree-ring chronology from a site that is not conducive to fire ignition and spread, contains little evidence of frequent fires, and is dominated by ponderosa pine trees.
- Develop tree-ring chronologies from trees within the fire history site.

- Develop a history of past fire in ponderosa pine stands in the French Creek and Fall Creek drainages in the Payette National Forest, central Idaho.
- Describe the historical fire regimes of those stands statistically including the frequency, severity, and seasonality of past fires.
- Describe the fire-climate relationships for the sites.
- Describe the effects wildfire events have on ponderosa pine growth.
- Describe the consequences of using chronologies developed from fire-affected sites in climate studies.

My research compares several subsites that regularly experienced fire with a control site that is not conducive to fire ignition and spread. All of these sites should have nearly identical climate signals. I hypothesize that fire activity would be a large factor in any differences between the tree-ring chronologies from the control site and from the cluster of sites collected for fire history.

Chapter 2

Ecology of Ponderosa Pine
(*Pinus ponderosa* Douglas ex. P. Lawson & C. Lawson)

2.1 Biogeography

Ponderosa pine, or western yellow pine, is the most widely distributed pine in North America today. Ponderosa pine is classified in the genus *Pinus* and subgenus *Pinus* (the hard pines). Within the subgenus *Pinus*, the species falls in the section Trifoliae, subsection Ponderosae (Gernandt *et al.* 2005). *Pinus ponderosa* has two recognized varieties, sometimes termed geographic “races” (Conkle and Critchfield 1988): *Pinus ponderosa* var. *ponderosa* (Pacific ponderosa pine) and var. *scopulorum* (Rocky Mountain ponderosa pine). Although currently recognized as a separate species (Peloquin 1984), the closely related Arizona pine (*P. arizonica*) is sometimes considered a variety of ponderosa pine (e.g., Read 1980).

The Latin name is derived from the word “*ponderosus*” meaning “heavy, weighty, significant” (Murphy 1994). In keeping with the meaning of its name, the mature ponderosa pine reaches heights of 25–50 m (70 m maximum) and 80–120 cm (260 cm maximum) in diameter (Oliver and Ryker 1990, Richardson and Rundel 1998). The bark of mature ponderosa pines consists of large gold-colored plates broken up by dark-colored furrows. Younger ponderosa pines lack the gold bark, instead being dark in color which explains why they are sometimes called “blackjacks” when young and “yellowbellies” once they reach maturity (Murphy 1994). These “yellowbellies” often achieve ages of 300–600 years (Oliver and Ryker 1990).

Ponderosa pines often have three needles per fascicle, or cluster of needles, but may have as few as two or as many as five needles in a bundle (Richardson and Rundel 1998). The needles are relatively long (17–25 cm) compared to other pines and remain on the tree for four to six years. Ponderosa pine is monoecious with the pineapple-shaped female cones reaching lengths of 5–15 cm at the conclusion of a 2 year maturation period (Richardson and Rundel 1998).

Although the ponderosa pine enjoys an extensive range today, little is known of its distribution prior to the late Holocene other than its presence in present-day Yellowstone National Park during the previous interglacial and in the Sierra Nevada mountains approximately 12,000 years BP (MacDonald *et al.* 1998). Ponderosa pines have likely attained their present distribution through shifts in latitude and/or elevation as climate has changed with glacial and interglacial periods, leaving behind "islands" of isolated populations of ponderosa pines. This geographic isolation has led to the different varieties. The Pacific ponderosa pine (var. *ponderosa*) occupies the northwestern portion of the species range from southern British Columbia south to California and as far east as eastern Montana (Oliver and Ryker 1990). The Rocky Mountain ponderosa pine (var. *scopulorum*) has its northern limits in north central Montana and then follows the Rocky Mountains discontinuously southward to northern Mexico (Oliver and Ryker 1990). A gap occurs in southwestern Montana, western Wyoming, southern Idaho, and the Great Basin where ponderosa pine is not found. Within its range, which includes much of the West, ponderosa pines can be found at elevations from sea level to 3050 m, with the general trend of elevation increasing from north to south in the species' range (Oliver and Ryker 1990).

Ponderosa pine forests are often transitional between nonforested grasslands of lower elevations and mixed-conifer forests found at middle elevations. Ponderosa pines also occur as a dominant seral species in the middle elevation forests (Oliver and Ryker 1990, Agee 1993). The associated tree species vary geographically. Associates include Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), lodgepole pine (*Pinus contorta* Douglas ex. Louden), true firs (*Abies* spp.), and western larch (*Larix occidentalis* Nutt.) in the northern parts of its range. In the more southern locations, ponderosa pine can occur with many of those same species in addition to various junipers (*Juniperus* spp.) and Gambel oak (*Quercus gambelii* Nutt.). Ponderosa pine is often accompanied by an understory of shrubs (e.g., *Arctostaphylos, Ceanothus, Purshia*, *Artemisia, Quercus, Rosa, Prunus, Spirea, Symphoricarpos, Physocarpus,* and *Berberis*) and grasses (e.g., *Agropyron, Andropogon, Bouteloua, Festuca, Muhlenbergia*, and *Poa*) (Oliver and Ryker 1990). Site-specific characteristics control which species may occur in a given location.

2.2 Fire Ecology

Ponderosa pine is an excellent example of adaptation to wildfire found in the genus *Pinus*. Pines generally rely on disturbance in order to compete against other species, and fire is commonly the disturbance upon which pines rely for continued dominance (Richardson and Rundel 1998). For example, ponderosa pine can out-compete its more shade-tolerant associates through its resistance to fire, allowing it to maintain dominance in places it otherwise would be unable to without repeated fires.

Ponderosa pine forests are commonly associated with low-severity fire regimes and short fire-return intervals (Agee 1998). Frequent lightning fires, coinciding with warm, dry summers and the build-up of fine fuels that consist of pine needles and components of the herbaceous understory, combine to lend the fire regime its characteristics (Dieterich and Swetnam 1984, Baisan and Swetnam 1990). Mature ponderosa pines have thick, fire-resistant bark and are self-pruning, which allows them to survive surface fires, while the shade intolerant seedlings are not as likely to survive fire but are able to establish in patches opened up by such a disturbance (Agee 1993).

The historical fire regimes in forests that contain ponderosa pine vary from frequent, low-severity fires occurring every 3 to 7 years in the Southwest (Dieterich and Swetnam 1984, Baisan and Swetnam 1990, Grissino-Mayer and Swetnam 2000) to the less frequent, mixed-severity fires that occurred every 25 to 50+ years in the Colorado Front Range (Brown *et al*. 1999, Grissino-Mayer *et al*. 2004), with other ranges in between these depending on geographic location and elevation (Hessl *et al*. 2004).

Without frequent fire, ponderosa pine is no longer able to compete against its competitors, such as more shade-tolerant conifers. The resultant fuel accumulation as competitors invade can lead to more destructive effects once a fire does occur (Agee 1993). Such complications are a common result of the era of fire suppression during the 20th century. Compounding such changes, invasive grasses, which are often annuals, compared to the native perennial grasses, can change the fire regime (Agee 1993, Richardson and Rundel 1998). Grazing activity, which has taken place since the late 1800s, works to lengthen fire intervals by reducing the available fuels in the understory (Savage and Swetnam 1990) and changing the composition of the grasses from perennials to annuals (Agee 1993).

2.3 Significance and Status of the Species

Ponderosa pines have a high aesthetic value to the public because they are often seen along forest highways in the west and their open forests are at the lower elevations where year-round recreational uses can take place. In addition to recreation, other principal uses of the ponderosa forests are timber production and livestock grazing (Oliver and Ryker 1990). Little (1980) described ponderosa pine as the most commercially important western pine. The common harvest practice is to selectively remove the larger trees in a stand while leaving behind the smaller individuals (Agee 1993). Ponderosa pine is logged for lumber, with the higher quality wood well-suited for use in millwork, while the lower quality material is used for boxes, crates, particle board, and paper. Much of the old-growth ponderosa has been eliminated by extensive harvesting, especially at the more accessible lower elevations, which has possibly affected the diversity of the gene pool of ponderosa pine (Ledig 1993). The lower elevation individuals have adapted to the hotter and drier conditions encountered there. Such a loss in diversity may affect the ability of the species to cope with climatic changes.

Native Americans recognized the ponderosa pine as a potential food source, eating the seeds and the sweet phloem inside the bark (Murphy 1994). Native American people in the West also had other uses for the pine, including for construction material for homes and canoes, fuel, needles for baskets, and medicinal uses and dyes (Murphy 1994). Although these traditional uses are dying out, the ponderosa pine is still important to wildlife throughout its range. The trees provide habitat for Abert's and Kaibab squirrels, the snags are used for nesting and roosting by various bird species, and larger game such as elk and deer use the forests for food and shelter (Schubert 1974, Oliver and Ryker 1990, Murphy 1994). Smaller wildlife that eat the seeds and the nutcrackers and chipmunks that cache the seeds also serve to aid the ponderosa pine in regeneration (Little 1980).

Ponderosa pines have also been at the heart of the science of dendrochronology since its inception. The first tree rings carefully observed by astronomer A.E. Douglass in his search for a proxy record of sunspot activity were contained in the stumps of recently cut ponderosa pines in northern Arizona in 1904 (Richardson and Rundel 1998, Nash 1999). Ponderosa pines have been used in the dating of prehistoric structures in the Southwest since the beginning of dendroarchaeology (Nash 1999) and have been used extensively in dendroclimatic studies because of the sensitivity of the species to climate, particularly precipitation (e.g., Stockton and Meko 1975, Meko 1982, Earle 1993, Grissino-Mayer 1996, Grissino-Mayer *et al.* 1997, Woodhouse and Brown 2001, Benson *et al.* 2002, Pohl *et al.* 2002).

Chapter 3

Study Sites

3.1 Payette National Forest, Idaho

The land in west central Idaho that was to eventually become the Payette National Forest (PNF) was initially protected within the Weiser Reserve in 1905 and the Idaho Reserve in 1908. The two reserves were combined to become the Payette National Forest in 1944. The Payette National Forest's 930,000 ha include great variations in terrain, with a range in elevation from 480 m in the Hell's Canyon portion of the Snake River Canyon to peaks reaching over 2,900 m in the Salmon River Mountains. The Salmon River, "The River of No Return," (Figure 3.1) runs along the northern boundary of much of the forest. The forest is divided into five ranger districts: Weiser Ranger District in the southwest portion, Krassel Ranger District in the easternmost portion bordering the Frank Church River of No Return Wilderness, and the McCall, New Meadows, and Council Ranger Districts in between. The forest headquarters is based in McCall. The forest is bordered by the Boise National Forest to the south, the Frank Church River of No Return Wilderness to the east, the Salmon-Challis National Forest further east, and the Nez Perce National Forest to the north (USFS 2003).

3.1.1 Climate

The climate of the Payette National Forest is greatly influenced by Pacific air masses steered by the movement of the Aleutian Low in the winter and the Pacific High

Figure 3.1 The difficult terrain of the Salmon River Canyon.

in the summer (Barry and Chorley 1976). These interactions cause the area to receive most of its precipitation in the winter with very little during the summer months, especially July and August. The mean annual total rainfall is 68.6 cm at McCall, Idaho (Western Regional Climate Center 2006). The mean monthly temperatures at McCall range from a low of –6.2 °C in January to a high of 16.9 °C in July (WRCC 2006).

The climate of Payette National Forest is affected by oceanic teleconnections that involve the Pacific Ocean. The El Niño-Southern Oscillation (ENSO) enters an El Niño phase every 3–7 years. This phase is caused by a shift in pressure systems in the tropical Pacific. The normally dominant high pressure found off the coast of Peru weakens, resulting in a decline in coldwater upwelling along the coast of Peru, weakened tradewinds along the Equator, and increased ocean temperatures off the west coast of South America. These changes in the tropical Pacific affect weather patterns in western North America during an El Niño event (Mote *et al.* 1999). The Pacific Northwest experiences the inverse of the southwestern U.S., with warmer and drier winters during an El Niño event and cooler, wetter winters during a La Niña event (Redmond and Koch 1991).

The Pacific Decadal Oscillation (PDO) is similar to ENSO in that it involves shifts in ocean temperatures and pressure centers but PDO occurs in the northern Pacific and occurs on a multi-decadal scale (20–40 year cycles) (Norman and Taylor 2003). Phases of PDO are linked with the strength of the Aleutian low in the northern Pacific Ocean (Gershunov *et al.* 1999). While in a positive phase, the Aleutian low is intensified and conversely pressure is higher along the Pacific Northwest coast resulting in warmer, drier winters in the Pacific Northwest including the Payette National Forest. The conditions during a positive phase PDO are similar to those during El Niño events. A weakened Aleutian low in the negative phase of PDO results in cooler, wetter winters for the Payette NF because of lower pressure over the Pacific Northwest (Mantua *et al.* 1997). Phases of the PDO can serve to modulate simultaneous El Niño or La Niña events, causing them to be muted or strengthened depending on the phases. A positive phase of PDO will intensify an El Niño event while diminishing a La Niña event (Gershunov and Barnett 1998).

3.1.2 Geology

The extremes of the terrain of the PNF include the deepest river gorge in North America (2,400 m from rim to bottom in places) and peaks over 2,900 m. During the Pleistocene, the higher elevations were modified by the advancing and receding glaciers that formed the three Payette Lakes (USFS 2003). The higher elevations have been further modified by freeze-thaw processes since. Streams cutting down to create sharply defined drainage patterns characterize the middle and lower elevations. The eastern part of the PNF is on a portion of the Idaho Batholith that formed 75 to 100 million years ago (Armstrong *et al.* 1977). The western part of the forest is underlain by Columbia River basalts. The line where these two portions meet marks the boundary between lithosphere of accreted terranes to the west and Precambrian craton to the east (Camp and Hanan 2008).

3.1.3 Soils

The soils of the PNF are generally young and rocky, a reflection of the recent glacial activity and relatively young geological age of the region's surface. The USDA soil orders commonly found in the Payette include Entisols, Inceptisols, and Mollisols (Soil Survey Staff 1999). Mollisols are limited to the western most portion of the PNF. The parent materials are often either granite of the Idaho Batholith or volcanic material related to the Columbia flood basalts. Much of the eastern part of the PNF is characterized by granitic, coarse-textured soils that readily absorb precipitation. Because of this property, these soils are not associated with high rates of surface runoff unless the soils have been disturbed or a high-intensity rainfall event occurs (USFS 2003).

3.1.4 Plant communities

Most of the PNF (83%) is considered forested while the remaining non-forested portions (16%) are dominated by grass, forbs, and shrubs. To be considered forested, the landscape must have at least 10% crown cover by forest trees of any size or historically have had tree cover. Areas not meeting these criteria are designated non-forested and are found at low elevations, hot dry southern aspects, or high elevation alpine environments (USFS 2003).

Between the non-forested lowest and highest elevations, the species composition of forested areas changes based on elevation, a typical pattern in the Northern Rocky Mountains (Peet 2000). Common tree species found in low to mid-elevation forests are ponderosa pine (*Pinus ponderosa* Douglas ex. C. Lawson), Douglas fir (*Pseudotsuga* *menziesii* (Mirb.) Franco), grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), western larch (*Larix occidentalis* Nutt.), aspen (*Populus tremuloides* Michx.), and lodgepole pine (*Pinus contorta* Douglas ex Loudon). High elevation tree species include subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and whitebark pine (*Pinus albicaulis* Engelm.) (USFS 2003).

3.1.5 Land-use history

Native Americans were present in the Salmon River mountains and surrounding areas for 12,000 years based on archaeological evidence (USFS 2003). The area was seasonally occupied by the Shoshone, Northern Paiute, and Nez Perce tribes. In addition to harvesting plants and hunting game, Native Americans used fire on the landscape to keep campsites and trails cleared and enhance subsistence food gathering areas. While most Native Americans had been removed to reservations by 1900, they continue to have treaty rights to hunt, fish, and gather on the forest lands (USFS 2003).

The formidable terrain of the Salmon River mountains and nearly impossible to navigate waters of the Salmon River discouraged most Euro-Americans from entering the area in the early 1800s, including Lewis and Clark in 1805 (Idaho State Historical Society 1965). After exhausting the surrounding areas of the Snake River, trappers explored the area during the 1820s and early 1830s with little success in finding the beaver pelts they sought. Mormons attempted to create a settlement on the Salmon River in the mid-1850s, but it had to be abandoned after an attack by local Native American tribes. Shortly afterward, gold was discovered in the Salmon River mountains in 1861, causing a gold rush to the area and the first major influx of Euro-American settlers, including farmers and ranchers who settled the area to supply the prospectors and instant towns. Mining altered the landscape through movements of large volumes of earth, diversion of stream courses, and the cutting of timber. As more mines were established in the area during the 1860s and 1870s, hostilities with Native American tribes increased. The United States Army rounded up the remaining Native Americans in the Salmon River mountains in the late 1870s. With the threat of attacks removed, mining expanded into the most remote areas of the Salmon River mountains during the rest of the 1800s. The last gold rush in the area took place in 1902 (Idaho State Historical Society 1965).

3.1.6 Forest management

The original Forest Plan for the Payette National Forest was completed in 1988. The Forest Plan has since been revised in 2003 with forest-wide goals and objectives to reach a set of desired conditions with emphasis on maintaining and restoring the function of ecosystems in the PNF while allowing for adaptive management and monitoring. The PNF is further divided into 14 management areas with specific management goals and prescriptions to support those of the overall Forest Plan. Designated wilderness is the largest single management prescription, comprising 33% of forest area with another 9% of the PNF recommended for wilderness designation. The PNF is managed so that ecosystems are dynamic and resilient to disturbances, provide habitat for desired species, are managed sustainably, and are managed with American Indian Tribal needs and interests addressed. The PNF is also managed so that ecosystem processes can perform their desired functions. These desired conditions for ecosystems are supported by desired conditions for soils, air, hydrologic elements, plant communities, invasive species, disturbance processes, recreation opportunities, cultural resources, and sustainable production of goods and resources (USFS 2003).

3.2 French Creek

The French Creek site is located at the northern end of the French Creek watershed on the slope to the east of the creek with a westerly aspect (Figures 3.2 and 3.3). The French Creek site includes the fire history subsites French Creek High (FCH/FCX), French Creek 2 (FC2), and French Creek South (FCS) (Figure 3.4). The site contains Forest Road 246, including a portion of the road known locally as “The Fingers” due to the winding switchbacks that traverse the steep slopes. Elevations at the site range from around 1150 m to 1400 m. The vegetation is open canopy ponderosa pine forest with grasses and shrubs in the understory. The French Creek site did not have evidence of livestock grazing, which does occur on the opposite slopes to the west of the creek. Very little evidence of regeneration was found at the site, with only a handful of seedling or sapling ponderosa pines noted. Numerous stumps were present that indicated previous logging at the site, and many of the pines had open fire scar wounds (Figure 3.5). Charred wood was still present from the 1992 (809 hectares) and much larger 1985 (1,638 hectares) French Creek fires (USFS 2003).

Figure 3.2 View of the northern portion of the French Creek site (subsite French Creek High), including one switchback of Forest Road 246.

Figure 3.3 View of the middle portion of the French Creek site (subsite French Creek 2), including a portion of Forest Road 246.

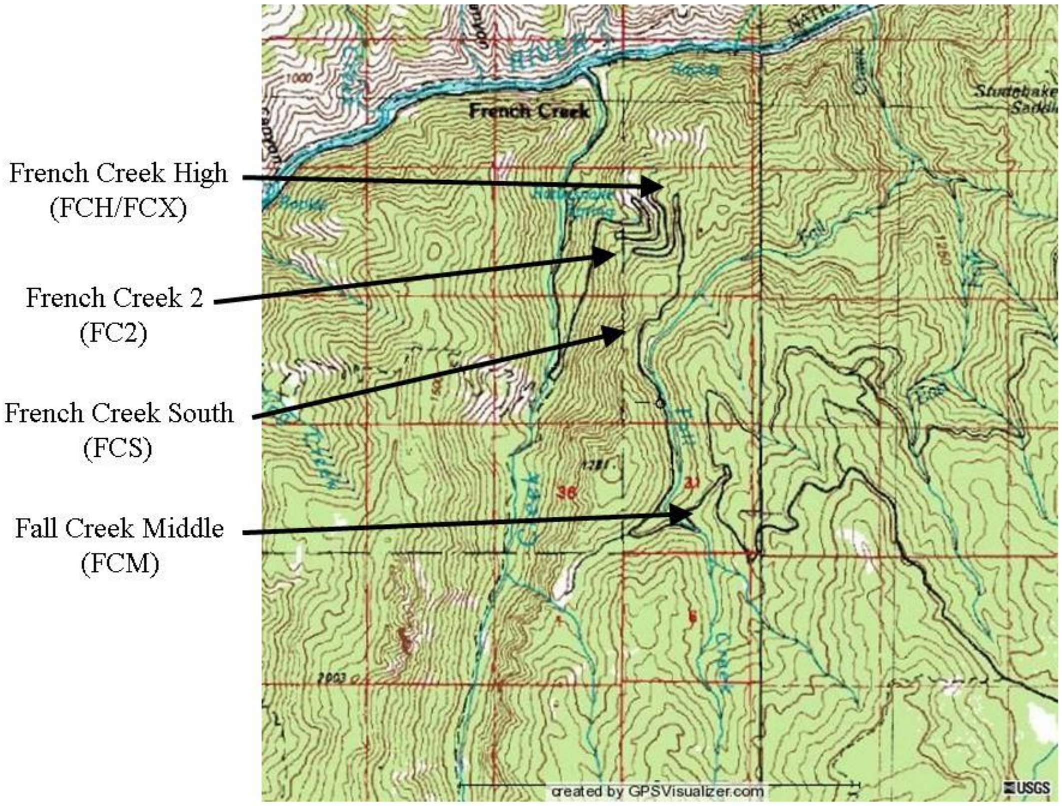


Figure 3.4 Topographic map of study sites and subsites (adapted from GPSVisualizer 2006).

Figure 3.5 Ponderosa pine at the French Creek site (subsite French Creek South) with fire scar wound or “catface.” The stump to the right is one of many that indicate selective logging.

3.3 Fall Creek

The Fall Creek site is further from the Salmon River Canyon and to the south of the French Creek site. The site is also adjacent to Forest Road 246. Elevations at the Fall Creek site range from around 1500 m to 1600 m. The terrain at the Fall Creek site is less steep and the aspect is northwesterly. The canopy at Fall Creek is much less open than at the French Creek site (Figure 3.6). Douglas-firs were found in the understory, along with grasses and shrubs. The ponderosa pines did not have visible fire scar wounds and no charred wood was present at the site. This absence of evidence of frequent fire allowed the site to be designated the control site. Since the possibility of any location being "fire-free" is unlikely, the distance of the Fall Creek site from the French Creek site makes the possibility of any fire spread between the two unlikely. No stumps from previous logging were found at the Fall Creek site, and no evidence of grazing was present at the site. As at the French Creek site, very little regeneration is occurring at Fall Creek. While both sites are considered "suited timberland," portions of the Fall Creek site are in the French Creek Inventoried Roadless Area.

Figure 3.6 The more dense ponderosa pine forest at the Fall Creek site.

