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I am submitting herewith a dissertation written by Lisa Battaile LaForest entitled "Fire Regimes of Lower-elevation Forests in Great Smoky Mountains National Park, Tennessee, U.S.A.." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Henri D. Grissino-Mayer, Major Professor

We have read this dissertation and recommend its acceptance:

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# FIRE REGIMES OF LOWER-ELEVATION FORESTS IN GREAT SMOKY MOUNTAINS NATIONAL PARK, TENNESSEE, U.S.A.

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Lisa Battaile LaForest
August 2012

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# DEDICATION

This dissertation is dedicated to my family members, friends, colleagues, and companion animals who helped keep me sane (mostly) during the Ph.D. journey.

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# ABSTRACT

Disturbance is a natural part of any forest ecosystem. When disturbance regimes are altered, the forest stands will reflect those changes. Southern Appalachian xeric pine-oak woodlands are one forest type that has experienced such change, primarily in the form of fire suppression. The western side of Great Smoky Mountains National Park contains stands of large trees that escaped earlier intensive logging, show evidence of past fire, and provide an ideal setting for reconstructing stand histories. For three lower-elevation (ca. 500 m ASL) study sites, I used crossdated yellow pine tree-ring chronologies and records from cross-sections taken from living and dead pines to reveal historical patterns and relationships of wildfire, climate, and human activity. Cores and vegetation data collected at three 20 x 50 m plots per site provided age structure, stand structure, and stand composition. All three chronologies displayed a high degree of sensitivity to yearly environmental fluctuations and extended back through the 1700s. Yellow pine growth was strongly and positively correlated with winter temperatures, which were primarily influenced by the North Atlantic Oscillation. The tested climate variables displayed relationships that appeared to shift over time, or across an ambiguous boundary on which the park resides. Climate oscillations in both the Atlantic Ocean and Pacific Ocean modulated wildfire frequency and events. Wildfire events occurred frequently prior to park establishment in 1934 and were primarily anthropogenic in origin. Most fires burned during dormancy or early in the growing season, but widespread and more recent fires tended to occur later. Fire frequency peaked in the 1800s with an average return interval of two years. Absence of wildfire during suppression was associated with establishment of fire-sensitive species, such as red maple and eastern white pine. Yellow pine regeneration was weak and dominated by Virginia pine. Results from this study can be used by park personnel to plan and manage fires to restore ecosystem processes to a pre-suppression state. The chronologies provided three centuries of data that can be used to reconstruct climate variables and to enhance our understanding of climate dynamics.

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# CHAPTER 1

## SOUTHERN APPALACHIAN PINE AND PINE-OAK FORESTS: ECOLOGICAL COMMUNITIES ON THE DECLINE

### 1.1 Purpose

The purpose of this study was to determine the response and relationships of pine and pine-oak forests to climate and wildfire in the in Great Smoky Mountains National Park (GSMNP), using the science of dendrochronology, and is part of a collaborative project between the University of Tennessee and Texas A&M University that investigates historical fire regimes in the southern Appalachian Mountains (Flatley *et al*. 2011). The number of yellow pines (*Pinus* subgenus *diploxylon*) in many pine-oak communities is declining (Vose *et al.* 1995). This trend was noted as early as the 1970s in western North Carolina forests where 98% of the pine-oak stands were determined to have minimal numbers of pine trees remaining on the landscape (Smith 1991). The suppression of fire has heavily affected pine-oak forests (Hubbard *et al.* 2004, Dumas *et al.* 2007). Both yellow pines and oaks are not regenerating sufficiently to maintain these forests, and are apparently being replaced by fire-sensitive species, such as red maple (*Acer rubrum* L.) (Harrod *et al*. 1998, Harrod and White 1999, Abella and Shelburne 2003). In conjunction with lack of fire on the landscape, extended droughts (*e.g.* mid-1980s) and southern pine beetle (*Dendroctonus frontalis* Zimm.) infestations (Price *et al*. 2002, Kloeppel *et al*. 2003, Lafon and Kutac 2003) have also contributed to the loss of yellow pine trees. The loss of these key pine and oak species can negatively affect the wildlife community by reducing sources of food, such as acorns and pine nuts, and shelter (*e.g.* nesting cavities).

Within GSMNP (Harrod *et al.* 1998, Harrod and White 1999), a protected area of great diversity and a refuge for many endemic species, evidence suggests that the pine-oak forest type there is disappearing (Knebel and Wentworth 2007). This study will provide much-needed information on the status of yellow pine stands and their associated communities in the park, and will reveal how the trees are responding to environmental factors in both short- and long-term time frames. It will also present a detailed history of the fire regimes of these stands in the park prior to Euro-American colonization, during settlement of the Great Smoky Mountains, and after fire suppression policies were enacted.