Chapter 4

Methods

4.1 Field Methods

4.1.1 Fire history

Partial cross-sections of living trees and full cross-sections from snags, stumps, and logs that exhibited single or multiple fire scars were collected in July 2006 (Table 4.1) with a chain saw from the French Creek fire history site following standard fire history sampling techniques (Arno and Sneck 1977). Samples were collected from three locations at French Creek to maximize information on spatial aspects of fire. A field team consisting of Henri Grissino-Mayer, Lisa LaForest, Maggie Stevens, and myself (hereafter referred to as “we”) sampled only those trees that displayed (1) an inverted V-shaped scarred surface extending to the ground (a “catface”), often found on the upslope side of the tree and (2) presence of charcoal on the scarred surface or bark. These characteristics are considered classic features of trees injured by fire as opposed to other mechanisms that can scar trees, such as lightning and wildlife (Gutsell and Johnson 1996). For each sample taken, information on species type, sample condition, location, visible fire scars, and a sketch of the sample were recorded. Such information is invaluable during laboratory analyses in identifying and reassembling broken samples and aiding in the crossdating process. We collected 71 cross-sections, 27 of which were sampled from living trees and 44 sampled from stumps, logs, and snags. In addition to samples collected during this field season, 10 fire history samples previously collected by

Table 4.1 Types and purposes of samples collected at each site or subsite.

Site Name (Site Code)	Number and Type of Sample	Purpose of Sample
French Creek		
French Creek High (FCH/FCX)	150 increment cores	Creation of fire site core chronology
French Creek 2 (FC2)	81 cross-sections	Creation of fire site cross-section chronology and fire history
French Creek South (FCS)		
Fall Creek Middle (FCM)	80 increment cores	Creation of control chronology

Grissino-Mayer *et al.* (2005) during the 2005 North American Dendroecological Fieldweek (NADEF) were also used in this project.

4.1.2 Control

We cored several possible sites within the vicinity of the fire history sites while exploring for a control site where fire would have had a minimal impact on tree growth. A control site was established at the Fall Creek site where increment cores were collected from old-growth ponderosa pine trees for climate analysis. The criteria for the control site included that it be dominated by ponderosa pines, display little evidence of frequent fire, be underlain by thin, rocky soils which would both promote sensitivity to climate and inhibit the spread of fire, and had no history of logging.

We collected increment cores from 40 trees at the control site using increment borers (Table 4.1). Only living ponderosa pines were sampled. From each tree selected for coring, we took two cores parallel to the slope’s contour at a height as close to the ground as possible while still allowing for the length of the borer’s handles to be turned (Grissino-Mayer 2003). The cores were then placed into paper straws for storage and transportation. I recorded the general location of the tree, diameter at breast height, crown density, estimated tree height, lean direction and degree, and other relevant characteristics.

Increment cores had been collected at the French Creek fire history site (Table 4.1) during the 2005 NADEF (Grissino-Mayer *et al.* 2005). The cores had been collected mostly from living trees that did not display evidence of fire injury, although some of the living trees sampled did have fire scars. Because these cores were collected from the French Creek fire history site, they were not suitable to be used as a control chronology and would be expected to contain the same effects on tree growth as the fire history site cross-sections. These cores were included in later analyses as the fire site core chronology.

4.2 Laboratory Methods

4.2.1 Sample preparation

Cross-sections and increment cores were allowed to air dry at the laboratory. Each increment core was mounted onto a wooden core mount with the cells aligned vertically so that the ring boundaries were visually apparent after sanding. The cross-sections were treated for pests, and then dried before being glued onto plywood boards (if necessary) to stabilize them for sanding. The cores and cross-sections were sanded using progressively finer sandpaper, beginning with ANSI 80-grit (177–210 μm) and ending with ANSI 400-grit (20.6–36.0 μm) (Orvis and Grissino-Mayer 2002). The sanding process allowed the cellular structure of the tree rings to be visible under standard 10X magnification. On samples collected from living trees, I counted each ring from the outermost (youngest) ring (incomplete 2005 or incomplete 2006, depending upon during which field season the sample was collected) and dotted with a mechanical pencil each decade ring (i.e., 2000, 1990, 1980, etc.). Fire history samples from snags, stumps, and logs were considered floating in time and so were dotted every 10 years, with the inner year being year 1 continuing to the outermost year. Once dotted, the ring widths on the increment cores and fire history sections were measured to the nearest 0.001 mm using a Velmex measuring system interfaced with Measure J2X software. I measured the cross-sections along radii located as far away as possible from the fire scars to avoid the erratic growth that often occurs around an injury. More than one radius per sample was measured if there were visible breaks along the measurement radius. I also measured ring widths from 150 additional cores taken from both non-scarred and scarred trees at two of the fire history subsites collected during the 2005 NADEF.

4.2.2 Crossdating and chronology construction

I crossdated my samples using visual, graphical, and statistical crossdating techniques to assign calendar years to each ring in my samples. I also used the list method by identifying and recording notable marker rings to assist in crossdating (Yamaguchi 1991). Visual crossdating was accomplished through recognition of patterns of wide and narrow rings common to all my sites (Fritts 2001). For graphical crossdating, I used the skeleton-plot method (Stokes and Smiley 1996), which involved keying in on the narrow rings relative to the surrounding rings in a moving window throughout the sample. All crossdating was verified statistically through use of ring-width measurements and the computer program COFECHA (Holmes 1983, Grissino-Mayer 2001b). Samples which could not be conclusively crossdated using these methods were excluded from any additional analyses.

The measurement files generated by Measure J2X were consolidated into one file of measurements for each site. The measurements were then entered into the program

COFECHA (Holmes 1983, Grissino-Mayer 2001b) to be statistically crossdated with all the other series to check for missing rings, false rings, miscounting, and misdating. COFECHA is used as a tool by dendrochronologists to ensure crossdating quality and measurement accuracy of and among series (Grissino-Mayer 2001b) after the samples have been crossdated visually or graphically. The program first removes age-related and other low-frequency trends to emphasize the high-frequency trends necessary for successful crossdating. COFECHA then compares the dating accuracy of 50 year segments, overlapped 25 years, of each series to the same segments on a master chronology consisting of all the other series. Correlation coefficients were calculated for each segment as a measure of the strength of the relationship it had with a temporary chronology created from the other series for that same segment. COFECHA flagged low correlations ($r < 0.32$, $p > 0.01$) that required reinspection. If the alternate dating position suggested by COFECHA was unrealistic (for example, a "+3" adjustment when both 50-year segments on either side were dated correctly) or had a similar correlation to the original placement, the segment was kept at its original placement. Segments that required shifting were checked visually before I used the program EDRM (Holmes 1999) to shift the segments the suggested amount to their correct temporal placement.

Measurement files from cross-sections of non-living trees were entered into COFECHA as undated series. COFECHA uses segmented time series correlation techniques to crossdate the undated series against the master chronology created from living tree samples. For an undated series to be considered dated, the temporal placements had to be systematic for all or most of the tested 50-year segments. The correlation coefficients at the suggested placement also had to be statistically significant ($r \geq 0.32$, $p < 0.01$). For all series, the final placement of a series in time had to be both visually and statistically convincing (Grissino-Mayer 2001b).

Once dated, raw ring-width measurements must undergo one final transformation to account for age-related growth trends that introduce noise into the final chronology. I used the program CRONOL to standardize the raw measurement data (Cook 1985). This created a standardized master index chronology for each site that preserved trends associated with climate (Fritts 2001). The standardization process removed the age-related growth trend by fitting a negative exponential trend line to the individual series data using the least squares technique and then dividing the actual ring width by the value predicted by the regression (Fritts 2001). The final ring-width index chronology for each site was created by averaging the indices of each series for each year. The resulting standardized indices have a mean value of one, display a flatter linear trend, and have less variability related to juvenile growth.

4.2.3 Fire history

I identified fire events by fire scars (and associated embedded charcoal) found within the tree rings of my cross-sections (Arno and Sneck 1977). Because each ring was dated to the exact year of formation after crossdating, the year the tree was scarred by fire was observed and recorded, as well as the season in which the fire occurred based on the location of the scar within the ring itself (Baisan and Swetnam 1990). In the northern Rocky Mountains, ponderosa pine cambial activity extends from mid-May to late August

(Daubenmire 1950). I used the following definitions for assigning seasonality to fire scars:

- Early season (E): The injury is located in the first third of the earlywood, indicating occurrence in early spring (May).
- Middle season (M): The injury is located in the middle third of the earlywood, indicating occurrence in late spring to early summer (June).
- Late season (L): The injury is located in the last third of the earlywood, indicating occurrence in early to mid-summer (July).
- End of growing season (A): The injury is located in the latewood, indicating occurrence in late summer (August).
- Dormant season (D): The injury is located between the latewood of the previous year's growth and the earlywood of the following year's growth, indicating occurrence of fire during the tree's dormancy period. The fire season in the Northern Rocky Mountains begins in late summer or early autumn (Brown *et al*. 1994), therefore fire scars that occurred at this position were assigned to the preceding year (September to October).

I designated each ring on my fire history samples as either a "recorder" or a "non-recorder" year. Recorder years are the non-eroded rings that formed after an initial fire scar and have the potential to record later fire events. Once fire creates an open wound on a pine tree, that tree is more likely to record subsequent fire events as fire scars because of the flammable resin used by the tree to compartmentalize the injury (Romme 1980). Rings that formed before the initial fire scar recorded by a tree or are too eroded or damaged to provide fire data were considered non-recorder years. Only recorder years were included in the statistical analyses (Grissino-Mayer 1995, 1999). The period beginning from the first year with two or more recorder trees is the period of reliability (Grissino-Mayer 1999). The period of reliability is the portion of the fire history data deemed suitable for statistical analyses. I entered all information derived from my fire history samples (year and season of fire events, recorder/non-recorder status, inner ring or pith date, and outer ring or bark date) into the FHX2 software to construct fire history charts, calculate descriptive statistics, and conduct temporal and spatial analyses (Grissino-Mayer 2001a). I constructed four fire chronologies, one for each fire history subsite, and a master fire chronology consisting of the combined information from all three subsites.

4.3 Graphical Analyses

I made fire history charts for each of my fire history subsites and the composite fire history chart using the graphics module in FHX2 (Grissino-Mayer 2001a). The fire history charts displayed the fire history information contained in each sample and the composite fire history information. I visually and statistically examined the charts for temporal changes (changes in fire frequency through time) and spatial changes (fire spread within a subsite and throughout subsites) of fire activity.

4.4 Statistical Analyses

I calculated descriptive statistics, analyzed possible temporal and spatial changes in fire regimes and possible temporal changes in seasonality, and examined the relationship between fire occurrence and changes in tree growth over the period of reliability for each subsite chronology and the combined master chronology. The descriptive statistics provided measures of central tendency, dispersion, range, and shape of the fire interval distributions which characterized the historical range of variability of each composite fire chronology (Dieterich 1980).

I used four statistics to describe central tendency: Mean Fire Interval (MFI), Median Fire Interval (MDI), Weibull Median Interval (MEI), and Weibull Modal Interval (MOI) (Table 4.2). The MFI is the simple mean of years between consecutive fire dates in a composite chronology. Because fire interval distributions are often positively skewed by long fire-free intervals (Grissino-Mayer 1995), the MFI is not considered a good descriptor of fire regimes. The MDI is the median of a distribution of fire intervals, and so is more resistant to outliers than the MFI. By modeling the fire interval data with the Weibull distribution (Weibull 1951), a superior fit for the often positively-skewed fire interval distributions can be achieved than with the less flexible normal distribution (Grissino-Mayer 1999). The MEI and MOI were derived from the Weibull distribution. The MEI is the fire interval associated with the 50th percentile of the fitted distribution (Grissino-Mayer *et al.* 2004) and is highly resistant to outliers (Grissino-Mayer 2001a). The MOI is the theoretical mode of the distribution that represents the greatest area under the probability density function (Grissino-Mayer 2001a).

Table 4.2 Definitions of descriptive statistics used for fire history chronologies.

Name of Statistic	Abbreviation	Description
Period of Reliability	POR	The period of the fire history with two or more recorder trees.
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 resistant 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 Exceedance Interval	LEI	The interval that delimits a significantly short fire-free interval, derived from the Weibull distribution.
Upper Exceedance 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.

I used five statistics to describe the range in fire interval data: Minimum Fire Interval (MIN), Maximum Fire Interval (MAX), Lower Exceedence Interval (LEI), Upper Exceedence Interval (UEI), and Maximum Hazard Interval (MHI). The MIN and MAX are the shortest and longest fire intervals in a distribution. The LEI and UEI are the intervals associated with the 12.5 and 87.5 percentiles of the Weibull distribution, respectively. Intervals above or below these values were considered to be significantly short or long (Grissino-Mayer 1999). The MHI represents the theoretical maximum fire interval that an ecosystem can experience before fire becomes highly probable based on the preceding fire intervals in the distribution (Grissino-Mayer 1995). The MHI is derived from the Weibull hazard function (Grissino-Mayer 1999).

The standard deviation (SD) and coefficient of variation (CV) were used as measures of dispersion about the mean of the fire interval distributions. The SD is calculated by taking the square root of the variance. Plus or minus one SD contains 68% of the fire intervals and plus or minus two SD contains 95% of the fire intervals. The CV is calculated by dividing the mean by the SD. The CV is preferred over the SD for comparison of fire interval distributions because it provides a standardized value (Grissino-Mayer 2001a).

Skewness and kurtosis were calculated to describe the shape of the fire interval distributions (Grissino-Mayer 1999). Skewness describes the symmetry of a distribution. Because fire intervals cannot be less than one year, distributions are often positively skewed (skewness > 0). The peakedness of a distribution relative to a normal distribution is described by the statistic kurtosis (a normal distribution has a kurtosis = 0). Data with few outliers are highly peaked (kurtosis > 0), while data with many outliers are flat (kurtosis < 0).

I examined each fire chronology for temporal changes in fire frequency during two equal periods from the beginning of the period of reliability to the start of fire suppression (1756–1842 and 1843–1929). I also compared these two periods to the fire suppression or late historic period (1930–2006). To determine if there was a significant difference in fire activity between two periods, I used the following statistical tests: Student's t-tests for difference of means, folded F-tests for difference in variability about the mean, and two-sample Kolmogorov-Smirnov tests for difference in distributions of intervals (Grissino-Mayer 1995). The spatial analysis used the same tests as the temporal analyses to compare the fire chronologies of each subsite to one another. I conducted the tests over a common set of years for which both chronologies contained data.

I analyzed the seasonality of fire for my chronologies by grouping the fires as early-season (seasons E, M, and L) or late-season (season A and D). By calculating the percentage of fire events in each seasonality group, I determined the historically dominant season of fire activity at each subsite and for the master chronology.

4.5 Fire-Tree Growth Relationships

To determine whether a substantial growth release or growth suppression occurred in the years following a fire event, I used superposed epoch analysis (SEA) (Baisan and Swetnam 1990, Swetnam 1993, Hessl *et al*. 2004) to analyze the effects of fire events on tree growth 10 years before the fire year, the fire year itself, and 10 years after the fire event. The window typically used in fire history research is five years before the fire, the fire year itself, and two years after the fire. I extended the window of analysis to examine trends in tree growth following a fire. For superposed epoch analysis, bootstrapped confidence intervals were calculated for the window of analysis from 1000 randomly selected events from the population of observations. I used three chronologies, each affected by fire to decreasing degrees, as the variables to be compared to the fire event years. The three chronologies included one chronology created from the fire-scarred cross-sections, one from the cores collected at the fire history site, and one from the control site cores. I used three different fire event chronologies: one consisting of all fire events in the fire history, one with a filter for 10% and a minimum of two trees scarred, and one with a filter for 25% and a minimum of two trees scarred. The different event classes allowed for comparison of the effects of larger, more widespread fires on tree growth. I also conducted SEA with these same fire event chronologies and a reconstruction of the Palmer Drought Severity Index (PDSI) (Cook *et al.* 2004) to assess relationships between fire activity and regional climate.

The differences in variance between the three tree-ring chronologies were compared by subtracting one from another to create a difference chronology. A difference chronology will remove the common variance highlighting the portions of the chronologies which differ. If fire events affect tree growth, the difference in variance between the fire site chronologies and the control chronology should be larger following fire events.

The computer program OUTBREAK (Swetnam *et al.* 1995, Speer *et al.* 2001) is used to quantify insect outbreaks in a set of host trees through comparison with a chronology created from non-host trees to control for climate. Instead of identifying changes in growth patterns associated with insects, I used the program OUTBREAK to quantify changes in growth associated with fire events. The fire site chronologies were the “host” trees and the control site chronology represented the “non-host” trees. For the fire site chronologies, tree-level index chronologies were used. Each fire year represented the start of a known “outbreak.” The years following the fire year were examined for significant reductions or increases in growth.

Chapter 5

Results

5.1 Crossdating and Chronology Construction

We collected 71 fire-scarred cross-sections and 80 increment cores from the study sites. I was given an additional 10 fire-scarred cross-sections and 150 increment cores collected during the 2005 NADEF from the fire history study site (Grissino-Mayer *et al.* 2005). Especially narrow "marker" rings common to all sites were formed in 1665, 1783, 1840, and 1865. Series of narrow rings were formed 1756–1757, 1797–1798, 1846–1847, 1889–1891, 1935–1937, and 1973–1974. A slightly narrow ring in 1899 followed by a wide ring in 1900 was found at all sites and also assisted in the crossdating.

Three ring-width chronologies were developed from the study sites. The cores collected from the fire history site were used for a separate chronology from the chronology developed from the fire-scarred cross-sections collected at the same site near French Creek (Figure 5.1c and 5.1b). The third chronology was developed from the cores collected from the control (Fall Creek Middle) site (Figure 5.1a). The Fall Creek Middle chronology provided the longest record, while the French Creek core chronology contained the shortest (Table 5.1). Individual measurement series ranged from 38–513 years in length. The mean sensitivity of the French Creek core chronology and the French Creek cross-section chronology were very similar, as would be expected. The French Creek cross-section chronology has a lower mean interseries correlation than the French Creek core chronology. The mean interseries correlation and mean sensitivity of

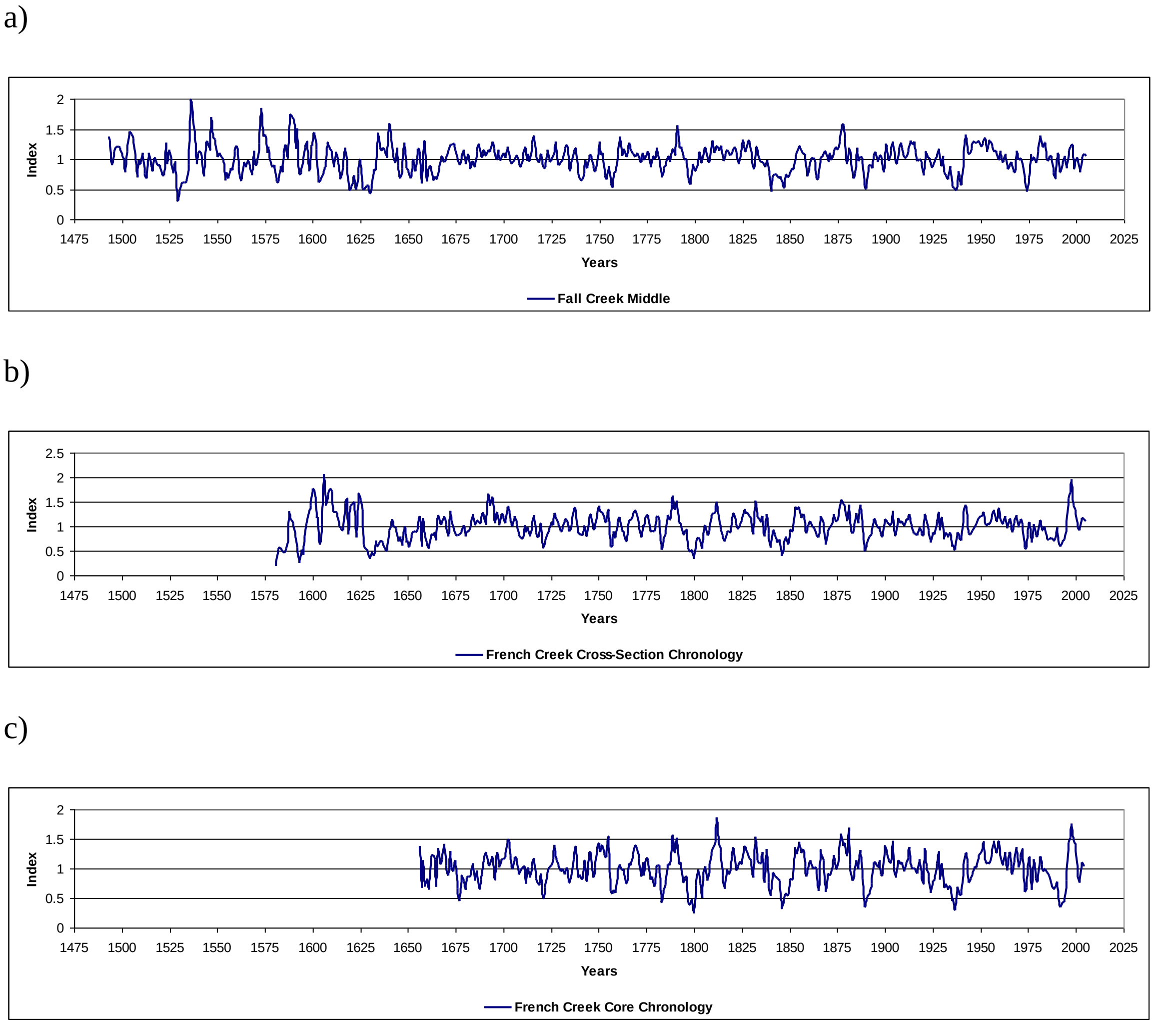


Figure 5.1 Individual chronologies for the three sites.

(a) Fall Creek Middle chronology showing 15th through 21st century growth.

(b) French Creek chronology developed from cross-sections showing 16th through 21st century growth.

(c) French Creek chronology developed from increment cores showing 17th through 21st century growth.

Table 5.1 Statistics for tree-ring chronologies developed from ponderosa pines in the French Creek and Fall Creek drainages, Payette National Forest, Idaho.

	French Creek cross-sections	French Creek cores	Fall Creek Middle
No. Trees/Series	52/60	70/137	37/74
Time Span	1581–2005	1656–2004	1493–2005
Mean Series Length (yrs.)	158.5	174.6	262.9
Mean Interseries Correlation	0.578	0.696	0.579
Mean Sensitivity	0.300	0.329	0.261

the Fall Creek Middle chronology were lower than those of the French Creek core chronology.

5.2 Fire History

The fire-scarred samples contained 276 fire scars representing 41 fire events at the three fire history subsites (Table 5.2). Within the period of reliability (POR), I assigned seasonality to 84.3% (n = 226) of the fire scars. The majority of fire scars were in the end of the growing season (44.2%, n = 100) and dormant season (36.3%, n = 82). While some fire events were recorded by 1–3 trees at a subsite, each subsite fire chronology included at least one fire that scarred trees throughout the subsite.

5.2.1 French Creek High (FCX)

The fire history data for French Creek High (FCX) indicated a fire regime consisting of relatively frequent fires that occurred throughout the subsite (Figure 5.2). Fires were not widespread prior to 1800, but this is more likely because of lower sample depth. Five fires were recorded prior to 1800: in 1717, 1764, 1777, 1790, and 1798. Throughout the early to mid-1800s, with the exception of the 1844 fire, fires were relatively patchy throughout the subsite. The 1889 fire was exceptionally widespread in comparison and was followed by a period with no fires recorded until another widespread fire in 1914. From the mid- to late 1900s, very little fire activity was recorded at the subsite until two widespread fires in 1985 and 1992. Multiple trees were scarred in 1818

Table 5.2 Descriptive statistics for fire history chronologies developed from ponderosa pine in the French Creek drainage, Payette National Forest, Idaho. See Table 4.2 for definitions of abbreviations used.

Statistic	French Creek High	French Creek 2	French Creek South	All subsites
No. Trees	25	13	25	63
Total No. Fire Scars/Events	85/21	77/22	114/29	276/41
Earliest Fire	1717	1756	1601	1601
POR	1818–2006	1756–2006	1756–2006	1756–2006
No. Fire Scars/Events in POR	80/16	77/22	107/22	268/33
MFI (yrs)	11.60	11.24	11.24	7.38
MDI (yrs)	8.00	7.00	7.00	6.00
MEI (yrs)	10.55	9.44	8.91	6.64
MOI (yrs)	7.69	4.66	2.76	4.65
MIN (yrs)	4.00	2.00	2.00	2.00
MAX (yrs)	27.00	34.00	56.00	21.00
LEI (yrs)	3.97	2.81	2.27	2.42
UEI (yrs)	20.25	21.16	22.19	13.02
MHI (yrs)	95.31	815.70	>1000	36.51
SD	7.72	8.96	11.61	5.02
CV	0.67	0.80	1.03	0.68
SKW	0.88	1.08	2.78	1.38
KUR	–0.82	0.12	8.13	0.98

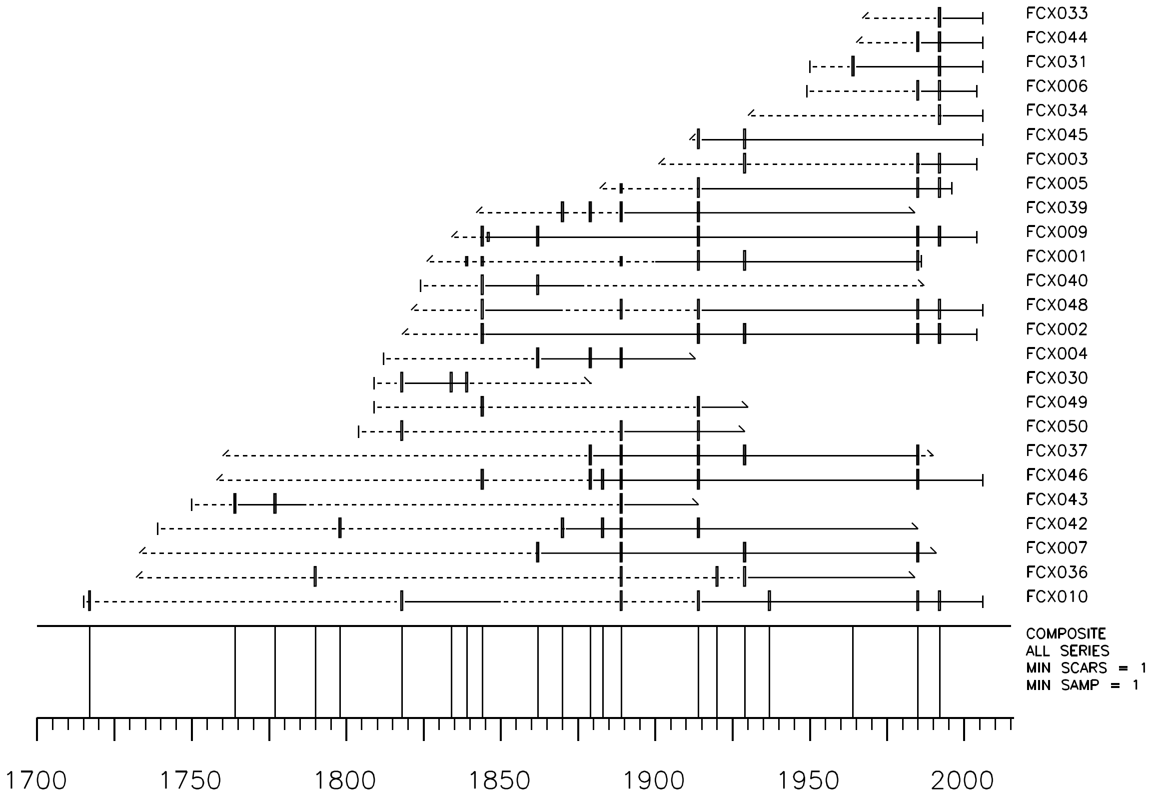


Figure 5.2 Fire history chart for the French Creek High (FCX) subsite, Payette National Forest, Idaho. Each horizontal line represents one tree. Dashed portions of the line represent non-recorder years while solid portions are recorder years. Long vertical bars indicate a year when fire was recorded by that sample. Short vertical bars represent other injuries. The vertical lines on the composite chronology at the bottom of the chart represent years during which at least one tree within the site recorded a fire event.

(n = 3), 1844 (n = 6), 1862 (n = 4), 1870 (n = 2), 1879 (n = 4), 1883 (n = 2), 1889 (n = 11), 1914 (n = 13), 1929 (n = 7), 1985 (n = 12), and 1992 (n = 11).

5.2.2 French Creek 2 (FC2)

The fire regime of French Creek 2 was similar to that of French Creek High (FCX) but appears to have more frequent and less patchy fires (Figure 5.3). Four fires were recorded prior to 1800: in 1756 (n = 2), 1783 (n = 1), 1786 (n = 1), and 1798 (n = 3). Fires were frequent and widespread throughout the 1800s. Unlike the record at the FCX subsite, between the widespread (widespread throughout the subsite) 1889 and 1914 fires, a widespread fire was recorded also in 1899. After the 1914 fire, little fire activity occurred at the subsite throughout the 1900s until the widespread 1985 fire. Multiple trees were scarred in 1756 (n = 2), 1798 (n = 3), 1818 (n = 4), 1844 (n = 4), 1862 (n = 3), 1867 (n = 5), 1870 (n = 3), 1879 (n = 7), 1883 (n = 9), 1889 (n = 10), 1899 (n = 4), 1914 (n = 7), 1960 (n = 2), 1985 (n = 5), and 1992 (n = 2).

5.2.3 French Creek South (FCS)

The fire history for FCS was the longest of the three subsites and includes the most fire scars and the most fire events (Figure 5.4). The fire history of FCS suggested a fire regime of frequent and widespread fires similar to French Creek 2 (FC2). Several fires were recorded prior to 1750 in 1601, 1604, 1663, 1695, 1714, 1720, and 1741. While fire was frequent at the subsite throughout the 1600s and early 1700s, each fire was recorded by only one sample, most likely a result of lower sample depth rather than

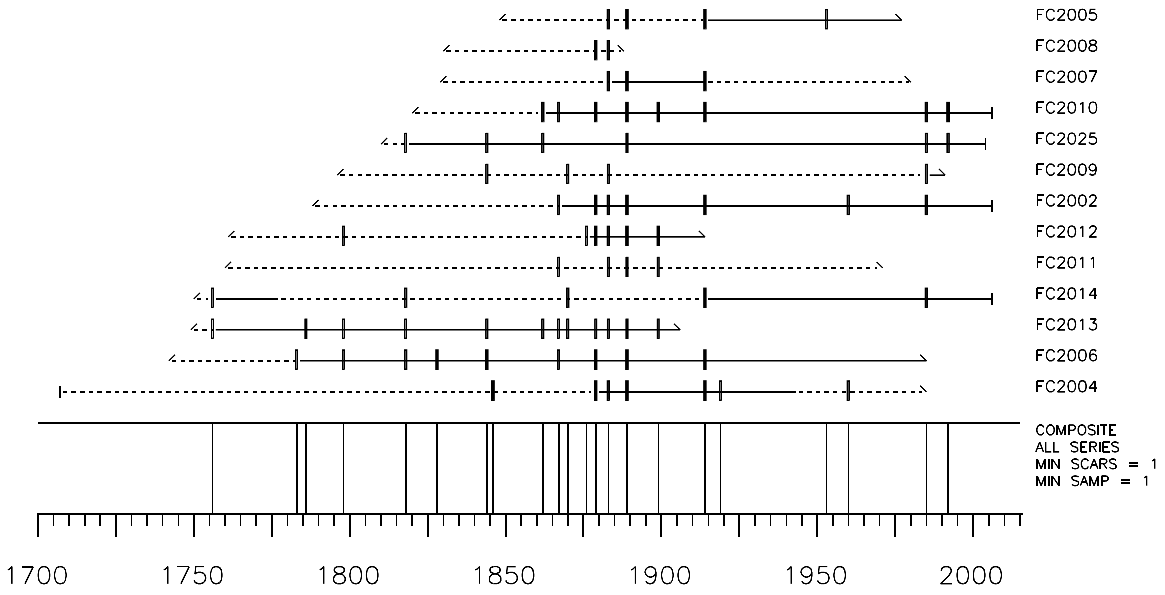


Figure 5.3 Fire history chart for the French Creek 2 subsite, Payette National Forest, Idaho. See Figure 5.2 for an explanation of the symbols used in the chart.

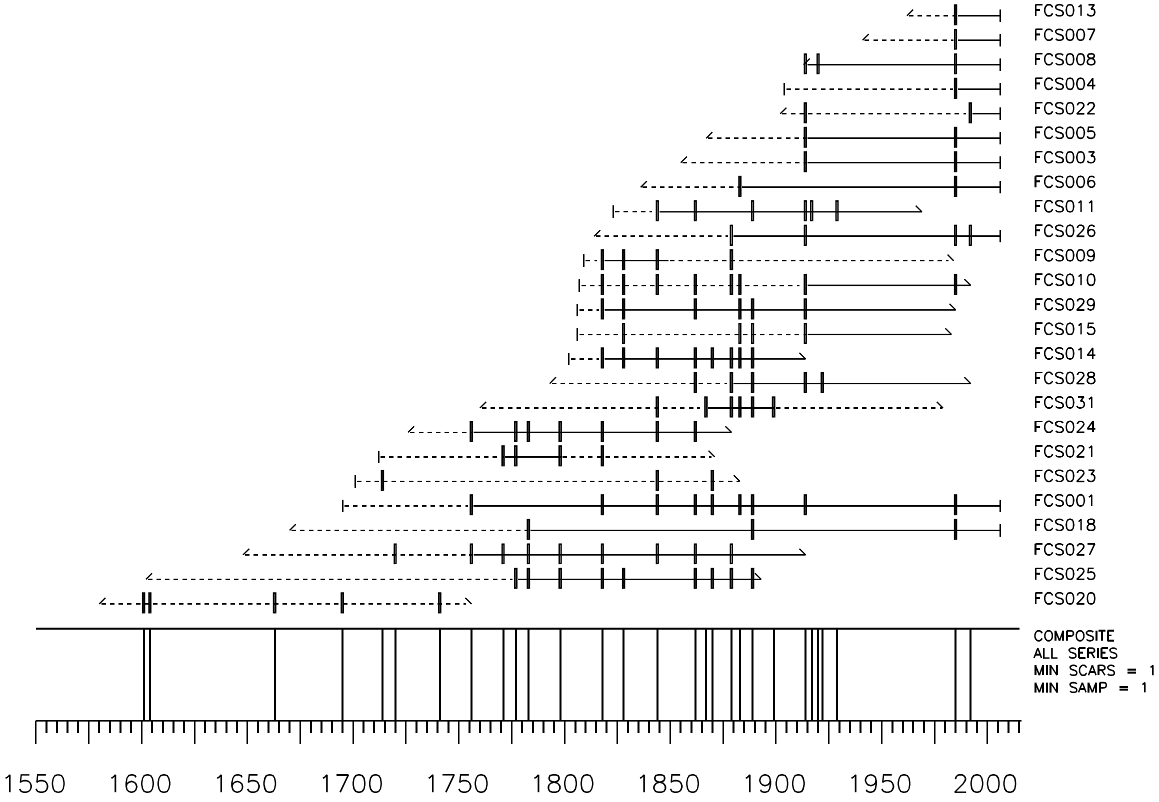


Figure 5.4 Fire history chart for the French Creek South subsite, Payette National Forest, Idaho. See Figure 5.2 for an explanation of the symbols used in the chart.

smaller fires. Several widespread fires occurred at FCS from the late 1700s through the late 1800s, with single-scarred fires being the exception rather than the rule. Fires in 1867 and 1899 were each recorded by one tree. After the widespread 1914 fire, very little fire activity occurred at the subsite until the late 1900s. No fires were recorded from 1929 to 1985 at FCS. Multiple trees were scarred in 1756 (n = 3), 1771 (n = 2), 1777 (n = 3), 1783 (n =4), 1798 (n = 4), 1818 (n = 9), 1828 (n = 6), 1844 (n = 9), 1862 (n = 9), 1870 (n = 4), 1879 (n = 8), 1883 (n = 7), 1889 (n = 9), 1914 (n = 11), 1985 (n = 11), and 1992 (n = 2).

5.2.4 All subsites combined

The composite master fire chronology contains a record of frequent fire activity at the three subsites from the mid-1600s to the mid-1900s (Figure 5.5); however, fires that scarred multiple trees at all three study subsites only occurred from the mid-1700s to the early 1900s with the exception of the two fires in the late 1900s (Figure 5.6). Very little fire activity occurred during the mid-1900s at the three subsites. French Creek South contained the most fires that scarred multiple trees. Several fires were synchronous across the three subsites.

5.3 Statistical Analyses

5.3.1 Descriptive statistics

Fire was a common disturbance occurring in the study area, with 41 separate events recorded within the last 405 years (Table 5.2). The characteristics of fire at the

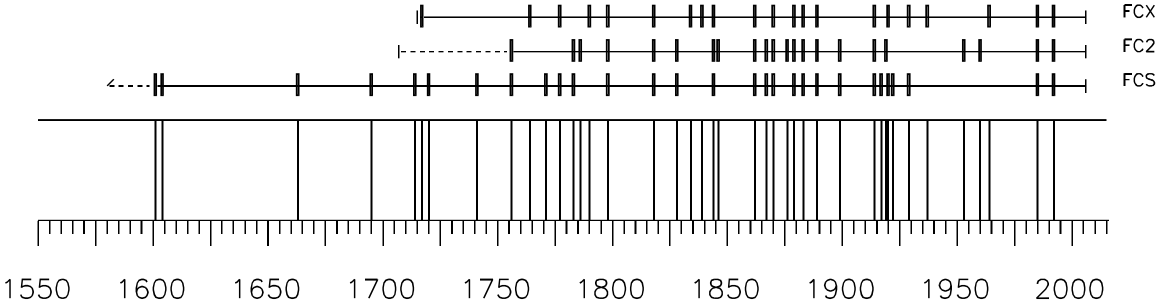


Figure 5.5 The master fire chart for the French Creek High, French Creek 2, and French Creek South subsites, Payette National Forest, Idaho. The horizontal lines represent the individual subsite composite chronologies and the composite master fire chart at the bottom includes all fire years for the three subsites.

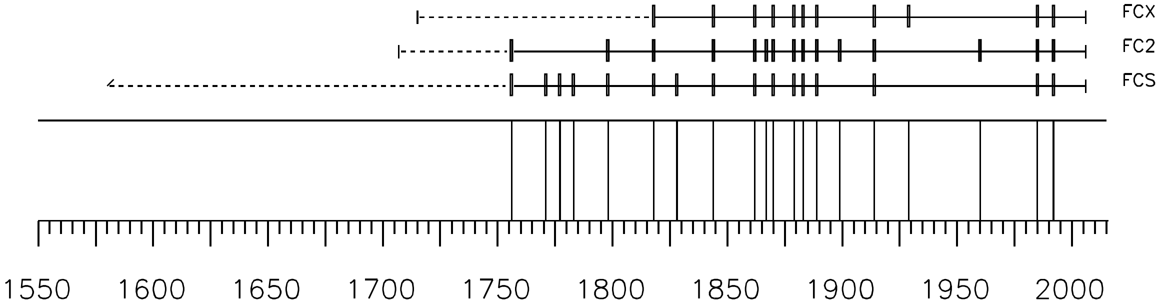


Figure 5.6 The master fire chart for fires that scarred multiple trees at the French Creek High, French Creek 2, and French Creek South subsites, Payette National Forest, Idaho. See Figure 5.5 for an explanation of the symbols used in the chart.

three subsites were similar. The MFI was nearly identical at the three subsites. The MDI and MEI, which are more resistant to outliers than the MFI, are both lower than the MFI and indicate a trend of more frequent fire at French Creek 2 and French Creek South than at French Creek High. None of the subsites followed the pattern found in other fire history studies, where MFI $\geq$ MDI $\geq$ MEI $\geq$ MOI (Grissino-Mayer *et al.* 2004). The only exception to the pattern is that the MDI was smaller than the MEI at all three subsites. From the northernmost subsite (French Creek High) to the southernmost subsite (French Creek South) with French Creek 2 in between (Figure 3.4), the MEI and the MOI were progressively smaller, indicating more frequent fire.

The minimum fire-free intervals of the three subsites ranged from 2 to 4 years, while the maximum fire-free intervals ranged from 27 to 56 years. French Creek 2 and French Creek South had smaller minimum fire-free intervals (2 years) and higher maximum fire-free intervals (34 and 56 years, respectively) than French Creek High (minimum 4 years, maximum 27 years), indicating greater variability in length of fire-free intervals at these two subsites. The French Creek High had the highest LEI (3.97 years), while the LEIs of French Creek 2 and French Creek South were similar to one another (2.81 and 2.27 years, respectively). The UEIs followed a reverse pattern. French Creek South had the highest (22.19 years), while the UEIs of French Creek 2 and French Creek High were 21.16 and 20.25 years respectively. French Creek South had the highest MHI (>1000 years), French Creek High had the lowest MHI (95.31 years), and French Creek 2 fell between (815.7 years).

The SD of fire-free intervals was lowest at French Creek High and highest at French Creek South. Distributions of fire-free intervals are typically skewed. Skewed data highly affect the SD of a distribution (Grissino-Mayer 1995), therefore the CV is better for comparison of variability of fire-free intervals. The CVs of the three subsites followed the same pattern as the SDs: French Creek High had the least variability of fire-free intervals and French Creek South had the greatest variability of fire-free intervals, with French Creek 2 in between. All three subsites were positively skewed. Kurtosis varied between the subsites. While the distribution of fire-free intervals at French Creek High was platykurtic (more flat), the distributions of French Creek 2 and French Creek South were more leptokurtic (more peaked). The distribution of French Creek South was especially leptokurtic.

5.3.2 Temporal changes analyses

The temporal changes analyses are limited by a lack of fire-free intervals during the early historic period (POR–1842), especially at French Creek High (Table 5.3), and a lack of fire-free intervals during the late historic period (1930–2006), especially at French Creek South (Tables 5.4 and 5.5). The MFIs were most dissimilar for French Creek 2 and French Creek South (14.4 years and 12 years, respectively) during the early historic period. The MFIs of French Creek 2 and French Creek South were most similar during the middle historic period (1843–1929; MFI = 6.82 years and 7.08 years respectively). While French Creek 2 and French Creek South both had decreasing MFIs from the early historic period to the middle historic period, the MFI for French Creek High remained

Table 5.3 Results of temporal changes analyses between the early historic (POR–1842) and middle historic (1843–1929) periods, ending at the beginning of effective fire suppression in the Payette National Forest.

	French Creek High	French Creek 2	French Creek South	All Subsites
No. of fire-free intervals				
POR–1842	2	5	6	11
1843–1929	8	11	12	14
Difference in means				
POR–1842	10.5	14.4	12	7.55
1843–1929	10.63	6.82	7.08	6.07
|*t*|-value	–0.01	1.69	2	1.27
p > *t*	0.99	0.14	0.06	0.21
Differences in variance				
POR–1842	60.5	86.3	31.6	20.87
1843–1929	51.41	22.96	25.9	20.84
F-value	1.83	1.65	1.56	1.78
p > F	0.42	0.48	0.66	0.37
Difference in distributions				
K-S *d*-statistic	0.38	0.53	0.5	0.34
p > *d*	0.98	0.29	0.27	0.48

Table 5.4 Results of temporal changes analyses between the early historic (POR–1842) and late historic (1930–POR) periods.

	French Creek High	French Creek 2	French Creek South	All Subsites
No. of fire-free intervals				
POR–1842	2	5	6	11
1930–POR	3	3	*	5
Difference in means				
POR–1842	10.5	14.4	12	7.55
1930–POR	18.33	13	*	11
|*t*|-value	*	0.2	*	–1.08
p > *t*	*	0.85	*	0.29
Differences in variance				
POR–1842	60.5	86.3	31.6	20.87
1930–POR	105.33	108	*	51.5
F-value	*	1.27	*	1.88
p > F	*	0.74	*	0.38
Difference in distributions				
K-S *d*-statistic	*	0.47	*	0.35
p > *d*	*	0.81	*	0.81

* too few intervals to test between periods

Table 5.5 Results of temporal changes analyses between the middle historic (1843–1929) and late historic (1930–POR) periods.

	French Creek High	French Creek 2	French Creek South	All Subsites
No. of fire-free intervals				
1843–1929	8	11	12	14
1930–POR	3	3	*	5
Difference in means				
1843–1929	10.63	6.82	7.08	6.07
1930–POR	18.33	13	*	11
|*t*|-value	–1.38	–1.5	*	–1.82
p > *t*	0.19	0.13	*	0.09
Differences in variance				
1843–1929	51.41	22.96	*	20.84
1930–POR	105.33	108	*	51.5
F-value	1.68	1.45	*	1
p > F	0.51	0.51	*	0.84
Difference in distributions				
K-S *d*-statistic	0.54	0.73	*	0.51
p > *d*	0.54	0.17	*	0.28

* too few intervals to test between periods

nearly the same (10.5 years during the early historic period and 10.63 years during the middle historic period).The MFI for the three subsites combined decreased from the early historic to middle historic periods though not as drastically as French Creek 2 and French Creek South did individually. None of the shifts in fire frequency during the early historic and middle historic periods were statistically significant.

During the late historic period (associated with the era of fire suppression), the MFI was lower than during both the early historic and middle historic periods, but not significantly lower (Tables 5.4 and 5.5). For French Creek High and French Creek 2, as well as all subsites combined, the MFIs had increased to about twice the length from the middle historic period to the late historic period. French Creek South had too few fire intervals during the late historic period for analysis.

5.3.3 Spatial analyses

The spatial analyses found no significant differences in MFI, variance, or distributions between the fire chronologies of the three subsites (Table 5.6). Fire and non-fire years were significantly synchronous ($p \leq 0.01$) among all three subsites, but when analyzing only fire years French Creek 2 and French Creek South were the only subsites significantly synchronous ($p \leq 0.05$) with one another. The Wald-Wolfowitz runs test also found fire dates at French Creek South were significantly synchronous with French Creek High and French Creek 2 ($p \leq 0.05$).