Dendrochronology and standardized vegetation survey techniques were used to determine canopy tree ages and changes in stand composition, and the dates and temporal distribution of historical fire events. Statistical analyses were performed to determine relationships between yellow pine growth and selected climate variables, and to ascertain any correlation between past wildfires and climate. Results from this study can be used by scientists to better understand fire-adapted ecosystems undergoing change, and also by land managers who wish to document historical fire regimes to more properly judge and implement restorative treatments in degraded forest stands.

### 1.2 Research Questions

Four major research questions will be addressed in this dissertation.

1) Which climate factors influence growth in the mixed-pine/pine-oak stands in the western Great Smoky Mountains National Park?

2) What were the historical fire regimes over the past three centuries and were any regime changes associated with human activity?
3) What is the current age structure and composition of the stands and is pine regeneration favored?
4) Were specific wildfires correlated to climate conditions, or were they possibly related to other factors such as anthropogenic activity or lightning?

## 1.3 Justification

Southeastern forests have been modified by the suppression of fire, which began in the 1920s on U.S. federal lands (Stephens and Ruth 2005). This policy changed the character of the national forests and parks established in the region in the 1930s and 1940s, including Great Smoky Mountains National Park (Frome 1966, Pyle 1988). At the time, fire was primarily viewed as a destructive force that led to a loss of forest resources, especially lumber. It was not understood that fire was, and is, a natural and critical component of many ecosystems. A lack of fire is now known to cause changes in species composition and vegetation structure in ecosystems (Buckner and Turrill 1999, Vose 2000).

Fire suppression allows the understory and midstory of forests to become more crowded with saplings (Chapman *et al.* 2006), which stresses the trees through increased competitive pressure. Under severe drought conditions, a crowded understory can also provide a ladder for fire to reach up into the canopy, which increases the incidence of mortality in the mature trees. Some species cannot adequately reproduce, or compete, in the absence of fire.

Table Mountain pine (*Pinus pungens* Lamb.), for example, typically has serotinous cones that require heat to liberate the seeds. Fire also clears away excess organic matter on the forest floor, releasing nutrients and exposing a cleared mineral surface upon which pine seeds can out-compete deciduous trees in germination (Groeschl *et al.* 1993).

Public land managers are increasingly using prescribed burning to clear forest stands and restore ecosystem processes to a pre-suppression state (Brose *et al.* 2001, Fulé *et al.* 2005, Whitlock *et al.* 2003), and realize that different ecosystems require different management plans (Dellasala *et al.* 2004). Other methods of thinning, such as logging, do not adequately mimic the effects of fire on the landscape (Gallant *et al.* 2003, Kauffman 2004). To properly implement a prescribed burning policy, a thorough understanding of the historical fire regime, and how the vegetation responds to the presence and absence of fire, is needed.

Fires vary in intensity and frequency. High-severity fires are extremely hot and often reach up into the crown, which kills the larger trees and causes major changes to the affected ecosystem (Waldrop *et al*. 2003). Low severity fires generally creep along the forest floor, clearing duff and debris, and inhibit fire-intolerant tree species from competing with those species that are adapted to the presence of fire. Fires that occur too frequently can be detrimental by not allowing time for desirable plants to recover before the next fire. Inversely, if fire events are too widely spaced over time, an excess of fuels may build-up along with an increase in understory vegetation density. Historically, most fires in the southern Appalachian Mountains were low-severity (Lafon *et al.* 2007) and occurred on a regular basis. Without the maintenance function of this type of fire, woody fuels accumulate, and, under severe drought conditions could possibly contribute to high-severity, stand-replacing fires.

Dendrochronology is a useful tool for fire history studies and other types of ecological research (Fritts and Swetnam 1989). This science uses tree-ring series that have been visually and statistically crossdated to accurately record the pattern of year-to-year variability in annual growth. These series are then used to generate tree-ring chronologies on varying scales, from forest stands to larger geographical regions. An anchored chronology is linked to series acquired from living trees and can, therefore, have exact calendar dates applied to the individual rings. Under certain conditions, a fire will leave a scar at the base of the tree and in the growth ring forming at the time of the fire (Arno and Sneck 1977). The scar will eventually heal over unless the tree dies. An unhealed tree can accumulate multiple pyrogenic scars at its base as a "catface," a term borrowed from the turpentine industry (Prizer 2010). Each scarred ring in the tree can be assigned a calendar year by crossdating the pattern of the ring series that contains the scar to an existing anchored chronology, for which the ring dates are known. Optimally, these chronologies would be developed from the same species as the fire-scarred sample, and would be created using tree-ring series from the same geographical area from which the sample to be dated were collected. The chronology samples should be collected from trees for which the ring pattern variability is primarily driven by climate fluctuation (*e.g.* temperature and precipitation) rather than from other factors that just affect individual trees, or small groups of trees. It is also important that the rings have clear ring boundaries and show minimal intra-annual variation for optimal crossdating. Yellow pines are excellent recorders of fire events as they tend to have clearly-defined rings (Hoadley 1990), and also preserve well due to their high resin content. Oaks and other hardwoods also scar, but they are more difficult to use as the wood tends to rot, obscuring or obliterating the tree-ring record. Ring series from these species can be difficult to accurately date because of intra-ring variability or unclear boundaries.