Table 5.6 Results of spatial analyses of fire chronologies developed from ponderosa pine in the French Creek drainage in the Payette National Forest, Idaho. The analyses tested for differences between subsites in mean fire intervals, variance, and distributions and for fire date synchroneity.

	French Creek High	French Creek 2
MFI (|*t*|-value)		
French Creek South	0.9129	–0.1140
French Creek High	--	–0.9064
Variance (F-value)		
French Creek South	1.8073	1.0009
French Creek High	--	1.9280
Distributions (K-S *d*-statistic)		
French Creek South	0.208	0.095
French Creek High	--	0.208
Fire Date Synchroneity		
Chi-squared test, all years		
French Creek South	101.90**	123.37**
French Creek High	--	58.09**
Chi-squared test, only fire years		
French Creek South	2.79	6.11*
French Creek High	--	0.06
Wald-Wolfowitz Runs Test		
French Creek South	19.27*	18.89*
French Creek High	--	11.08

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

5.3.4 Fire seasonality analyses

The majority of fires recorded at all three subsites took place near the end of the growing season, August to October of the fire year (Tables 5.7 and 5.8). None of the subsites had any fires recorded at the very beginning of the growing season, while all subsites did have some fires recorded during the middle portions of the growing season. FC2 recorded the most early season fires (Table 5.8).

5.4 Fire-Tree Growth Relationships

5.4.1 SEA

Superposed epoch analysis (SEA) was conducted on the control chronology, fire site core chronology, and the fire site cross-section chronology using all fire events and filters of minimum 10% and 25% scarred. With all fire events, the control site chronology had significantly narrower rings the year of a fire event ($p < 0.01$, Figure 5.7a). Three years after a fire event (t+3), the rings were narrow, but not significantly. The fire site core chronology and cross-section chronology also showed significantly lower than average tree growth the year of a fire event ($p < 0.05$, Figure 5.7b and c). All three chronologies had a general pattern of mostly above average tree growth in the 10 years prior to a fire event. The fire site core chronology and cross-section chronology had above average tree growth 4 to 5 years after a fire event.

The control site chronology followed a similar pattern after filtering fire events to fire years in which > 10% of recorder trees were scarred (Figure 5.8a). The year of the fire event was still significantly below average growth ($p < 0.05$) and the third year after a

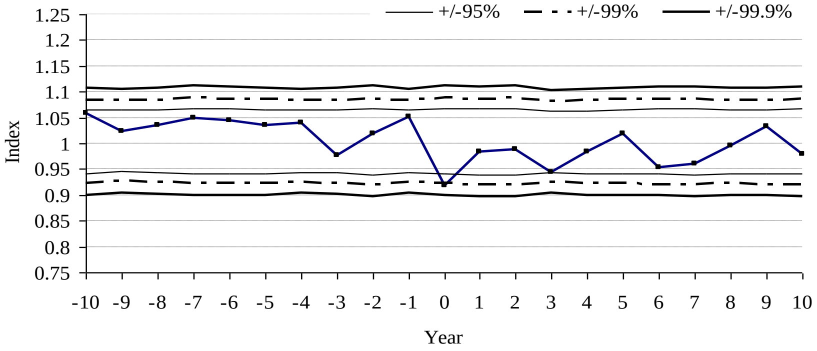
Table 5.7 Fire scar seasonality in ponderosa pine forests in the French Creek drainage in the Payette National Forest, Idaho during the POR.

	Number of Fire Scars (% of total)			
Fire Season	French Creek High	French Creek 2	French Creek South	All Subsites
E: May	0 (0)	0(0)	0 (0)	0 (0)
M: June	2 (2.8)	2 (3.2)	7 (7.9)	11 (4.9)
L: July	11 (15.5)	13 (20.6)	9 (10.1)	33 (14.6)
A: August	31 (43.7)	28 (44.4)	40 (44.9)	100 (44.2)
D: September to October	27 (38)	20 (31.7)	33 (37.1)	82 (36.3)
U: Undetermined	9 (11.3)	14 (18.2)	18 (16.8)	42 (15.7)

Table 5.8 Fire seasonality in ponderosa pine forests in the French Creek drainage in the Payette National Forest, Idaho during the POR. Early season includes fire scars recorded in the earlywood. Late season includes fire scars recorded in the latewood and dormant season. Fire scars for which seasonality was undetermined were not included.

	Early Season (E, M, L)	Late Season (A, D)
French Creek High (n = 71)	18.3%	81.7%
French Creek 2 (n = 63)	23.8%	76.2%
French Creek South (n = 89)	18.0%	82.0%
All Subsites (n = 226)	19.5%	80.5%

a)



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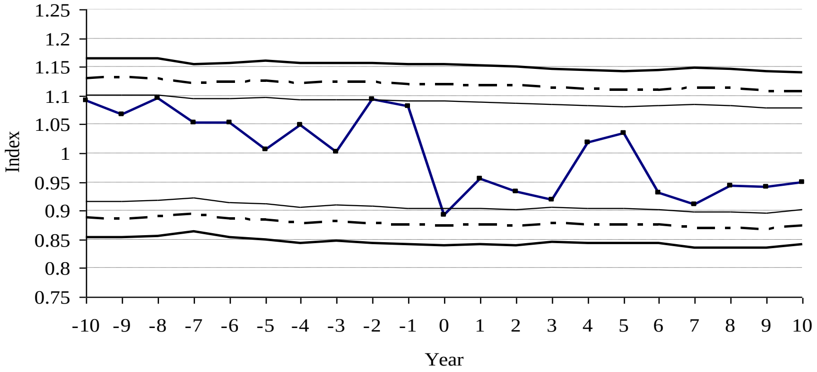

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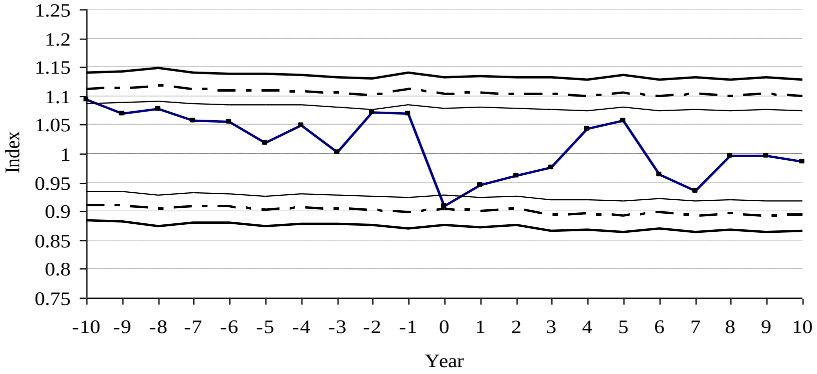

Figure 5.7 Results from superposed epoch analyses of the relationship between all fires and tree growth for the control site chronology (a), the fire site core chronology (b), and the fire site cross-section chronology (c).

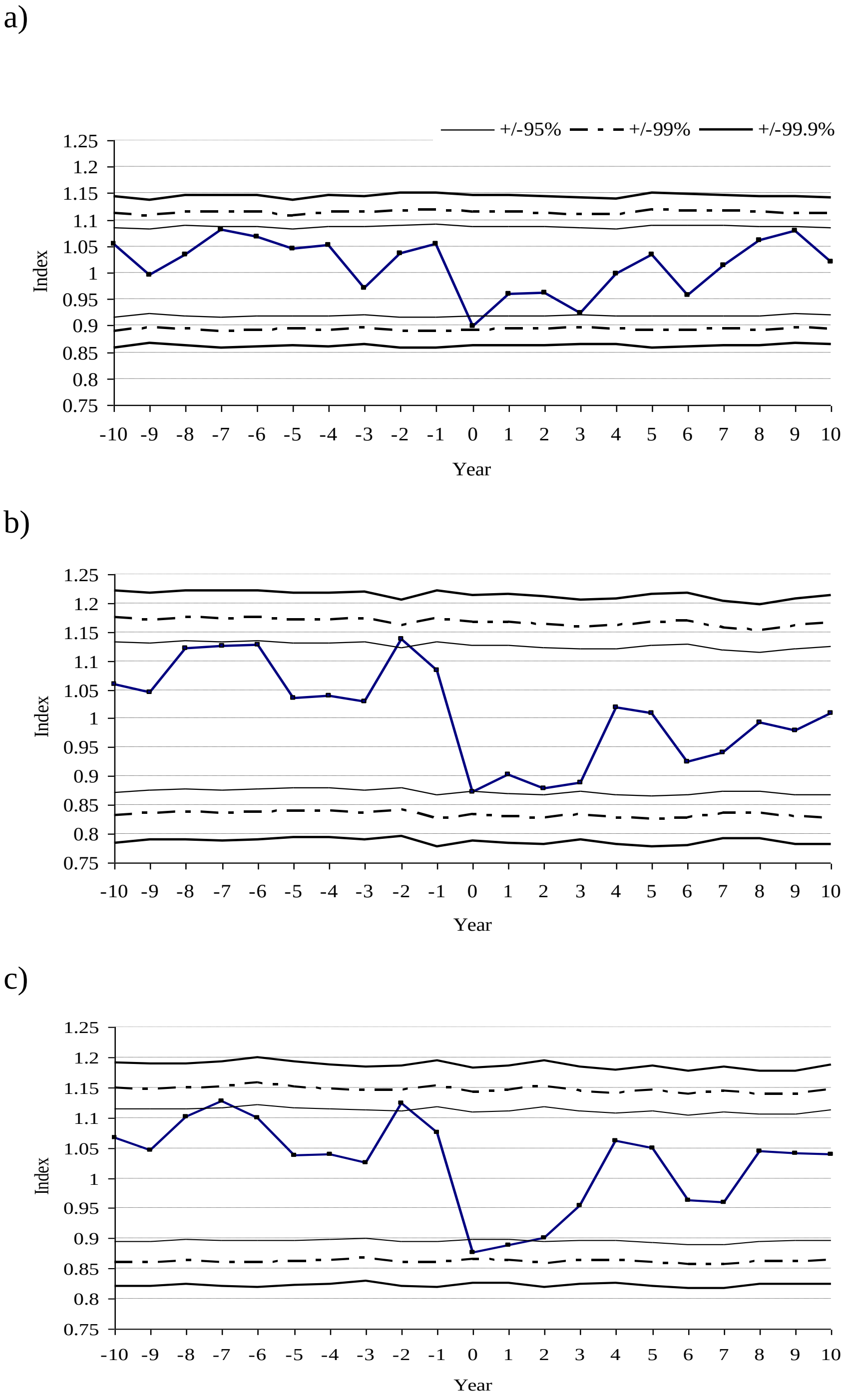

Figure 5.8 Results from superposed epoch analyses of the relationship between fires that scarred >10% of trees and tree growth for the control site chronology (a), the fire site core chronology (b), and the fire site cross-section chronology (c).

fire event (t+3) was again a below average year for tree growth. The fire site cross-section chronology had significantly lower tree growth in the year of the fire ($p < 0.05$), while the fire site core chronology did not, but still showed lower than average tree growth (Figure 5.8b and c). At the fire sites, tree growth was below average for the years after a fire (t+1 to t+3), and significantly so the year after the fire (t+1) for the fire site cross-sections ($p < 0.05$). Tree growth was significantly above average in year t–2 ($p < 0.05$) for the cores and the cross-sections, and year t–7 for the cross-sections ($p < 0.05$).

With the > 25%-scarred fire event class, all three chronologies had above average growth 7 years prior to the fire event (t–7), significantly for the fire cores and sections ($p < 0.05$, Figure 5.9a and c). The control chronology had significantly low growth the year of a fire event ($p < 0.05$). Tree growth was above average 10 years prior to the fire event and below average the three years after a fire event (t+1 to t+3) for the control chronology. The fire site core chronology had significantly above average tree growth in years t–7 and t–6 ($p < 0.05$). Tree growth was also above average 2 years prior to a fire event (t–2). The year of the fire event and the third year after a fire event were below average growth. The fire section chronology had significantly above average growth 7 and 2 years prior to a fire event ($p < 0.05$) and significantly below average growth the year of the fire event and 1 year after ($p < 0.05$). Tree growth remained below average during the second and third years after the fire event.

Comparison of fire events with the Palmer Drought Severity Index (PDSI) illustrated the relationships between climate and fire at the sites. With all fire events, t–9 was significantly wetter than average ($p < 0.05$) but this was likely a spurious result

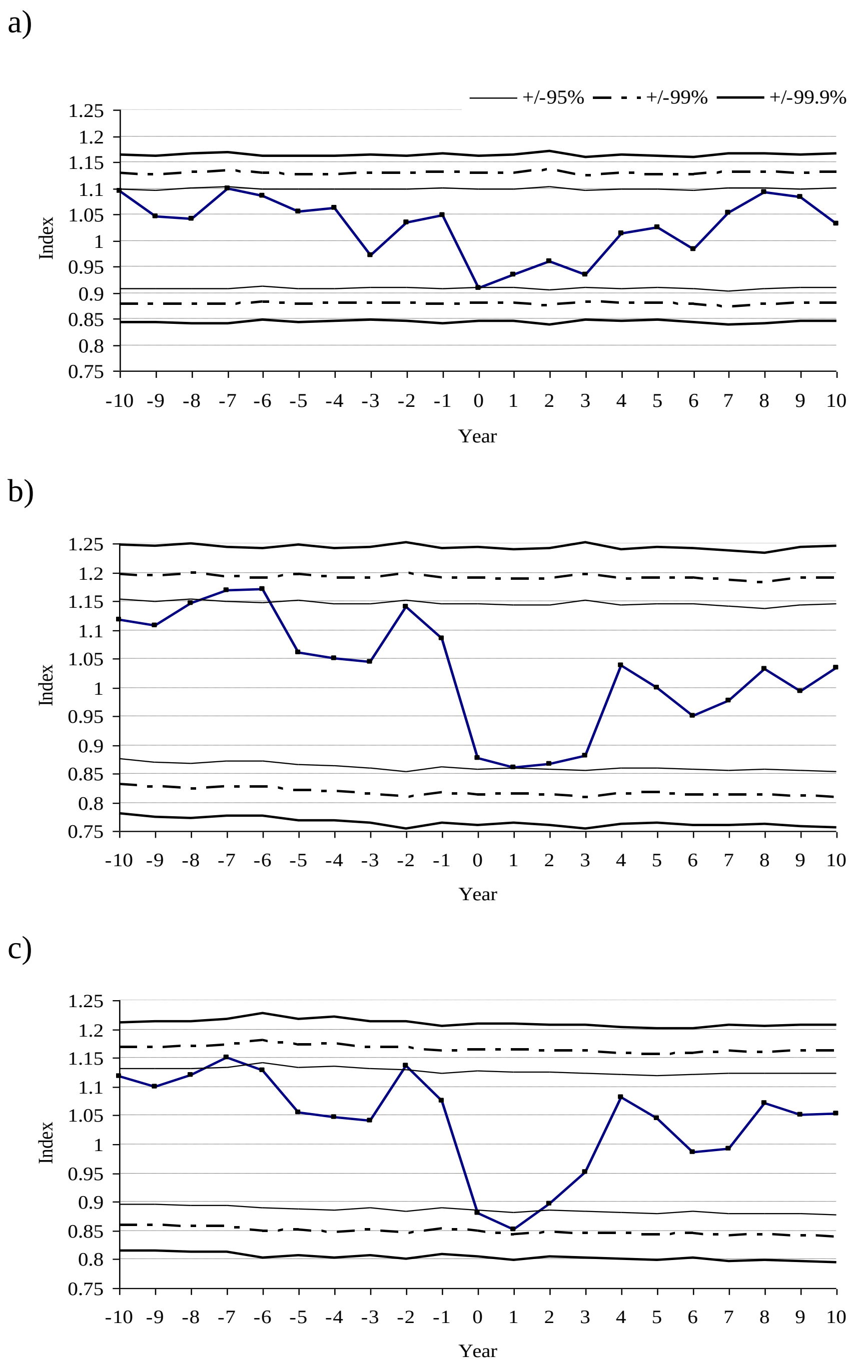

Figure 5.9 Results from superposed epoch analyses of the relationship between fires that scarred >25% of trees and tree growth for the control site chronology (a), the fire site core chronology (b), and the fire site cross-section chronology (c).

related to the cyclic nature of drought and fire occurrence. The year of the fire event was significantly drier than average ($p < 0.001$, Figure 5.10a). The years after a fire event were average. The year of the fire event was significantly drier than average ($p < 0.05$) with the 10%- and 25%-scarred fire event classes (Figure 5.10b and c). Year t–2 was significantly wetter than average in the 10% scarred class. In both of the filtered fire classes, years t+1 and t+2 were average while years t+3 and t+6 were drier than average.

5.4.2 Difference chronologies

Three chronologies were developed from the differences between (1) the Fall Creek Middle (FCM, the control chronology) and the French Creek fire site core chronology, (2) the Fall Creek Middle chronology and French Creek fire site cross-section chronology, and (3) the French Creek fire site core chronology and the French Creek fire site cross-section chronology (Figure 5.11). Each of the difference chronologies was compared with the fire years in which >10% of trees were scarred. Fall Creek Middle and the French Creek core chronology had the most noticeable amount of difference while the French Creek core and cross-section chronologies had the least amount of difference. With both the Fall Creek Middle and French Creek cross-section difference chronology and the Fall Creek Middle and French Creek core difference chronology comparisons, an increased difference is noticeable after many of the fire years.

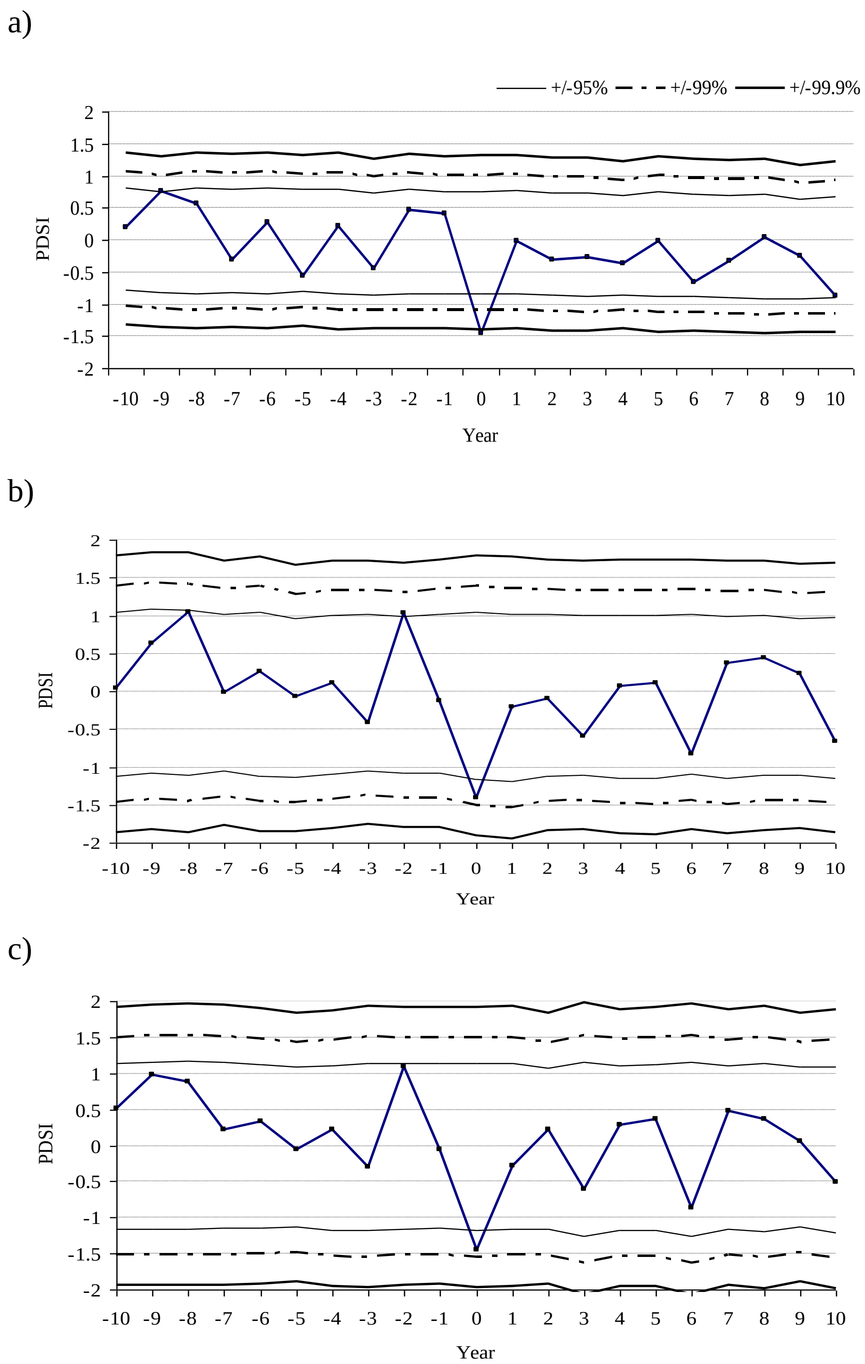

Figure 5.10 Results from superposed epoch analyses of the relationship between fire and PDSI for all fires (a), fires that scarred >10% of trees (b), and fires that scarred >25% of trees (c).

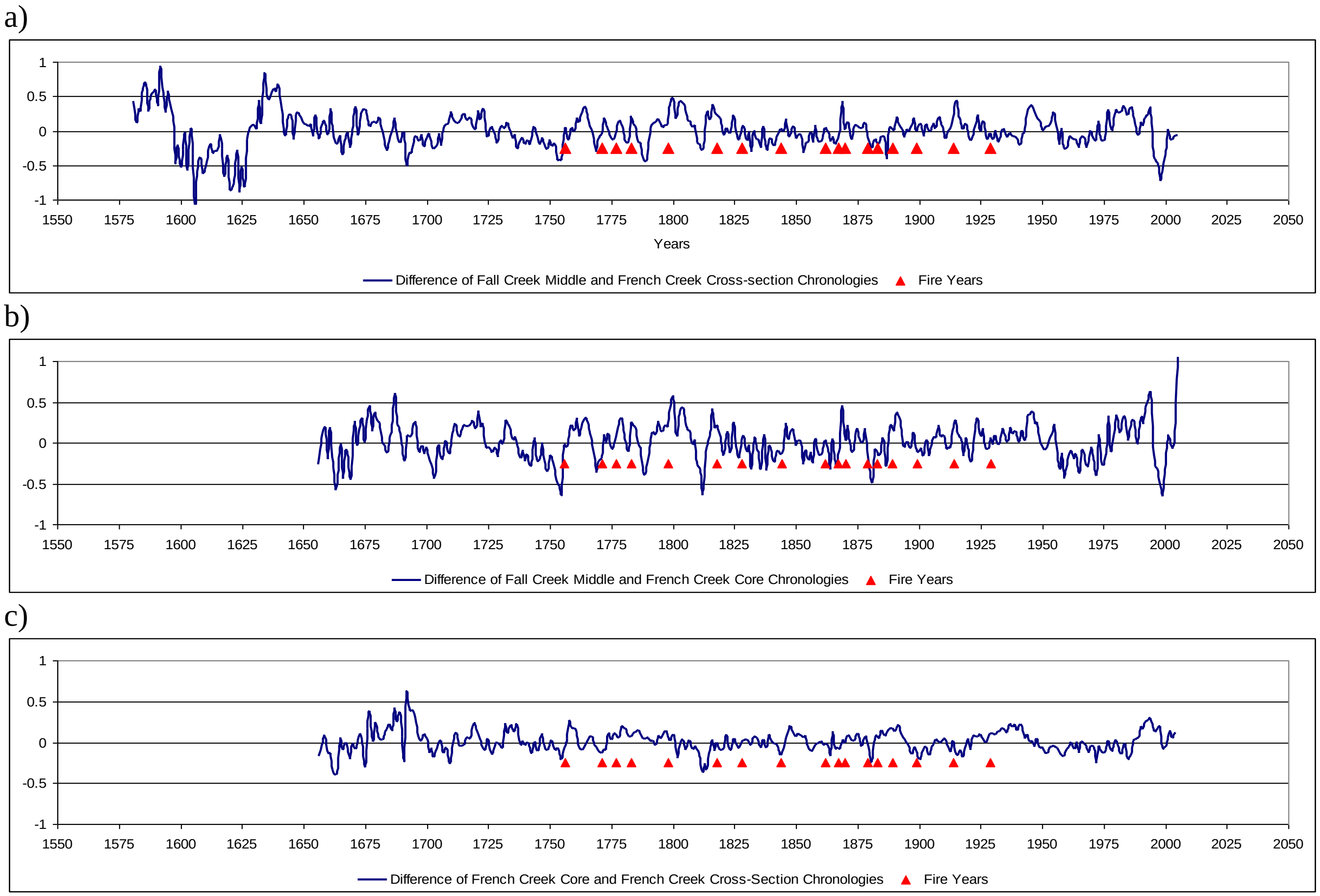

Figure 5.11 Graphs of individual difference chronologies. Fire events that scarred > 10% of trees are indicated by triangles.

a) Difference of Fall Creek Middle chronology and French Creek cross-section chronology.
b) Difference of Fall Creek Middle chronology and French Creek core chronology.
c) Difference of French Creek core chronology and French Creek cross-section chronology.

5.4.3 OUTBREAK

The fire site (French Creek cores and French Creek cross-sections) chronologies were compared to the Fall Creek Middle control site to identify periods of 2 to 4 years with significantly decreased growth using the computer program OUTBREAK (Swetnam *et al.* 1995, Speer *et al.* 2001). The growth depressions were identified as series of 2 to 4 years in which tree growth in the fire site chronology was significantly lower than tree growth in the control chronology. The year with the most decreased growth within each growth depression was also identified. The periods of decreased growth were compared with all fire years within the period of reliability and those fires that scarred >25% of trees. No clear pattern was found between fire years and minimized growth years. After the fire years 1771, 1790, 1798, 1867, and 1914, the French Creek core chronology had several minimal growth years (Figure 6.12). After the fire years 1771, 1790, 1876, 1889, and 1914, the French Creek cross-section chronology showed depressed growth (Figure 6.13). More widespread fires did not appear to cause decreased growth more than the less widespread fires.

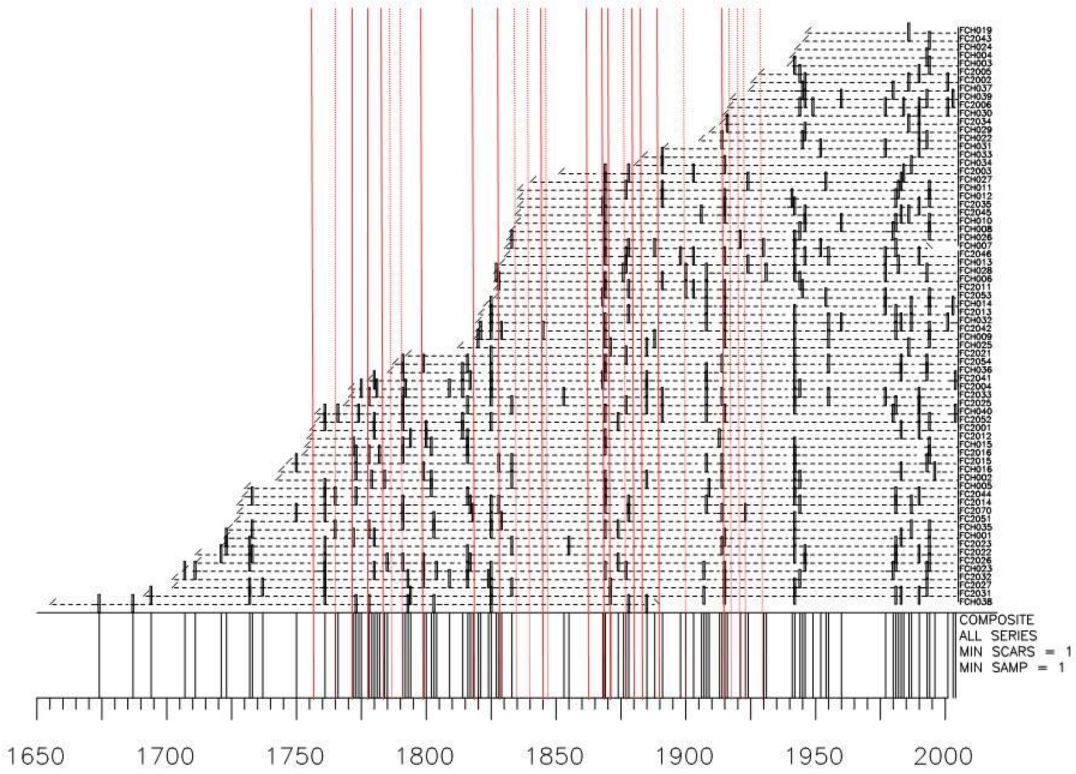

Figure 5.12 OUTBREAK results for the French Creek cores. Periods of decreased growth lasting 2–4 years and the year within each period with the most decreased for individual trees are displayed using FHX2 graphical software. Each horizontal line represents one tree. Solid portions of the line represent periods of decreased growth. Vertical bars indicate the year of most decreased growth within each period. The vertical lines on the composite chronology at the bottom of the chart represent years during which at least one tree within the site recorded a decreased growth year. The red vertical lines represent fire years. Solid red lines are fires which scarred >25% of trees and dashed red lines include all fires within the period of reliability.

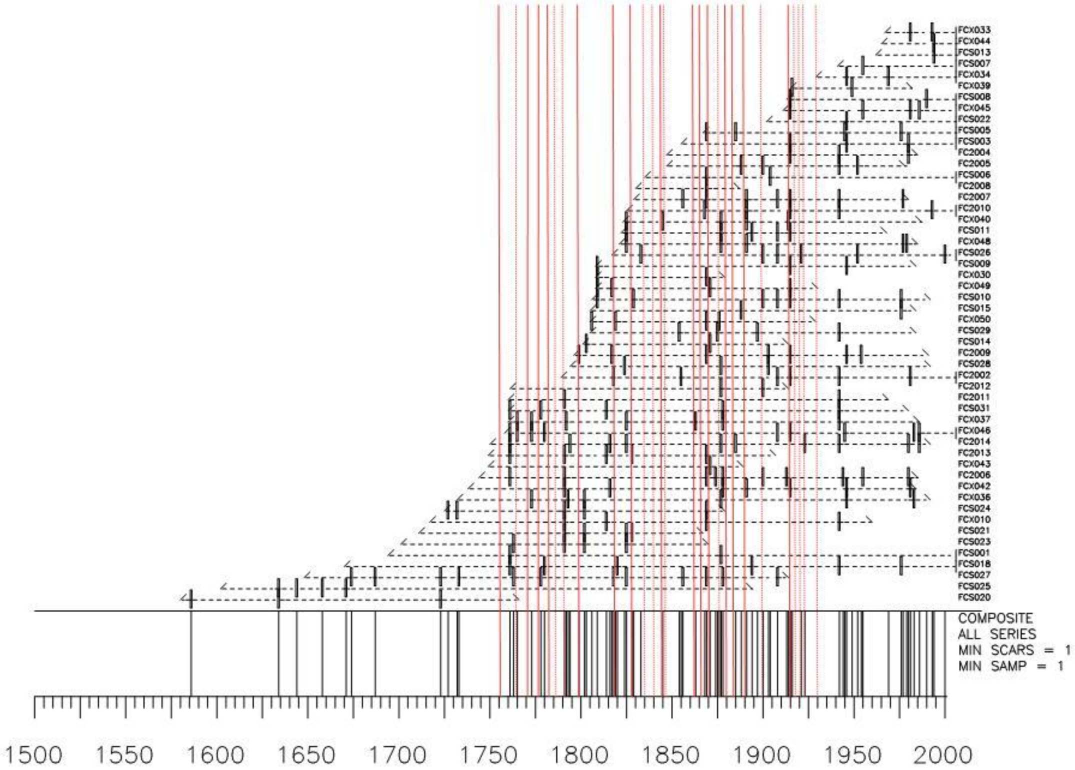

Figure 5.13 OUTBREAK results for the French Creek cross-sections. See Figure 5.12 for an explanation of the symbols used in the chart.

Chapter 6

Discussion, Conclusions, and Future Research

6.1 Crossdating and Chronology Construction

Overall, the three chronologies had comparable or higher mean sensitivities and interseries correlations to those found in other ponderosa pine chronologies in Idaho (Brubaker 1975, Brubaker 1976). The French Creek core chronology had higher interseries correlation and mean sensitivity values than the other Idaho chronologies, while the Fall Creek Middle chronology and the French Creek cross-section chronology were similar to the other Idaho chronologies. The French Creek cross-section chronology and Fall Creek Middle chronology extended the tree-ring record further back in time (to 1581 and 1493, respectively) than other Idaho ponderosa pine chronologies in the International Tree-Ring Data Bank (ITRDB). The interseries correlations of all three chronologies were higher than the minimum 0.40 required as a sign of quality crossdating.

The Fall Creek Middle tree-ring chronology, from the less fire-affected control site, was the longest and oldest chronology of the three. The Fall Creek Middle chronology had a lower mean sensitivity and lower interseries correlation than the French Creek core chronology. Nearing the upper elevational limit of ponderosa pine, the Fall Creek site was more densely covered with trees and less steep than the French Creek site but had a similar west-northwesterly aspect. The lower mean sensitivity and lower interseries correlation of the Fall Creek Middle chronology may be caused by abundant moisture at the higher elevation site, decreased sensitivity to growth limiting factors with increasing tree age, and/or more competition among trees in the denser forest, resulting in a weaker climate signal.

Despite the differences between the chronologies, the Fall Creek site and French Creek sites had common marker rings. These years were most limiting to tree growth, dry years resulting in narrow growth rings, and were common to all the sites. Especially narrow, single-year "marker" rings were formed in 1665, 1783, 1840, and 1865. Series of narrow rings were formed 1756–1757, 1797–1798, 1846–1847, 1889–1891, 1935–1937, and 1973–1974. A slightly narrow ring in 1899 followed by a wide ring in 1900 was found at all sites. These common narrow rings indicate that the trees at Fall Creek and French Creek were experiencing the same climate and responding in similar ways. Many of the marker rings were the same as those found in the NADEF 2005 French Creek chronology (Grissino-Mayer *et al.* 2005), but the tree-ring record developed in my study extended further back in time and had increased sample depth with both the French Creek core and cross-section chronologies. The quality of crossdating was improved, resulting in higher interseries correlations than those found in the NADEF 2005 French Creek chronology.

The chronology created from the French Creek cross-sections showed some differences when compared to the French Creek core chronology, despite the chronologies' origination from the same sites. The French Creek cross-section chronology had lower mean sensitivity and lower interseries correlation compared with the French Creek core chronology. A majority of the French Creek cores were collected from trees at the site that did not have fire scars, whereas every tree sampled for the cross-section chronology contained at least one fire scar and many contained multiple fire scars. Despite care taken during measuring of the cross-sections to avoid the abnormal growth patterns sometimes present near the fire-caused injury, noise caused by the fire injuries may have been introduced into the cross-section chronology. The lower correlation indicated that the noise introduced by the fire injuries is not a systematic signal common to all trees. If all the fire-scarred samples were responding to fire in the same way, the correlation would be expected to be higher.

Although the French Creek cross-section chronology exceeds the minimum interseries correlation for quality crossdating, the differences between the cross-section chronology and the core chronology taken at the same site demonstrates the importance of sampling methods to crossdating quality. The core chronology is of a higher overall quality although it is from the same site. The core chronology was created mostly from trees without fire scars, and unlike the Fall Creek cores, at a site where climate would be more limiting to growth. Simply using the cross-section chronology for a climate study would not yield such robust results.

6.2 Fire History and Statistical Analyses

A more comprehensive picture of fire history at the French Creek site was developed in my study than that of the NADEF 2005 fire history collected at the same site. The NADEF 2005 fire history contained only 11 fire events (Grissino-Mayer *et al.*

2005), compared to 41 fire events in my fire history. A larger overall sample size and an increased study site area resulted in the increased number of fire events recorded.

Some of the samples in the set of 10 fire history samples collected at the 2005 NADEF showed large growth rings after the 1985 and 1992 fire years (Grissino-Mayer *et al.* 2005). The apparent release in growth recorded by these samples appears to have more to do with the lack of fire activity for several decades before those two large fires. It is likely that a buildup of shrubs in the understory occurred after the large 1914 fire. The removal of competing shrubs and/or release of nutrients aided in a large increase in tree growth at the French Creek site. No other fire years in the fire history samples were followed by a similar release.

The results of seasonality analyses indicated a later occurrence of fires than the results of the NADEF 2005 fire history study. Fires occurred mostly in the middle and late earlywood (May–July) in the NADEF 2005 samples, while the French Creek fire history samples contained mostly latewood and dormant season fire scars (August–October). Most fires that occurred in the middle to late earlywood in the French Creek fire history were found at the fire history subsites French Creek 2 and French Creek High, which correspond to those at which the NADEF 2005 samples were collected. The fire history subsite French Creek South had a larger percentage of fires recorded in the latewood and dormant seasons, along with an overall larger share of the total number of fire scars in the fire history, which gives French Creek South more influence on the seasonality analyses for all subsites combined. Differences in seasonality of a fire between the subsites could indicate separate fires within the same year at the subsites or a single fire which burned over several weeks spreading slowly among the subsites.

The fire histories of French Creek 2 (FC2) and French Creek South (FCS) had more similarities when compared to the fire history at French Creek High (FCX). Along a north-south gradient, FCX is the northernmost of the subsites and closest to the Salmon River canyon, FC2 is in the middle, and FCS is the furthest south. FC2 and FCS are closest to one another, resulting in their more similar fire histories. FCX had many patchier fires from the early to mid-1800s and changed to a pattern of fewer but more widespread fires from the late 1800s on. This shift to more widespread fires occurred about the same time that mining activity was vastly expanding in the area, especially along the Salmon River which served as a major travel route. Both FC2 and FCS had frequent widespread fires throughout the 1800s. All three subsites had a period throughout the mid-1900s with very little fire, a result of effective fire suppression. Variability in fire-free intervals was greater at FC2 and FCS than at FCX. The reason for the differences between FCX and the other two subsites may be the drainage separating FCX from FC2 and FCS. The drainage is less exposed and moister than the surrounding area, and may have impeded the spread of fire between the sites. Differences in fuels at the subsites and individual site characteristics of the subsites may be additional reasons for differences in the fire histories of the subsites.

Although there are some differences between the subsite fire histories, I found no statistically significant differences between the fire histories of the subsites in mean fire interval, variance, or distribution. Fire years were synchronous between all three subsites, but particularly at FC2 and FCS. This indicates that fires tended to be widespread, with fires often spreading to all three subsites, and rarely occurred at only one of the subsites.

The French Creek fire history is similar to a nearby fire history study in the Bannock Creek area of the Boise Experimental Forest, also in central Idaho (Brown *et al.* 2005). The study by Brown *et al.* found no fire occurrence after 1890, which the authors attributed to settlement of the area and fire suppression. The French Creek site continued to experience fire into the early 1900s and again in the late 1900s, perhaps as a result of the more isolated location and the less permanent, less dense settlement of the Salmon River area. The French Creek fire history also has more samples obtained from living trees than the Bannock Creek fire history, resulting in greater sample depth in the 1900s. The Bannock Creek study was also divided into three subsites or clusters for spatial analyses. As in the case of French Creek, the three clusters had no significant differences in fire frequency.

The seasonality of fire occurrence at the Bannock Creek site was very similar to the fire seasonality at French Creek. At Bannock Creek, 85% of fires occurred in the latewood or dormant season and none in the early to mid-earlywood. At French Creek, 80.5% of fires occurred in latewood or dormant season, none in the early earlywood, and 4.9% in the mid-earlywood. These results suggest that, historically, fire occurrence in central Idaho has commonly been from July through October, with very few fires occurring earlier in the season.

The mean fire intervals of French Creek and Bannock Creek were similar (7.38 and 8.7, respectably), however caution must be used when comparing the two because the

Bannock Creek fire statistics were for the 10% scarred class, while the French Creek fire statistics were for all fires. The French Creek fire history had a lower Weibull median fire interval of 6.64 years compared to the Weibull median of 8.5 years at Bannock Creek. Both of these are lower than the mean fire interval of 10.3 years found by Steele *et al.* (1986) in the Boise National Forest of central Idaho. The Weibull upper and lower exceedence intervals were also similar between French Creek and Bannock Creek.

6.3 Fire-Tree Growth Relationships

6.3.1 SEA

Typically, superposed epoch analysis (SEA) is conducted to determine whether climate has a forcing effect on fire activity, particularly periods of drought. Fire years and the years prior to the fire are compared with a reconstruction of the local precipitation. Often, fire years occur during particularly dry years preceded by wet years. The wet years lead to a build-up of vegetative material that becomes fuel during a drought year. Rather than compare the fire years with a reconstruction of climate, my SEA results compared fire years with tree growth which is a proxy for moisture availability. Similar to SEA with climate reconstructions, fire years occurred during narrow growth-ring years, indicating drier than average years. The years preceding a fire year were typically above average width. The control site chronology had significantly below average growth during fire years and above average growth during the years preceding fire. Growth during the years preceding fire was more above average for the fire site chronologies than for the control chronology.

Tree growth in the years after a fire was the primary focus to determine whether a fire signal could be present in tree-ring records. According to the SEA results, the only indication of a possible effect of fire on tree growth was below average growth the first three years after a fire. The three years after a fire had below average growth for both small and large fires. Growth three years post-fire was more limited in the fire site chronologies than in the control chronology, but the control chronology also showed below average growth during the three years after a fire year, even though the control site did not have fire-scar evidence of fire occurrence during that year. Below average growth after a fire was only statistically significant ($p < 0.05$) with the 10% and 25% scarred classes of the cross-section chronology. Less noticeably, the fourth and fifth years after a fire tended to be above average in growth. Again, the departure from average was stronger for the fire site chronologies than for the control chronology.

Because the control chronology had similar tree growth patterns in the years after a fire, this suggests that fire years tended to be followed by drier years less favorable to tree growth for the first three years after a fire, and then by wetter years more favorable to tree growth. It is unlikely that the increase in growth four or five years after a fire is related to a fire-caused release in tree growth because above average growth also occurs in the control chronology four to five years after a fire event year. The significantly below average growth of the cross-section chronology indicates that the trees directly affected by the fire did experience a more severe limitation on growth during the years after the fire, but the limitation on growth can not be attributed solely or primarily to the occurrence of a fire a few years before. The decreased growth after a fire event may be localized to the area of the tree near the fire-scar injuries as a sort of abnormal growth pattern near the site of injury. Sampling the fire-scarred trees at different heights along the trunk would confirm this possibility.

When SEA was conducted with the fire years and PDSI, the year of the fire was significantly dry. Years preceding fire had above average moisture. The third and sixth years following a fire were drier than average, but not significantly so. This indicates that below average growth in the chronologies for the years after fire was most likely a result of less favorable growth conditions rather than a fire-induced reduction in tree growth.

6.3.2 Difference chronologies

As would be expected, because they were derived from the same site, the fire site core chronology and fire site cross-section chronology had the smallest differences of the three chronologies. The control site chronology had a greater amount of difference with the fire site core chronology than with the fire site cross-section chronology. I would have expected the greatest difference between the control chronology and the fire site cross-section chronology because the sections came from trees that were affected directly by fire, while the majority of trees sampled for the fire site core chronology did not show external evidence of fire injury. This suggests that the difference between the fire site chronologies and the control chronology could be caused by differences in microsite conditions, or that the climate signal was somehow more corrupted by fire in the core chronology than the cross-section chronology.

Upon visual inspection of the years after fire events, there appears to be a slight increase in difference between the control chronology and the fire site chronologies after many, but not all, fires. Increased differences between the control chronology and fire site chronologies also occurred as often in years that do not follow a fire. While fires may cause changes in tree growth, the effect is not systematic and appears to be comparable to other noise in the chronology.

6.3.3 OUTBREAK

The use of the program OUTBREAK to detect possible growth suppression caused by fires was an exploratory exercise. It is possible that the parameters (significantly suppressed growth for periods 2–4 years in length in comparison with tree growth at the control site) used were not the most ideal. Despite the limitations, some insight into tree growth and fire effects can be gained from these results. The periods of suppressed growth were identified in relation to the control site chronology. Some fire years did appear to cause growth suppression. The percent-scarred class did not seem to be the determining factor for whether a particular fire was associated with lower growth. Between the two fire site chronologies, the cross-section chronology had more possible fire-related growth suppressions than the fire site core chronology. Several 2–4 year growth suppressions not related to fire years were also identified that occurred simultaneously for several trees at the site. These growth suppressions are periods of lower growth in comparison to the control chronology, so they would have to be caused by something specific at the fire site, not related to regional climate. Like the results of the difference chronologies, the changes in tree growth that may be caused by fire do not appear to be systematic and appear to be part of the other noise in the chronology.

6.4 Implications

Fires affect tree growth but not in a clearly identifiable or consistent way. While the years after a fire were generally characterized by narrower growth rings, indicating drier climate, trees with visible damage from fires (the French Creek cross-section chronology) appear to be more limited in their growth during the years following a fire event according to both the SEA and OUTBREAK results. However, there is no consistent pattern to the suppressed growth nor is it statistically significant. The size of the fire also does not appear to be a factor in growth suppression. Additionally, because visibly fire-scarred trees were mostly avoided during sampling, the fire site core chronology contained less of the fire-related growth suppression than the fire site cross-section chronology.

The results reiterate the importance of following the principles of dendrochronology (Fritts 2001). By avoiding trees with visible fire damage, some noise caused by fire events can be avoided for researchers wishing to reconstruct climate. Although technology is rapidly advancing, the importance of visual inspection of dendrochronological samples is also reinforced. Unusual growth patterns should be inspected by the researcher to determine how best to gather the information contained within a particular tree’s growth record.

Because climate reconstructions play a major role in climate research and climate policy, it is paramount that they be as reliable as possible. The reliability of climate reconstructions depends upon a clear understanding of any factors that may affect their interpretation. The French Creek site demonstrates that, while fire may cause a slight introduction of noise into the climate signal, it is not a systematic effect nor is it strong. By continuing to follow accepted dendrochronological methods, any possible effect of fire damage on the climate signal can be greatly minimized.

6.5 Future Research

The potential for further research into the effects of fire on tree growth is great. The growth of ponderosa pines may be affected differently by fire events in other geographical locations in their range and in different forest types. Trees existing near the limits of their range may be more sensitive to the effects of fire so their growth may be more affected by fire events. Other species' tree growth may be affected by fire differently or to a greater degree than ponderosa pine. Species used for climate research, which are also affected by fire, should be studied for any possible fire "signal" in their growth patterns. Additionally, tree growth within an individual tree may be more or less affected by fire depending on location within the tree. Sampling individual trees at different locations could provide more information on fire-tree growth relationships.

Of the analytical methods used to examine fire-tree growth relationships, SEA showed the most promise and appeared to be the most refined. Because SEA compared tree growth with fire years and the years before and after fire events, it should continue to be a valuable tool in the analysis of fire-tree growth relationships, especially because it provides the information along with confidence intervals. Continued use of difference chronologies should corroborate any indications of a “fire signal” found through use of SEA or OUTBREAK. The difference chronologies are a simple tool to highlight and evaluate the differences between chronologies. Further exploration with the use of OUTBREAK could provide more information on fire-tree growth relationships. By experimenting with different settings, OUTBREAK could become more useful in evaluating the relationship between tree growth and fire events.

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Appendices

Appendix A1. Correlation of series by segments for French Creek core samples.

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Correlations of  50-year dated segments, lagged  25 years
 Flags:  A = correlation under   .3281 but highest as dated;  B = correlation higher at other than dated position

 Seq Series   Time_span   1650 1675 1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975
                          1699 1724 1749 1774 1799 1824 1849 1874 1899 1924 1949 1974 1999 2024
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   1 FCH037A  1953 2004                                                              .73  .72
   2 FCH019B  1952 2004                                                              .77  .75
   3 FC2045B  1950 2004                                                              .47  .49
   4 FC2043A  1949 2004                                                         .66  .67  .68
   5 FCH019A  1947 2004                                                         .66  .70  .73
   6 FC2043B  1946 2004                                                         .66  .74  .74
   7 FCH024B  1945 2004                                                         .41B .53  .55
   8 FCH024A  1943 2004                                                         .71  .74  .73
   9 FCH004B  1943 2004                                                         .63  .71  .73
  10 FCH004A  1941 2004                                                         .74  .77  .80
  11 FCH003A  1940 2004                                                         .60  .60  .57
  12 FC2002A  1935 2004                                                         .60  .57  .55
  13 FC2005A  1930 2004                                                         .73  .76  .78
  14 FC2006B  1930 2004                                                         .70  .75  .78
  15 FC2005B  1929 2004                                                         .80  .84  .85
  16 FC2002B  1926 2004                                                         .65  .59  .61
  17 FCH037B  1925 2004                                                         .70  .68  .68
  18 FCH022B  1923 2004                                                    .81  .85  .87  .87
  19 FCH039A  1919 2004                                                    .66  .66  .66  .63
  20 FCH039B  1918 2004                                                    .56  .61  .74  .73
  21 FC2006A  1917 2004                                                    .59  .63  .74  .78
  22 FCH029B  1917 2004                                                    .64  .66  .66  .68
  23 FC2034B  1915 2004                                                    .43  .65  .69  .72
  24 FCH030A  1915 2004                                                    .73  .73  .74  .75
  25 FCH030B  1915 2004                                                    .58  .54  .60  .61
  26 FC2034A  1914 2004                                                    .54  .67  .45  .45
  27 FCH029A  1910 2004                                                    .65  .60  .66  .67
  28 FCH022A  1906 1992                                                    .66  .79  .72
```

Appendix A1. *Continued.*

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Seq Series  Time_span   1650 1675 1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975
                        1699 1724 1749 1774 1799 1824 1849 1874 1899 1924 1949 1974 1999 2024
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 29 FCH033B  1899 2004                                                .67  .69  .86  .77  .77
 30 FCH031B  1898 2004                                                .65  .65  .69  .72  .73
 31 FCH031A  1892 2004                                                .60  .69  .77  .85  .85
 32 FCH034A  1884 2004                                                .55  .74  .77  .74  .75
 33 FCH034B  1881 2004                                                .50  .70  .78  .79  .78
 34 FC2004B  1881 2004                                                .63  .69  .78  .72  .73
 35 FC2003A  1869 2004                                           .63  .63  .64  .77  .78  .83
 36 FC2045C  1864 2004                                           .84  .74  .52  .55  .48  .49
 37 FC2003B  1852 2004                                           .73  .67  .71  .80  .83  .81
 38 FCH011A  1847 2004                                      .73  .73  .74  .73  .68  .66  .63
 39 FCH028A  1844 2004                                      .81  .81  .63  .50  .66  .73  .72
 40 FCH033A  1884 2004                                                .49  .72  .74  .69  .68
 41 FCH012B  1843 2004                                      .81  .79  .68  .72  .64  .49  .47B
 42 FC2011B  1842 2004                                      .86  .87  .84  .81  .81  .78  .78
 43 FCH032B  1841 2004                                      .82  .83  .76  .69  .69  .66  .66
 44 FCH027B  1841 2004                                      .83  .83  .75  .79  .82  .80  .81
 45 FCH010A  1840 2004                                      .81  .83  .77  .80  .66  .58  .58
 46 FCH008B  1837 2004                                      .79  .80  .73  .53  .58  .72  .70
 47 FCH011B  1836 2004                                      .78  .73  .77  .84  .80  .78  .79
 48 FCH012A  1836 2004                                      .82  .80  .71  .71  .63  .52  .54
 49 FC2053B  1836 2004                                      .68  .75  .80  .79  .74  .74  .76
 50 FCH006B  1836 1985                                      .71  .73  .54  .65  .70  .71
 51 FC2035B  1836 2004                                      .47  .71  .76  .74  .73  .78  .78
 52 FCH026B  1835 2004                                      .80  .83  .54  .20B .44  .56  .55
 53 FC2016B  1835 2004                                      .70  .78  .74  .58  .52  .61  .60
 54 FC2042B  1835 2004                                      .65  .88  .80  .79  .81  .67  .65
 55 FCH010B  1835 2004                                      .70  .68  .73  .79  .51  .50  .50
 56 FC2045A  1835 2004                                      .55  .68  .57  .63  .50  .39  .38
 57 FCH008A  1833 2004                                      .85  .79  .70  .73  .73  .69  .66
 58 FC2046B  1833 2004                                      .65  .71  .70  .78  .76  .72  .72
 59 FCH026A  1832 2004                                      .79  .84  .51  .46  .66  .65  .67
 60 FCH009B  1832 2004                                      .79  .76  .73  .76  .75  .68  .67
```

Appendix A1. *Continued.*

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Seq Series  Time_span   1650 1675 1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975
                        1699 1724 1749 1774 1799 1824 1849 1874 1899 1924 1949 1974 1999 2024
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 61 FCH007B  1831 1994                                      .70  .80  .80  .75  .74  .68
 62 FC2046A  1831 2004                                      .60  .78  .74  .77  .78  .76  .75
 63 FCH013B  1829 2004                                      .76  .77  .78  .45  .35  .60  .63
 64 FCH016A  1828 1985                                      .73  .62  .57  .62  .57  .43
 65 FCH028B  1827 2004                                      .82  .86  .66  .57  .73  .71  .65
 66 FC2053A  1827 2004                                      .54  .74  .84  .81  .77  .73  .75
 67 FC2011A  1827 2004                                      .77  .84  .80  .80  .80  .77  .77
 68 FCH006C  1921 2004                                                     .71  .72  .59  .64
 69 FCH006A  1827 1918                                      .67  .79  .52
 70 FCH014A  1823 2004                                 .72  .70  .69  .50  .56  .68  .66  .65
 71 FCH025B  1823 2004                                 .80  .81  .78  .68  .51  .55  .56  .57
 72 FC2013B  1821 2004                                 .59  .58  .64  .75  .71  .57  .45  .49
 73 FC2001A  1821 2004                                 .69  .82  .71  .67  .75  .85  .87  .87
 74 FC2042A  1820 2004                                 .59  .78  .86  .87  .87  .87  .80  .80
 75 FCH032A  1820 2004                                 .66  .67  .73  .75  .54  .33  .37  .39
 76 FC2021B  1820 2004                                 .74  .73  .73  .56  .40  .58  .61  .62
 77 FCH009A  1819 2004                                 .56  .76  .83  .76  .78  .87  .71  .71
 78 FC2025B  1814 2004                                 .63  .74  .84  .73  .72  .70  .63  .62
 79 FCH025A  1813 2004                                 .65  .69  .65  .78  .70  .46  .53  .54
 80 FCH036A  1922 2004                                                     .64  .68  .63  .68
 81 FCH036C  1812 1920                                 .78  .86  .78  .75
 82 FCH035B  1794 2004                            .80  .84  .77  .63  .63  .71  .72  .68  .68
 83 FC2021A  1793 2004                            .76  .74  .73  .80  .75  .47  .40  .46  .45
 84 FC2054B  1791 2004                            .81  .79  .84  .83  .68  .66  .76  .70  .70
 85 FC2054A  1788 2004                            .68  .74  .85  .83  .77  .78  .69  .64  .68
 86 FCH036B  1872 2004                                           .68  .73  .75  .68  .67  .78
 87 FCH036D  1786 1870                            .81  .87  .80
 88 FC2033A  1782 2004                            .82  .84  .71  .48  .46  .69  .83  .78  .81
 89 FCH015A  1780 2004                            .55  .56  .63  .63  .70  .75  .78  .51  .48
 90 FC2041A  1778 2004                            .81  .84  .61  .60  .82  .83  .82  .80  .82
 91 FC2052B  1774 2004                       .50  .54  .62  .52  .55  .56  .57  .72  .72  .75
 92 FC2004A  1771 2004                       .40  .43  .77  .74  .72  .71  .72  .72  .70  .70
 93 FC2033B  1771 1984                       .75  .75  .82  .78  .64  .48  .56  .61  .63
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Appendix A1. *Continued.*

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Seq Series  Time_span   1650 1675 1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975
                        1699 1724 1749 1774 1799 1824 1849 1874 1899 1924 1949 1974 1999 2024
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 94 FC2023B  1770 2004                       .30A .28A .64  .67  .75  .77  .74  .69  .63  .63
 95 FC2025A  1769 2004                       .79  .83  .71  .78  .86  .74  .76  .79  .74  .75
 96 FC2012A  1765 2004                       .66  .71  .68  .64  .67  .70  .67  .82  .87  .89
 97 FCH040B  1916 2004                                                     .67  .71  .73  .74
 98 FCH040C  1852 1914                                           .86  .83
 99 FCH040D  1762 1850                       .67  .80  .78  .74
100 FC2015B  1761 1991                       .74  .79  .82  .87  .80  .67  .68  .68  .61
101 FC2052A  1758 2004                       .41  .45  .50  .35  .56  .74  .68  .70  .71  .77
102 FCH040A  1757 2004                       .51  .79  .83  .89  .83  .78  .79  .74  .76  .75
103 FC2001B  1756 2004                       .34  .55  .78  .80  .82  .79  .73  .80  .82  .84
104 FC2012B  1755 2004                       .73  .74  .69  .61  .68  .75  .76  .85  .84  .85
105 FCH015B  1754 2004                       .69  .63  .65  .67  .41  .48  .66  .74  .76  .72
106 FC2016A  1753 2004                       .61  .52  .33  .35  .56  .71  .75  .52  .52  .55
107 FCH002B  1751 2004                       .71  .56  .75  .81  .82  .69  .67  .68  .73  .74
108 FCH005A  1751 2004                       .78  .58  .54  .59  .68  .77  .78  .63  .58  .59
109 FC2044B  1751 1993                       .60  .78  .81  .86  .90  .82  .72  .66  .55
110 FC2022A  1747 1969                  .76  .76  .76  .71  .64  .53  .50  .68  .67
111 FC2015A  1747 2004                  .43B .51  .67  .70  .84  .80  .63  .69  .75  .67  .67
112 FC2014A  1744 1984                  .87  .86  .81  .68  .62  .73  .68  .60  .78  .74
113 FCH016B  1744 2004                  .51  .55  .51  .67  .75  .65  .51  .51  .56  .34  .33
114 FCH002A  1743 2004                  .42  .28B .52  .76  .87  .85  .75  .79  .87  .86  .84
115 FCH023A  1739 2004                  .77  .82  .83  .85  .90  .89  .81  .74  .71  .72  .75
116 FC2031A  1734 2004                  .84  .76  .82  .80  .76  .79  .54  .53  .63  .67  .67
117 FCH005B  1731 2004                  .67  .69  .60  .76  .71  .66  .70  .77  .73  .70  .72
118 FC2070B  1730 2004                  .23B .66  .75  .65  .68  .70  .48  .51  .65  .70  .72
119 FC2044A  1730 2004                  .71  .67  .76  .87  .85  .82  .70  .65  .67  .67  .65
120 FC2026A  1729 2004                  .73  .80  .64  .60  .77  .84  .75  .76  .76  .77  .78
121 FC2070A  1728 2004                  .52  .65  .72  .75  .75  .73  .68  .58  .53  .65  .69
122 FC2014B  1728 2004                  .73  .78  .86  .82  .81  .82  .74  .73  .78  .79  .79
123 FCH001A  1727 2004                  .72  .71  .64  .73  .75  .80  .72  .44  .37  .55  .59
124 FC2051B  1727 2004                  .58  .71  .82  .80  .78  .80  .74  .59  .59  .60  .59
125 FCH035A  1724 2004             .72  .75  .82  .85  .89  .89  .86  .75  .71  .72  .71  .69
126 FCH001B  1723 2004             .60  .61  .68  .59  .64  .71  .71  .64  .73  .75  .69  .70
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Appendix A1. *Continued.*

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Seq Series  Time_span   1650 1675 1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975
                        1699 1724 1749 1774 1799 1824 1849 1874 1899 1924 1949 1974 1999 2024
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127 FC2023A  1722 2004             .63  .63  .63  .60  .52  .60  .80  .79  .76  .83  .81  .81
128 FC2032B  1714 2004             .42  .73  .83  .86  .88  .82  .80  .76  .66  .63  .68  .71
129 FC2027B  1712 2004             .65  .67  .74  .69  .72  .65  .68  .62  .45  .57  .66  .65
130 FC2022B  1712 2004             .76  .74  .73  .68  .69  .64  .69  .80  .71  .77  .78  .76
131 FC2026B  1712 2004             .72  .74  .81  .73  .71  .69  .69  .69  .69  .73  .72  .72
132 FCH023B  1707 2004             .79  .77  .79  .81  .85  .88  .82  .75  .72  .65  .62  .68
133 FC2027A  1703 2004             .43  .40  .72  .71  .73  .78  .77  .65  .53  .67  .76  .76
134 FC2032A  1703 2004             .74  .77  .79  .84  .87  .78  .67  .68  .67  .68  .68  .69
135 FC2031B  1692 2004        .59  .60  .78  .84  .83  .82  .79  .73  .64  .57  .61  .73  .73
136 FCH038A  1663 1851   .73  .73  .76  .72  .77  .77  .69  .66
137 FCH038B  1656 1889   .68  .64  .54  .71  .80  .80  .76  .75  .77
Av segment correlation   .71  .65  .64  .66  .67  .70  .72  .73  .75  .69  .67  .69  .68  .69
```

Appendix A2. Descriptive statistics for French Creek core samples.

```
                                               Corr  //-------- Unfiltered --------\\   //---- Filtered -----\\
                          No.    No.    No.    with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
Seq Series   Interval   Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
  1 FCH037A  1953 2004     52      2      0    .721   3.33   8.31  1.365   .650   .256   2.54   .466  -.052   1
  2 FCH019B  1952 2004     53      2      0    .777   4.49   8.80  2.171   .673   .470   2.52   .475   .039   1
  3 FC2045B  1950 2004     55      2      0    .491   2.15   3.81   .632   .542   .250   2.48   .431   .049   1
  4 FC2043A  1949 2004     56      3      0    .682   3.22   8.48  1.504   .697   .390   2.58   .549  -.097   1
  5 FCH019A  1947 2004     58      3      0    .670   4.60   8.70  2.072   .668   .361   2.65   .537   .026   1
  6 FC2043B  1946 2004     59      3      0    .685   4.61  10.70  2.212   .680   .379   2.57   .554   .020   1
  7 FCH024B  1945 2004     60      3      1    .456   4.96   9.73  2.029   .629   .283   2.80   .476   .074   2
  8 FCH024A  1943 2004     62      3      0    .718   4.63  11.22  2.200   .714   .255   2.61   .475  -.059   1
  9 FCH004B  1943 2004     62      3      0    .661   4.41   7.20  1.524   .729   .219   2.56   .422   .008   1
 10 FCH004A  1941 2004     64      3      0    .770   4.61   9.58  1.511   .645   .226   2.50   .521  -.034   1
 11 FCH003A  1940 2004     65      3      0    .600   2.93   6.02  1.293   .746   .271   2.59   .457  -.066   2
 12 FC2002A  1935 2004     70      3      0    .560   2.02   4.11   .900   .702   .302   2.67   .574  -.078   1
 13 FC2005A  1930 2004     75      3      0    .749   3.91   6.63  1.405   .608   .258   2.58   .487  -.063   1
 14 FC2006B  1930 2004     75      3      0    .717   4.14   8.06  1.653   .473   .352   2.66   .503   .023   1
 15 FC2005B  1929 2004     76      3      0    .801   4.33   7.49  1.491   .526   .281   2.64   .520  -.031   3
 16 FC2002B  1926 2004     79      3      0    .631   2.16   4.30  1.019   .777   .300   2.48   .507  -.049   1
 17 FCH037B  1925 2004     80      3      0    .690   3.92   6.66  1.340   .621   .252   2.62   .604  -.076   1
 18 FCH022B  1923 2004     82      4      0    .853   3.25   6.39  1.372   .708   .363   2.47   .417  -.043   1
 19 FCH039A  1919 2004     86      4      0    .679   3.40   6.18  1.174   .596   .255   2.67   .578   .048   1
 20 FCH039B  1918 2004     87      4      0    .680   3.53   6.16  1.300   .597   .266   2.82   .583  -.010   2
 21 FC2006A  1917 2004     88      4      0    .698   3.26   6.51  1.325   .534   .327   2.56   .512  -.041   1
 22 FCH029B  1917 2004     88      4      0    .694   3.47   8.49  1.594   .674   .350   2.62   .478  -.044   1
 23 FC2034B  1915 2004     90      4      0    .577   2.41   5.54  1.322   .817   .322   2.59   .542  -.017   1
 24 FCH030A  1915 2004     90      4      0    .752   2.64   4.61   .930   .654   .262   2.74   .543   .026   1
 25 FCH030B  1915 2004     90      4      0    .640   2.78   5.48  1.089   .650   .260   2.74   .459  -.013   1
 26 FC2034A  1914 2004     91      4      0    .483   3.01   6.23  1.221   .649   .263   2.45   .328  -.063   1
 27 FCH029A  1910 2004     95      4      0    .661   2.79   7.94  1.260   .720   .255   2.90   .524   .001   1
 28 FCH022A  1906 1992     87      3      0    .713   2.76   4.53   .971   .646   .253   2.50   .430  -.034   1
 29 FCH033B  1899 2004    106      5      0    .711   2.81   6.00  1.073   .410   .303   2.98   .581   .016   1
 30 FCH031B  1898 2004    107      5      0    .677   2.81   8.10  1.476   .876   .217   2.49   .405   .014   5
 31 FCH031A  1892 2004    113      5      0    .735   2.44   6.02  1.452   .924   .199   2.53   .376  -.005   1
 32 FCH034A  1884 2004    121      5      0    .673   2.15   4.83   .898   .523   .336   2.72   .506  -.034   1
 33 FCH034B  1881 2004    124      5      0    .630   2.53   6.34  1.418   .726   .373   2.71   .426   .045   1
 34 FC2004B  1881 2004    124      5      0    .696   1.74   5.56   .822   .678   .319   2.58   .572   .022   1
 35 FC2003A  1869 2004    136      6      0    .717    .75   1.54   .314   .625   .296   2.62   .408  -.048   2
 36 FC2045C  1864 2004    141      6      0    .597   2.33   5.91  1.028   .765   .253   2.49   .366   .004   3
```

Appendix A2. *Continued.*

```
                                            Corr  //-------- Unfiltered --------\\  //---- Filtered -----\\
                        No.    No.    No.   with   Mean   Max     Std   Auto   Mean   Max    Std   Auto  AR
Seq Series   Interval  Years  Segmt  Flags  Master msmt   msmt    dev   corr   sens  value   dev   corr  ()
--- -------- --------- -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
 37 FC2003B  1852 2004   153      6      0    .732   .75   1.70   .283   .436   .311   2.63   .378  -.019   3
 38 FCH011A  1847 2004   158      7      0    .708  1.32   3.40   .793   .876   .302   2.60   .474   .009   1
 39 FCH028A  1844 2004   161      7      0    .696  2.63   6.92  1.533   .850   .266   2.60   .462   .015   1
 40 FCH033A  1884 2004   121      5      0    .620  2.11   5.22   .901   .646   .287   2.66   .450   .004   1
 41 FCH012B  1843 2004   162      7      1    .686  1.56   4.49  1.017   .756   .399   2.64   .409   .026   1
 42 FC2011B  1842 2004   163      7      0    .816  2.24   5.10  1.160   .768   .299   2.55   .487   .032   1
 43 FCH032B  1841 2004   164      7      0    .730  2.56   5.56  1.090   .479   .354   2.83   .521   .002   1
 44 FCH027B  1841 2004   164      7      0    .804  1.96   5.35  1.058   .769   .326   2.69   .465  -.024   2
 45 FCH010A  1840 2004   165      7      0    .737  2.12   6.79  1.579   .874   .308   2.45   .339   .003   3
 46 FCH008B  1837 2004   168      7      0    .696  1.38   5.66  1.311   .856   .326   2.58   .410   .002   1
 47 FCH011B  1836 2004   169      7      0    .786  1.65   4.21   .907   .823   .299   2.43   .338   .038   1
 48 FCH012A  1836 2004   169      7      0    .722  1.84   5.22  1.125   .757   .342   2.56   .380  -.025   1
 49 FC2053B  1836 2004   169      7      0    .715  1.66   5.31   .840   .722   .296   2.77   .452   .092   1
 50 FCH006B  1836 1985   150      6      0    .697  1.44   3.72   .796   .738   .334   2.52   .407   .038   1
 51 FC2035B  1836 2004   169      7      0    .664  2.53   5.90  1.071   .678   .295   2.48   .303   .010   1
 52 FCH026B  1835 2004   170      7      1    .611  2.04   6.79  1.454   .815   .372   2.60   .318   .023   1
 53 FC2016B  1835 2004   170      7      0    .637  1.53   5.18   .789   .709   .285   2.70   .421  -.021   1
 54 FC2042B  1835 2004   170      7      0    .694  1.61   4.14   .757   .738   .285   2.53   .429   .088   2
 55 FCH010B  1835 2004   170      7      0    .663  1.52   5.58  1.204   .871   .302   2.62   .495   .024   1
 56 FC2045A  1835 2004   170      7      0    .525  2.29   5.92  1.057   .787   .244   2.63   .449   .020   2
 57 FCH008A  1833 2004   172      7      0    .752  2.25  10.71  1.747   .834   .338   2.80   .490  -.035   1
 58 FC2046B  1833 2004   172      7      0    .708  1.93   6.84  1.308   .782   .324   2.61   .411   .031   1
 59 FCH026A  1832 2004   173      7      0    .677  2.25   8.09  1.385   .776   .355   2.55   .429   .005   1
 60 FCH009B  1832 2004   173      7      0    .741  1.83   6.33  1.076   .792   .288   2.73   .442   .011   1
 61 FCH007B  1831 1994   164      6      0    .722  1.99   6.73  1.359   .794   .399   2.61   .420   .050   1
 62 FC2046A  1831 2004   174      7      0    .705  1.94   7.09  1.329   .868   .295   2.67   .370   .030   1
 63 FCH013B  1829 2004   176      7      0    .678  1.55   6.38  1.334   .873   .421   2.53   .340   .001   2
 64 FCH016A  1828 1985   158      6      0    .629  1.26   3.96   .660   .691   .359   2.70   .427   .009   1
 65 FCH028B  1827 2004   178      7      0    .732  2.44   7.63  1.712   .877   .289   2.60   .447  -.003   1
 66 FC2053A  1827 2004   178      7      0    .709  1.96   7.82   .986   .776   .265   2.69   .430   .074   1
 67 FC2011A  1827 2004   178      7      0    .786  2.60   6.05  1.341   .773   .288   2.46   .392   .026   1
 68 FCH006C  1921 2004    84      4      0    .671  1.21   2.89   .407   .291   .318   2.77   .516  -.044   1
 69 FCH006A  1827 1918    92      3      0    .532  2.24   4.93  1.048   .752   .301   2.54   .388   .043   1
 70 FCH014A  1823 2004   182      8      0    .663  1.74   5.35  1.107   .785   .374   2.69   .316  -.022   1
 71 FCH025B  1823 2004   182      8      0    .640  1.62   4.54   .868   .636   .347   2.72   .443   .013   1
 72 FC2013B  1821 2004   184      8      0    .625  1.64   3.81   .822   .728   .322   2.97   .449   .042   1
```

Appendix A2. *Continued.*

```
                                                 Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                             No.    No.    No.   with   Mean    Max    Std   Auto   Mean    Max    Std   Auto  AR
Seq Series   Interval      Years  Segmt  Flags  Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------     -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
 73 FC2001A  1821 2004      184      8      0    .756    .89   2.28   .442   .652   .368   2.61   .376   .003   1
 74 FC2042A  1820 2004      185      8      0    .757   1.97   5.13   .981   .791   .275   2.55   .381   .003   1
 75 FCH032A  1820 2004      185      8      0    .566   1.96   5.51   .993   .612   .344   2.89   .432   .060   1
 76 FC2021B  1820 2004      185      8      0    .619   1.83   8.30  1.283   .861   .262   2.66   .497  -.056   1
 77 FCH009A  1819 2004      186      8      0    .690   2.13   7.01  1.392   .830   .289   2.63   .422  -.021   1
 78 FC2025B  1814 2004      191      8      0    .709   1.55   4.89   .916   .806   .316   2.77   .481  -.020   1
 79 FCH025A  1813 2004      192      8      0    .639   1.43   5.30   .768   .641   .321   2.65   .401  -.012   1
 80 FCH036A  1922 2004       83      4      0    .664    .95   3.30   .657   .750   .402   2.69   .435  -.014   1
 81 FCH036C  1812 1920      109      4      0    .769   1.94   4.13   .728   .483   .320   2.78   .480   .044   2
 82 FCH035B  1794 2004      211      9      0    .711   1.54   3.75   .652   .471   .378   2.78   .444  -.005   1
 83 FC2021A  1793 2004      212      9      0    .624   1.66   7.40   .973   .791   .296   2.82   .383  -.015   1
 84 FC2054B  1791 2004      214      9      0    .754   1.25   4.13   .671   .816   .275   2.69   .430   .032   1
 85 FC2054A  1788 2004      217      9      0    .753   1.09   3.40   .670   .837   .302   2.49   .352  -.004   2
 86 FCH036B  1872 2004      133      6      0    .748    .89   2.16   .495   .686   .434   2.61   .379   .028   1
 87 FCH036D  1786 1870       85      3      0    .777   2.14   4.52   .910   .567   .358   2.64   .457  -.016   1
 88 FC2033A  1782 2004      223      9      0    .730   1.86   4.30   .825   .764   .279   2.48   .327  -.006   1
 89 FCH015A  1780 2004      225      9      0    .652   1.20   5.94   .904   .741   .396   2.84   .485   .069   1
 90 FC2041A  1778 2004      227      9      0    .754   1.45   6.61   .874   .809   .296   2.85   .417  -.001   1
 91 FC2052B  1774 2004      231     10      0    .644   1.42   3.82   .701   .705   .333   2.62   .401  -.038   1
 92 FC2004A  1771 2004      234     10      0    .657   1.88   5.30  1.074   .806   .299   2.75   .433   .023   1
 93 FC2033B  1771 1984      214      9      0    .702   1.87   4.12   .755   .715   .279   2.42   .322  -.037   1
 94 FC2023B  1770 2004      235     10      2    .614   1.17   3.21   .627   .722   .338   2.91   .479   .013   1
 95 FC2025A  1769 2004      236     10      0    .763   1.79   4.95   .908   .715   .289   2.78   .449  -.008   1
 96 FC2012A  1765 2004      240     10      0    .748   1.16   4.10   .676   .778   .376   2.60   .386  -.023   3
 97 FCH040B  1916 2004       89      4      0    .736   1.05   2.99   .475   .340   .396   2.96   .643   .060   1
 98 FCH040C  1852 1914       63      2      0    .812   1.72   3.06   .609   .338   .348   2.56   .560   .028   1
 99 FCH040D  1762 1850       89      4      0    .691   1.79   4.05   .734   .468   .363   2.71   .545   .021   1
100 FC2015B  1761 1991      231      9      0    .736   1.46   6.85  1.422   .913   .351   2.89   .452  -.031   3
101 FC2052A  1758 2004      247     10      0    .615   1.18   3.98   .680   .722   .350   2.59   .397   .004   1
102 FCH040A  1757 2004      248     10      0    .740   1.53   3.51   .753   .577   .386   2.66   .388   .010   1
103 FC2001B  1756 2004      249     10      0    .703    .69   1.66   .350   .652   .344   2.69   .391   .010   1
104 FC2012B  1755 2004      250     10      0    .781   1.23   4.32   .741   .798   .393   2.48   .330  -.020   2
105 FCH015B  1754 2004      251     10      0    .685    .95   3.53   .572   .739   .375   2.53   .344  -.029   1
106 FC2016A  1753 2004      252     10      0    .558   1.84   4.41   .888   .705   .352   2.66   .476  -.009   2
107 FCH002B  1751 2004      254     10      0    .749   1.19   3.21   .625   .717   .377   2.87   .533  -.014   1
108 FCH005A  1751 2004      254     10      0    .662   1.68   4.72   .961   .826   .312   2.50   .314   .005   3
```

Appendix A2. *Continued.*

```
                                           Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                         No.   No.   No.   with   Mean   Max     Std   Auto   Mean   Max    Std   Auto  AR
Seq Series   Interval   Years Segmt Flags Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------  ----- ----- ----- ------ -----  -----  -----  -----  -----  -----  -----  -----  --
109 FC2044B  1751 1993    243     9     0   .720  1.01   3.24   .551   .669   .371   2.70   .458   .033   5
110 FC2022A  1747 1969    223     9     0   .649   .91   2.08   .391   .686   .271   2.67   .395  -.005   1
111 FC2015A  1747 2004    258    11     1   .680  1.33   6.25  1.179   .899   .333   2.79   .419   .012   2
112 FC2014A  1744 1984    241    10     0   .726  1.54   5.58   .920   .726   .356   2.76   .435   .010   1
113 FCH016B  1744 2004    261    11     0   .599  1.08   4.28   .656   .713   .408   2.53   .273   .003   2
114 FCH002A  1743 2004    262    11     1   .750  1.58   4.69   .859   .621   .370   2.66   .399   .015   1
115 FCH023A  1739 2004    266    11     0   .803  1.40   5.52   .972   .854   .307   2.61   .372   .045   1
116 FC2031A  1734 2004    271    11     0   .716  1.05   4.49   .789   .808   .372   2.67   .438  -.068   1
117 FCH005B  1731 2004    274    11     0   .700  1.38   4.38   .766   .847   .303   2.57   .351   .036   1
118 FC2070B  1730 2004    275    11     1   .625  1.16   4.48   .924   .868   .372   2.72   .355  -.023   1
119 FC2044A  1730 2004    275    11     0   .735  1.32   5.12   .775   .638   .408   2.71   .475   .010   1
120 FC2026A  1729 2004    276    11     0   .741  1.07   5.90   .648   .795   .294   2.56   .355  -.012   1
121 FC2070A  1728 2004    277    11     0   .678  1.41   4.70  1.057   .850   .365   2.68   .393   .015   1
122 FC2014B  1728 2004    277    11     0   .783  1.62   4.88   .860   .682   .361   2.63   .377  -.018   2
123 FCH001A  1727 2004    278    11     0   .621  1.45   6.08  1.131   .862   .305   2.56   .343   .002   1
124 FC2051B  1727 2004    278    11     0   .702  1.05   4.07   .665   .725   .368   2.84   .493  -.003   1
125 FCH035A  1724 2004    281    12     0   .789  1.47   4.83   .837   .760   .332   2.82   .428  -.014   1
126 FCH001B  1723 2004    282    12     0   .675  1.25   6.40  1.280   .916   .361   2.70   .372   .024   1
127 FC2023A  1722 2004    283    12     0   .700  1.40   4.05   .699   .715   .314   2.63   .415   .031   1
128 FC2032B  1714 2004    291    12     0   .682  1.39   4.64   .865   .772   .381   2.55   .343   .020   1
129 FC2027B  1712 2004    293    12     0   .648  1.40   4.00   .814   .752   .367   2.67   .457   .052   2
130 FC2022B  1712 2004    293    12     0   .719   .76   3.02   .476   .772   .337   2.61   .357  -.031   1
131 FC2026B  1712 2004    293    12     0   .713  1.07   3.52   .496   .744   .287   2.66   .336   .011   1
132 FCH023B  1707 2004    298    12     0   .737  1.37   5.98  1.191   .895   .345   2.62   .337   .047   1
133 FC2027A  1703 2004    302    12     0   .643  1.54   6.03  1.017   .833   .305   2.70   .436   .034   1
134 FC2032A  1703 2004    302    12     0   .752  1.44   4.74   .861   .756   .364   2.69   .354   .030   1
135 FC2031B  1692 2004    313    13     0   .718  1.15   6.31  1.134   .897   .366   2.61   .370  -.079   1
136 FCH038A  1663 1851    189     8     0   .725  1.94   4.78   .950   .702   .312   2.65   .443   .001   1
137 FCH038B  1656 1889    234     9     0   .696  1.74   5.19  1.194   .848   .302   2.56   .351  -.009   1
--- -------- ---------  ----- ----- ----- ------ -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:          23925   990     8   .696  1.71  11.22   .958   .744   .329   2.98   .417   .004
```

Appendix A3. Correlation of series by segments for French Creek cross-section samples.

```
Correlations of  50-year dated segments, lagged  25 years
 Flags:  A = correlation under   .3281 but highest as dated;  B = correlation higher at other than dated position

 Seq Series   Time_span   1600 1625 1650 1675 1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975
                          1649 1674 1699 1724 1749 1774 1799 1824 1849 1874 1899 1924 1949 1974 1999 2024
 --- -------- ---------   ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
   1 FCX033   1968 2005                                                                            .82
   2 FCX044   1966 2005                                                                            .46
   3 FCS013   1963 2005                                                                            .58
   4 FCS007   1942 2005                                                                       .41  .37  .44
   5 FCX034   1930 2005                                                                       .75  .68  .69
   6 FCS008   1914 2005                                                                  .23A .38  .33B .46
   7 FCX045   1912 2005                                                                  .42  .51  .60  .54
   8 FCS022   1903 2005                                                                  .55  .67  .69  .77
   9 FCS005   1868 2005                                                        .52  .38  .66  .77  .55  .55
  10 FCS003   1856 2005                                                        .48  .51  .58  .54  .40  .39
  11 FC2005   1848 1977                                                   .50  .50  .32A .31A .37  .42
  12 FCX039i  1843 1913                                                   .63  .58  .65
  13 FCX039o  1916 1982                                                                  .54  .59  .53
  14 FCS006   1836 2005                                                   .68  .71  .33A .42  .75  .63  .63
  15 FC2008   1831 1886                                                   .75  .76
  16 FC2007   1830 1979                                                   .79  .81  .73  .69  .62  .62
  17 FC2010   1826 2005                                                   .47  .46B .78  .79  .75  .73  .74
  18 FCX040   1824 1986                                              .40  .40  .62  .63  .68  .68  .64
  19 FCS011   1823 1967                                              .28A .28A .39  .39  .47  .49
  20 FCX048   1822 1984                                              .58  .61  .59  .46  .55  .60  .60
  21 FCS026   1818 2005                                              .63  .56  .50  .43  .35  .47  .40  .45
  22 FCX049   1809 1929                                              .49  .77  .73  .55  .52
  23 FCX030   1809 1878                                              .44  .47  .48
  24 FCS009B  1809 1983                                              .46  .45  .58  .55  .36  .22B .25B
  25 FCS010   1807 1991                                              .40  .59  .66  .60  .63  .72  .66
  26 FCS029   1806 1983                                              .35  .25A .40  .62  .53  .58  .52
  27 FCX050   1806 1928                                              .60  .72  .65  .56  .54
  28 FCS015   1806 1983                                              .67  .61  .41  .27B .28A .38  .28B
  29 FCS014   1802 1913                                              .68  .66  .59  .46
  30 FC2009   1797 1990                                         .70  .76  .84  .83  .81  .77  .64  .57
```

Appendix A3. *Continued.*

```
Seq Series  Time_span   1600 1625 1650 1675 1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975
                        1649 1674 1699 1724 1749 1774 1799 1824 1849 1874 1899 1924 1949 1974 1999 2024
--- -------- ---------  ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
 31 FCS028   1794 1991                                     .39  .44  .68  .63  .55  .52  .40  .32B
 32 FC2002   1790 2005                                     .55  .60  .60  .55  .44  .53  .62  .59  .60
 33 FC2006C  1779 1913                                     .63  .56  .68  .46  .35
 34 FC2012B  1775 1913                                     .72  .61  .61  .44  .40
 35 FC2012A  1762 1913                                .67  .76  .66  .65  .68  .65
 36 FCX037   1761 1985                                .73  .75  .79  .67  .61  .57  .48  .65  .64
 37 FCS031   1761 1979                                .64  .65  .73  .63  .58  .64  .57  .45  .29A
 38 FC2011   1761 1968                                .69  .71  .74  .61  .57  .58  .41  .28A
 39 FCX046   1759 2005                                .34B .59  .60  .60  .69  .59  .66  .72  .64  .68
 40 FCX036B  1752 1983                                .66  .46  .72  .77  .69  .67  .78  .76  .76
 41 FCX036A  1752 1981                                .68  .63  .76  .80  .68  .64  .79  .78  .76
 42 FC2014   1751 1991                                .87  .81  .76  .69  .59  .47  .50  .57  .43B
 43 FCX043   1750 1888                                .49  .52  .57  .54  .49
 44 FC2013   1750 1906                                .78  .80  .89  .82  .65  .66
 45 FC2006Ai 1745 1845                           .78  .81  .79  .69
 46 FC2006Ao 1848 1984                                               .61  .60  .39  .54  .64  .66
 47 FCX042   1739 1983                           .61  .69  .64  .73  .75  .59  .50  .61  .53  .54
 48 FCX036C  1733 1789                           .59  .51
 49 FCX036C  1794 1991                                     .62  .75  .80  .76  .76  .55  .51  .51
 50 FCS024   1726 1878                           .62  .52  .47  .83  .88  .85
 51 FCX010   1718 1959                      .75  .75  .75  .74  .70  .79  .82  .73  .56  .44
 52 FCS021   1712 1866                      .47  .39  .52  .45  .35  .24B
 53 FC2004i  1710 1844                      .62  .78  .83  .75  .72
 54 FC2004o  1848 1984                                               .75  .78  .65  .65  .59  .64
 55 FCS023   1702 1869                      .62  .72  .81  .68  .62  .66
 56 FCS001B  1695 2005                 .27B .27B .58  .64  .61  .61  .53  .45  .55  .59  .36  .28A .35
 57 FCS018   1671 2005            .61  .60  .59  .75  .65  .40  .53  .65  .72  .62  .65  .62  .43  .38
 58 FCS027   1649 1913       .43  .43  .56  .61  .47  .45  .43  .54  .64  .65  .63
 59 FCS025   1603 1893  .59  .47  .40  .39  .41B .45  .57  .62  .61  .57  .56
 60 FCS020   1581 1765  .60  .57  .53  .50  .70  .67
Av segment correlation  .60  .49  .49  .46  .56  .63  .65  .62  .61  .63  .61  .55  .55  .56  .54  .55
```

Appendix A4. Descriptive statistics for French Creek cross-section samples.

```
                                                   Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                             No.    No.    No.     with   Mean   Max     Std   Auto   Mean   Max    Std   Auto  AR
Seq Series   Interval       Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value   dev   corr  ()
--- -------- ---------      -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
  1 FCX033   1968 2005        38      1      0    .816   3.09   6.02  1.207   .619   .320   2.52   .485   .016   1
  2 FCX044   1966 2005        40      1      0    .460   3.12   9.00  2.129   .812   .345   2.53   .426   .099   1
  3 FCS013   1963 2005        43      1      0    .585   4.11  11.26  2.520   .730   .379   2.64   .494   .143   1
  4 FCS007   1942 2005        64      3      0    .414   1.29   2.81   .475   .601   .271   2.53   .465  -.058   1
  5 FCX034   1930 2005        76      3      0    .700   3.00   6.52  1.423   .628   .349   2.63   .520  -.074   1
  6 FCS008   1914 2005        92      4      2    .370   1.86   3.83   .788   .695   .273   2.61   .435  -.019   1
  7 FCX045   1912 2005        94      4      0    .511   1.91   4.89  1.220   .842   .306   2.58   .497  -.057   1
  8 FCS022   1903 2005       103      4      0    .645   2.06  10.46  1.833   .851   .327   2.78   .473   .006   1
  9 FCS005   1868 2005       138      6      0    .595   2.12   4.74   .754   .677   .231   2.57   .443  -.054   1
 10 FCS003   1856 2005       150      6      0    .495   2.06   5.33   .802   .657   .245   2.73   .397   .017   1
 11 FC2005   1848 1977       130      6      2    .425   1.85   5.70   .979   .516   .337   2.93   .478   .006   1
 12 FCX039i  1843 1913        71      3      0    .637   5.12  11.36  2.192   .686   .280   2.65   .549  -.025   1
 13 FCX039o  1916 1982        67      3      0    .501   1.02   2.49   .538   .639   .329   2.52   .468  -.066   4
 14 FCS006   1836 2005       170      7      1    .571   1.78   4.92   .723   .656   .266   2.71   .503   .003   1
 15 FC2008   1831 1886        56      2      0    .747   1.44   2.91   .565   .545   .311   2.72   .542  -.043   1
 16 FC2007   1830 1979       150      6      0    .697   1.48   4.90   .976   .728   .381   2.70   .441  -.003   2
 17 FC2010   1826 2005       180      7      1    .652   1.20   2.86   .501   .704   .277   2.56   .338   .038   1
 18 FCX040   1824 1986       163      7      0    .558   1.41   3.28   .571   .675   .256   2.62   .410   .082   1
 19 FCS011   1823 1967       145      6      2    .382   2.01   4.68  1.070   .813   .295   2.54   .341  -.085   1
 20 FCX048   1822 1984       163      7      0    .563    .92   2.91   .690   .889   .286   2.69   .429  -.014   1
 21 FCS026   1818 2005       188      8      0    .489   1.33   3.47   .687   .728   .325   2.76   .376  -.036   1
 22 FCX049   1809 1929       121      5      0    .617   1.64   3.67   .748   .698   .339   2.59   .454   .052   2
 23 FCX030   1809 1878        70      3      0    .380   1.10   2.46   .584   .808   .308   2.80   .588   .003   3
 24 FCS009B  1809 1983       175      7      2    .423   1.02   4.00   .807   .928   .221   2.60   .401  -.007   1
 25 FCS010   1807 1991       185      7      0    .542    .96   4.07   .780   .930   .266   2.60   .412   .001   1
 26 FCS029   1806 1983       178      7      1    .469   1.18   4.90  1.042   .907   .295   2.81   .504  -.014   1
 27 FCX050   1806 1928       123      5      0    .580   1.05   2.40   .409   .347   .374   2.61   .432   .005   1
 28 FCS015   1806 1983       178      7      3    .442   1.54   4.69   .937   .855   .285   2.69   .389  -.051   1
 29 FCS014   1802 1913       112      4      0    .570   1.85   5.50  1.209   .842   .315   2.61   .416  -.055   1
 30 FC2009   1797 1990       194      8      0    .719   1.98   4.22   .825   .659   .293   2.52   .433   .019   1
 31 FCS028   1794 1991       198      8      1    .477   1.26   3.04   .558   .682   .261   2.62   .392   .028   1
 32 FC2002   1790 2005       216      9      0    .555    .84   5.12   .655   .850   .292   2.63   .393  -.026   2
 33 FC2006C  1779 1913       135      5      0    .501   1.54   5.76   .999   .589   .359   2.84   .525  -.094   1
 34 FC2012B  1775 1913       139      5      0    .575   1.83   5.80  1.041   .694   .393   2.73   .507   .020   1
 35 FC2012A  1762 1913       152      6      0    .645   2.15   5.60  1.225   .753   .315   2.53   .321  -.027   1
 36 FCX037   1761 1985       225      9      0    .647   1.42   3.76   .785   .765   .313   2.62   .385   .000   3
```

Appendix A4. *Continued.*

```
                                              Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                          No.    No.    No.   with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
Seq Series   Interval   Years  Segmt  Flags  Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------  -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
 37 FCS031   1761 1979    219      9      1   .572    .97   4.63   .864   .850   .358   2.77   .403  -.033   1
 38 FC2011   1761 1968    208      8      1   .555    .97   4.54   .881   .885   .328   2.91   .462  -.048   1
 39 FCX046   1759 2005    247     10      1   .573   1.15   3.01   .546   .649   .317   2.60   .394  -.012   1
 40 FCX036B  1752 1983    232      9      0   .727   2.70   8.26  1.315   .697   .343   2.67   .471   .008   1
 41 FCX036A  1752 1981    230      9      0   .727   2.65   6.30  1.181   .635   .370   2.70   .451   .016   1
 42 FC2014   1751 1991    241      9      1   .642   1.65   5.40  1.200   .848   .331   2.60   .367  -.017   1
 43 FCX043   1750 1888    139      5      0   .514   1.43   5.29   .936   .794   .299   2.62   .411   .054   1
 44 FC2013   1750 1906    157      6      0   .780   2.48   5.60  1.075   .580   .338   2.66   .413   .072   1
 45 FC2006Ai 1745 1845    101      4      0   .739   1.70   3.62   .644   .555   .293   2.65   .433  -.042   1
 46 FC2006Ao 1848 1984    137      6      0   .588   1.18   2.53   .446   .486   .292   2.72   .442  -.004   1
 47 FCX042   1739 1983    245     10      0   .607    .85   2.52   .430   .831   .227   2.55   .360   .002   1
 48 FCX036C  1733 1789     57      2      0   .523   1.84   4.23   .779   .659   .317   2.61   .495  -.002   2
 49 FCX036C  1794 1991    198      8      0   .643   2.18   5.46  1.095   .785   .279   2.50   .313  -.038   3
 50 FCS024   1726 1878    153      6      0   .668   1.51   3.27   .616   .656   .293   2.68   .454   .013   1
 51 FCX010   1718 1959    242     10      0   .704   1.83   4.31  1.021   .822   .317   2.47   .357  -.049   1
 52 FCS021   1712 1866    155      6      1   .397    .48   2.37   .316   .754   .310   2.82   .425  -.024   1
 53 FC2004i  1710 1844    135      5      0   .675    .77   2.67   .581   .766   .372   2.69   .455  -.075   1
 54 FC2004o  1848 1984    137      6      0   .668    .93   2.07   .359   .638   .259   2.52   .389  -.006   1
 55 FCS023   1702 1869    168      6      0   .677   1.18   3.52   .564   .732   .281   2.63   .387  -.037   1
 56 FCS001B  1695 2005    311     13      3   .469   1.21   2.98   .575   .753   .261   2.58   .352   .007   1
 57 FCS018   1671 2005    335     14      0   .588   1.03   2.66   .507   .806   .246   2.73   .352  -.012   1
 58 FCS027   1649 1913    265     11      0   .520   1.18   3.61   .644   .806   .282   2.66   .449   .027   1
 59 FCS025   1603 1893    291     11      1   .509   1.38   3.42   .759   .775   .291   2.64   .460  -.002   2
 60 FCS020   1581 1765    185      6      0   .584   1.71   5.78   .747   .609   .271   2.71   .382   .033   1
--- -------- ---------  -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:           9510    379     24   .578   1.54  11.36   .825   .739   .300   2.93   .418  -.008
```

Appendix A5. Correlation of series by segments for Fall Creek samples.

```
Correlations of  50-year dated segments, lagged  25 years
Flags:  A = correlation under   .3281 but highest as dated;  B = correlation higher at other than dated position

Seq Series  Time_span   1650 1675 1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975
                        1699 1724 1749 1774 1799 1824 1849 1874 1899 1924 1949 1974 1999 2024
--- -------- ---------  ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
  1 FCM041B  1850 2005                                           .43  .50  .44B .61  .76  .82
  2 FCM007A  1817 2005                                 .59  .65  .58  .52  .52  .55  .54  .44
  3 FCM041A  1815 2005                                 .47  .47  .46  .45  .50  .59  .61  .61
  4 FCM025B  1815 2005                                 .37  .32A .54  .56  .61  .60  .65  .69
  5 FCM001B  1810 2005                                 .46  .62  .65  .55  .56  .48  .54  .56
  6 FCM037B  1808 2005                                 .40  .54  .64  .62  .60  .63  .62  .63
  7 FCM037A  1800 2005                                 .55  .56  .49  .30A .37  .67  .53  .50
  8 FCM005B  1780 2005                            .57  .44  .51  .65  .70  .50  .46  .46  .44
  9 FCM002A  1775 2005                            .56  .48  .54  .63  .65  .70  .67  .54  .50
 10 FCM033B  1772 2005                       .41  .43  .42  .67  .81  .75  .65  .66  .66  .65
 11 FCM017B  1766 2005                       .46  .50  .62  .63  .71  .63  .62  .75  .76  .73
 12 FCM014B  1761 2005                       .54  .65  .71  .49  .43  .56  .55  .70  .70  .55
 13 FCM026B  1756 2005                       .35B .49  .37  .49  .60  .60  .68  .71  .68  .66
 14 FCM020A  1755 2005                       .73  .70  .59  .61  .71  .67  .71  .78  .68  .66
 15 FCM015B  1750 2005                       .76  .67  .63  .73  .78  .80  .80  .77  .70  .68
 16 FCM010A  1747 2005                  .50  .53  .35  .49  .46  .60  .69  .68  .53  .47  .54
 17 FCM005A  1744 2005                  .67  .71  .66  .37  .33  .52  .60  .51  .47  .43  .43
 18 FCM018B  1743 2005                  .27A .35  .37  .57  .47  .29B .40  .49  .51  .49  .48
 19 FCM011C  1739 1923                  .62  .80  .71  .57  .62  .74  .50
 20 FCM011B  1936 2005                                                          .37  .29B .32B
 21 FCM011A  1738 1919                  .60  .66  .50  .38  .51  .50  .45
 22 FCM033A  1737 2005                  .53  .62  .59  .68  .82  .84  .76  .41  .28B .46  .55
 23 FCM002B  1735 2005                  .48  .46  .35  .40  .49  .53  .56  .71  .61  .57  .61
 24 FCM015A  1732 2005                  .70  .64  .61  .65  .70  .69  .63  .59  .54  .39  .36
 25 FCM017A  1730 2005                  .60  .57  .57  .71  .70  .75  .69  .56  .46  .37  .30A
 26 FCM007B  1728 2005                  .75  .78  .70  .60  .62  .56  .35  .45B .60  .66  .70
 27 FCM004C  1728 2005                  .54  .69  .62  .56  .58  .63  .66  .75  .75  .62  .59
 28 FCM016B  1727 2005                  .68  .78  .58  .55  .63  .70  .67  .62  .71  .56  .60
 29 FCM029B  1725 2005                  .63  .61  .59  .29A .35  .79  .84  .80  .72  .68  .73
```

Appendix A5. *Continued.*

```
Seq Series  Time_span   1650 1675 1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975
                        1699 1724 1749 1774 1799 1824 1849 1874 1899 1924 1949 1974 1999 2024
--- -------- ---------  ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
 30 FCM032B  1724 2005            .57  .57  .47  .40  .56  .63  .80  .78  .58  .51  .60  .66
 31 FCM027A  1723 2005            .72  .69  .71  .68  .75  .79  .74  .68  .48  .39  .62  .76
 32 FCM035B  1722 2005            .55  .50  .50  .56  .52  .59  .71  .63  .38  .41  .63  .65
 33 FCM013B  1721 2005            .65  .59  .60  .58  .62  .79  .84  .63  .59  .58  .46  .33
 34 FCM003A  1719 2005            .74  .71  .66  .56  .52  .45  .52  .61  .60  .53  .44  .43
 35 FCM029A  1718 2005            .53  .54  .60  .61  .56  .49  .64  .78  .78  .74  .71  .65
 36 FCM020B  1717 1909            .59  .58  .70  .66  .66  .70  .57  .54
 37 FCM028C  1717 1947            .68  .72  .74  .58  .45  .63  .76  .64  .59
 38 FCM028B  1950 2005                                                             .48  .47
 39 FCM018A  1717 2005            .55  .64  .56  .50  .63  .63  .57  .63  .71  .69  .52  .51
 40 FCM013A  1716 2005            .65  .63  .48  .46  .66  .76  .77  .77  .66  .47  .52  .48
 41 FCM038A  1716 2005            .54  .50  .52  .38  .35  .43  .49  .37  .37  .62  .68  .68
 42 FCM012B  1715 2005            .69  .69  .73  .59  .54  .70  .77  .68  .71  .66  .59  .65
 43 FCM006A  1715 1992            .71  .65  .72  .75  .68  .59  .54  .50  .55  .59  .45
 44 FCM008B  1711 2005            .55  .65  .64  .66  .69  .54  .43  .54  .51  .48  .27A .29A
 45 FCM016A  1710 2005            .77  .72  .70  .56  .55  .68  .56  .62  .75  .67  .68  .67
 46 FCM040B  1707 2005            .65  .65  .72  .62  .59  .56  .54  .61  .62  .49  .32A .36
 47 FCM027B  1706 2005            .60  .69  .71  .64  .59  .64  .75  .75  .67  .57  .59  .53
 48 FCM030A  1705 2005            .74  .82  .78  .69  .63  .64  .63  .55  .54  .60  .55  .55
 49 FCM012A  1703 2005            .78  .77  .75  .70  .65  .75  .67  .54  .61  .71  .67  .68
 50 FCM036A  1700 2005            .52  .50  .42  .42  .53  .47  .55  .65  .57  .56  .58  .57
 51 FCM035A  1698 2005       .72  .71  .67  .55  .47  .58  .58  .50  .47  .49  .47  .52  .53
 52 FCM014C  1695 1789       .40  .39  .61  .58
 53 FCM014A  1791 2005                                 .55  .52  .52  .73  .75  .70  .66  .49  .55
 54 FCM003C  1695 1951       .57  .59  .61  .59  .46  .40  .41  .49  .40  .23A .18A
 55 FCM030B  1695 2005       .63  .66  .68  .82  .76  .68  .73  .63  .59  .65  .52  .45  .35
 56 FCM022A  1694 2005       .70  .72  .69  .55  .45  .64  .76  .65  .61  .67  .62  .66  .72
 57 FCM010B  1693 2005       .52  .53  .50  .52  .46  .54  .34  .41  .69  .69  .51  .43  .49
 58 FCM001A  1693 2005       .76  .78  .71  .58  .51  .62  .66  .55  .51  .62  .60  .52  .53
 59 FCM038B  1690 2005       .46  .37  .53  .43  .38  .46  .44  .69  .62  .48  .62  .71  .73
 60 FCM009B  1690 1960       .50  .53  .57  .60  .60  .48  .29B .48  .62  .53  .41
 61 FCM032A  1689 2005       .37  .50  .66  .62  .46  .53  .65  .72  .80  .72  .53  .48  .56
 62 FCM004A  1684 2005       .48  .62  .55  .66  .58  .50  .53  .63  .66  .61  .61  .42  .29A
```

Appendix A5. *Continued.*

```
Seq Series  Time_span   1650 1675 1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975
                        1699 1724 1749 1774 1799 1824 1849 1874 1899 1924 1949 1974 1999 2024
--- -------- ---------  ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
 63 FCM009A  1684 1829        .58  .58  .56  .52  .50  .59
 64 FCM028A  1683 2005        .55  .66  .63  .65  .53  .50  .70  .72  .55  .58  .55  .38  .46
 65 FCM040A  1679 2005        .35  .52  .63  .67  .45  .41  .64  .68  .53  .32B .35  .32A .28A
 66 FCM031A  1676 2005        .49  .73  .72  .62  .51  .59  .54  .36  .42  .47  .40  .46  .48
 67 FCM022B  1674 2005   .47  .45  .52  .62  .48  .38  .43  .51  .63  .57  .49  .57  .69  .69
 68 FCM038C  1662 2005   .36B .37  .41  .50  .44  .52  .56  .36B .59  .59  .50  .40  .52  .46
 69 FCM024B  1661 2005   .60  .73  .77  .72  .65  .58  .66  .64  .68  .72  .69  .58  .48  .46
 70 FCM024A  1660 2005   .64  .66  .61  .70  .77  .74  .58  .59  .70  .59  .28B .13B .31A .32A
 71 FCM031C  1659 1845   .36  .46  .74  .75  .74  .69  .35
 72 FCM031B  1853 2005                                         .57  .70  .78  .78  .72  .70
 73 FCM004B  1659 2005   .53  .54  .51  .63  .69  .59  .59  .61  .55  .58  .75  .65  .59  .46
 74 FCM039A  1493 2005   .25A .43  .69  .73  .70  .61  .54  .62  .71  .60  .47  .50  .42  .47
Av segment correlation   .46  .53  .62  .63  .62  .56  .54  .58  .62  .60  .58  .56  .54  .54
```

Appendix A6. Descriptive statistics for Fall Creek samples.

```
                                               Corr  //-------- Unfiltered --------\\  //---- Filtered -----\\
                          No.    No.    No.    with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
Seq Series   Interval   Years  Segmt  Flags  Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
  1 FCM041B  1850 2005    156      6      1    .546  1.57   2.86   .464   .629   .213   2.57   .416   .004   1
  2 FCM007A  1817 2005    189      8      0    .512   .57   1.18   .214   .614   .290   2.52   .278   .008   1
  3 FCM041A  1815 2005    191      8      0    .508  1.65   3.13   .528   .715   .196   2.74   .382  -.010   1
  4 FCM025B  1815 2005    191      8      1    .544  1.51   3.42   .746   .786   .254   2.58   .381  -.005   1
  5 FCM001B  1810 2005    196      8      0    .532   .83   1.79   .269   .566   .223   2.46   .352  -.015   1
  6 FCM037B  1808 2005    198      8      0    .553  1.28   3.51   .604   .785   .256   2.53   .420  -.012   1
  7 FCM037A  1800 2005    206      8      1    .484  1.39   3.17   .582   .721   .240   2.58   .411   .007   1
  8 FCM005B  1780 2005    226      9      0    .541   .65   1.90   .291   .642   .307   2.75   .396   .002   2
  9 FCM002A  1775 2005    231      9      0    .581  1.20   3.27   .481   .456   .324   2.65   .376  -.010   1
 10 FCM033B  1772 2005    234     10      0    .612   .85   1.90   .373   .759   .275   2.45   .380   .041   2
 11 FCM017B  1766 2005    240     10      0    .648  1.12   2.48   .481   .791   .243   2.68   .430   .031   1
 12 FCM014B  1761 2005    245     10      0    .555  1.44   3.02   .460   .636   .214   2.59   .443  -.026   1
 13 FCM026B  1756 2005    250     10      1    .543  1.35   2.91   .541   .696   .252   2.67   .443  -.010   1
 14 FCM020A  1755 2005    251     10      0    .667  1.39   3.69   .612   .730   .254   2.73   .474  -.005   3
 15 FCM015B  1750 2005    256     10      0    .726  1.48   2.83   .523   .638   .255   2.61   .402  -.007   1
 16 FCM010A  1747 2005    259     11      0    .567   .77   2.02   .465   .809   .342   2.55   .344   .032   1
 17 FCM005A  1744 2005    262     11      0    .533   .84   2.98   .527   .826   .311   2.60   .345   .018   2
 18 FCM018B  1743 2005    263     11      2    .511   .39    .94   .178   .618   .342   2.61   .330   .028   1
 19 FCM011C  1739 1923    185      7      0    .598  1.32   3.06   .553   .752   .257   2.77   .513   .004   1
 20 FCM011B  1936 2005     70      3      2    .332  1.04   1.77   .385   .594   .252   2.57   .450   .044   1
 21 FCM011A  1738 1919    182      7      0    .550   .83   1.85   .357   .724   .302   2.48   .353   .038   1
 22 FCM033A  1737 2005    269     11      1    .635   .87   2.73   .500   .832   .291   2.58   .397   .008   1
 23 FCM002B  1735 2005    271     11      0    .563   .89   2.98   .481   .706   .290   2.66   .396   .002   4
 24 FCM015A  1732 2005    274     11      0    .603  1.09   2.94   .439   .671   .261   2.77   .429   .039   1
 25 FCM017A  1730 2005    276     11      1    .591   .77   2.45   .364   .815   .224   2.71   .327   .026   1
 26 FCM007B  1728 2005    278     11      1    .645  1.10   4.06   .659   .839   .280   2.61   .323   .006   2
 27 FCM004C  1728 2005    278     11      0    .626   .49   1.43   .243   .698   .317   2.58   .327   .008   2
 28 FCM016B  1727 2005    279     11      0    .633  1.14   2.76   .513   .764   .238   2.69   .366   .019   1
 29 FCM029B  1725 2005    281     11      1    .678  1.32   3.59   .718   .817   .281   2.42   .320  -.047   1
 30 FCM032B  1724 2005    282     12      0    .591   .85   1.62   .336   .704   .264   2.45   .299   .011   1
 31 FCM027A  1723 2005    283     12      0    .681  1.13   3.02   .454   .717   .234   3.02   .374   .039   2
 32 FCM035B  1722 2005    284     12      0    .543  1.23   3.12   .493   .596   .288   2.51   .304  -.003   2
 33 FCM013B  1721 2005    285     12      0    .587  1.15   4.25   .633   .839   .243   2.45   .263   .000   1
 34 FCM003A  1719 2005    287     12      0    .546  1.32   4.68   .642   .740   .260   2.49   .270  -.018   2
 35 FCM029A  1718 2005    288     12      0    .633  1.26   3.50   .712   .867   .253   2.41   .255   .018   1
```

Appendix A6. *Continued.*

```
                                               Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                          No.    No.    No.    with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
Seq Series   Interval   Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
 36 FCM020B  1717 1909    193      8      0     .607  1.40   3.06   .727   .829   .252   2.58   .418   .021   4
 37 FCM028C  1717 1947    231      9      0     .641  1.20   3.04   .502   .640   .277   2.72   .436  -.001   1
 38 FCM028B  1950 2005     56      2      0     .517   .63   1.25   .253   .593   .349   2.46   .445  -.066   1
 39 FCM018A  1717 2005    289     12      0     .586   .92   2.40   .371   .703   .263   2.66   .401  -.023   1
 40 FCM013A  1716 2005    290     12      0     .617  1.36   4.67   .706   .850   .246   2.59   .411   .060   1
 41 FCM038A  1716 2005    290     12      0     .490   .91   2.42   .404   .755   .258   2.52   .288  -.010   1
 42 FCM012B  1715 2005    291     12      0     .658  1.42   4.61   .717   .834   .254   2.72   .442   .000   4
 43 FCM006A  1715 1992    278     11      0     .619  1.52   4.39   .841   .843   .255   2.70   .476   .018   1
 44 FCM008B  1711 2005    295     12      2     .513  1.15   4.14   .678   .872   .274   2.60   .291  -.030   3
 45 FCM016A  1710 2005    296     12      0     .653  1.16   3.21   .593   .854   .244   2.57   .341   .053   2
 46 FCM040B  1707 2005    299     12      1     .566  1.16   2.91   .579   .831   .234   2.65   .403  -.019   1
 47 FCM027B  1706 2005    300     12      0     .658   .92   2.55   .481   .820   .257   2.58   .356  -.004   2
 48 FCM030A  1705 2005    301     12      0     .640  1.04   3.65   .684   .897   .215   2.68   .426   .026   1
 49 FCM012A  1703 2005    303     12      0     .684  1.33   4.70   .841   .895   .257   2.49   .335   .011   5
 50 FCM036A  1700 2005    306     12      0     .517  1.03   2.88   .475   .691   .273   2.60   .320  -.043   5
 51 FCM035A  1698 2005    308     13      0     .571  1.18   5.60   .814   .890   .247   2.61   .308  -.020   2
 52 FCM014C  1695 1789     95      4      0     .480  1.48   5.13  1.199   .924   .205   2.49   .511  -.061   1
 53 FCM014A  1791 2005    215      9      0     .593   .65   1.23   .207   .677   .218   2.46   .336   .004   2
 54 FCM003C  1695 1951    257     11      2     .462  1.23   5.02   .856   .842   .268   2.57   .413  -.005   2
 55 FCM030B  1695 2005    311     13      0     .633  1.12   4.11   .649   .874   .229   2.81   .429  -.011   1
 56 FCM022A  1694 2005    312     13      0     .637  1.40   4.47   .587   .670   .268   2.54   .336  -.011   1
 57 FCM010B  1693 2005    313     13      0     .513   .94   2.74   .547   .846   .313   2.49   .308  -.011   1
 58 FCM001A  1693 2005    313     13      0     .601  1.16   5.21  1.066   .926   .235   2.52   .282  -.021   1
 59 FCM038B  1690 2005    316     13      0     .521  1.28   3.43   .509   .813   .209   2.60   .385   .008   1
 60 FCM009B  1690 1960    271     11      1     .509   .97   4.72  1.020   .963   .258   2.50   .330   .013   1
 61 FCM032A  1689 2005    317     13      0     .574  1.30   3.47   .646   .846   .245   2.51   .368   .026   1
 62 FCM004A  1684 2005    322     13      1     .547   .66   4.84   .473   .686   .327   2.93   .473   .024   3
 63 FCM009A  1684 1829    146      6      0     .552  1.66   5.10  1.380   .959   .195   2.72   .439   .017   1
 64 FCM028A  1683 2005    323     13      0     .591   .94   3.38   .567   .818   .341   2.60   .352   .006   1
 65 FCM040A  1679 2005    327     13      3     .473   .97   3.11   .609   .879   .264   2.68   .419  -.001   1
 66 FCM031A  1676 2005    330     13      0     .524  1.09   5.91  1.001   .933   .264   2.94   .349   .036   1
 67 FCM022B  1674 2005    332     14      0     .528   .99   2.34   .419   .742   .242   3.03   .442   .012   1
 68 FCM038C  1662 2005    344     14      2     .508   .91   3.93   .744   .936   .245   2.47   .313   .008   1
 69 FCM024B  1661 2005    345     14      0     .637  1.00   4.32   .978   .953   .223   2.57   .343   .026   1
 70 FCM024A  1660 2005    346     14      4     .573  1.05   4.38   .929   .945   .277   2.45   .252   .001   2
 71 FCM031C  1659 1845    187      7      0     .507  1.26   4.66  1.152   .904   .234   2.72   .403  -.007   1
```

Appendix A6. *Continued.*

```
                                               Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                          No.    No.    No.    with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
Seq Series   Interval   Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
 72 FCM031B  1853 2005    153      6      0    .709   .63   1.34   .293   .823   .264   2.52   .315  -.018   1
 73 FCM004B  1659 2005    347     14      0    .593   .91   3.54   .613   .819   .291   2.81   .456   .017   3
 74 FCM039A  1493 2005    513     14      1    .537   .72   2.79   .478   .878   .222   2.81   .447   .000   1
--- -------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:          19457    785     29    .579  1.08   5.91   .592   .788   .261   3.03   .371   .005
```

Vita

Jessica Dominique Slayton was born in southern Idaho on Mountain Home Air Force Base in 1983. She developed an early interest in geography through lengthy family travel adventures during childhood, eventually assuming the role of navigator on a trip from New Mexico to Alaska. She attended Palmer High School in Palmer, Alaska and Union County High School in Maynardville, Tennessee, graduating valedictorian of her class. Jessica received a B.A. in Geography *summa cum laude* from the University of Tennessee in Knoxville before entering the graduate program in Geography in the fall of 2005. While in the graduate program, Jessica served as a graduate teaching assistant for several different geography courses as well as a graduate teaching associate for an introductory physical geography course. Upon completing her M.S. degree, Jessica plans to head generally northwards and pursue employment which will allow her to use her education to its potential.