Many fire studies have been conducted in the western U.S. (Baisan and Swetnam 1990, Dieterich 1983, Floyd *et al.* 2004, Grissino-Mayer *et al.* 2004, Miller *et al.* 2009) where spatially extensive wildfires are a common occurrence, but information is lacking on fire studies in the southeastern U.S. Evidence from the few studies done to date indicates that fires did play an important role in southern Appalachian ecosystems prior to suppression (Harmon 1980, Armbrister 2002, Waldrop *et al.* 2003, Feathers 2010).

To better understand the decline of yellow pine and pine-oak communities in the southern Appalachian Mountains, it is also necessary to determine the response of the trees to broad-level environmental factors over both short- and long-term time scales. Climate variables change over time. Long-term changes primarily influence forest type (*e.g.* pine-oak), and short-term changes generally affect the growth of the trees and variability in species composition. Climate fluctuations can additionally alter the presence, timing, and spread of wildfires.

### 1.4 Biogeography and Ecology of Southern Appalachian Pine and Pine-Oak Forests

Gymnosperms of the genus *Pinus* have been on the North American landscape for over 100 million years (Richardson and Rundel 1998). By 50 million years ago, pines diversified into two major categories, haploxylon and diploxylon. Haploxylon are "soft pines" with four to five needles per leaf bundle and a single vascular bundle per needle. Diploxylon are "hard pines" with one to six needles per leaf bundle and two vascular bundles per needle. The wood of diploxylon species is generally more dense and yellow than that of soft pines, especially the white pines. White pines tend to show a more gradual change in tracheid (elongated cells for water transport) density and cell wall thickness during the transition from early to late growing seasons, with less color change (Fralish and Franklin 2002). All pines have resin that helps to seal wounds and to deter burrowing insects. There are 37 species of pine extant in North America today (Poole 2009). These trees can be found in habitats ranging from deserts to high mountains.

Pines are widespread and ecologically important. They are often pioneer species in disturbed areas, improving conditions for other species in areas that are suitable for succession (Auten 1945, Hosner and Graney 1970, Sutherland *et al*. 2000). Pines are also resilient on rocky, nutrient-poor areas and perform beneficial services such as providing food for wildlife and erosion control (Van Dersal 1938, Harlow and Doyle 1990). These trees are also valuable to humans, supplying materials for building and other products.

In the southern Appalachian Mountains, pines are often found in association with oaks and hickories, especially in xeric stands (Braun 1950). Pines can also be seen in almost pure stands on harsher sites. The distribution of tree species, including pines, is strongly driven by environmental gradients, primarily moisture and elevation (Whittaker 1956, Reilly *et al.* 2006). Several species of pine are native to the region and have overlapping ranges.

Eastern white pine (*Pinus strobus* L.) projects its range down the Appalachian mountain chain from the Northeast (Little 1995). It is the only haploxylon pine native to the area. Pitch pine (*P. rigida* Mill.), a yellow pine, also has a northerly range that extends from Maine to north Georgia. Table Mountain pine (*P. pungens* Lamb.) is restricted to the Appalachian Mountains. The range of Virginia pine (*P. virginiana* Mill.) is also centered on the Appalachians, but it extends into the lower elevations on either side of the mountains. Shortleaf pine (*P. echinata* Mill.) is the most widespread of the southern yellow pines with a range that covers a large swath of land from Texas to New York (Little 1995).

Shortleaf pine is found in low to moderate elevations (up to about 1000 m) and it is not typically located on the highest ridge tops as is Table Mountain pine, which has a range that rises to approximately 1,200 m above sea level (ASL) (Little 1995). Shortleaf pine is a commercially-valuable species that is often grown in plantations at lower elevations across the South. The maximum documented life span for shortleaf pine was 300 years (Loehle 1988), but more typically the older trees are found to be about 200 years old (Haney and Lydic 1999). During my research, we documented a living specimen in GSMNP that exceeded 324 years in age. On optimal sites, shortleaf pine can attain heights of over 30 m. It is considered a large-sized tree and mature specimens have diameters up to 1 m. The needles are 7–11 cm long in bundles of two or three. Cones are 4 to 6 cm long with a spine on each scale. The bark is reddish-brown, thick and platy. The surface often has small resin ducts that resemble miniature (1 mm) volcanoes. Shortleaf pines compete well in areas that experience high fire frequency;

seedlings and young saplings often resprout after injury from axillary buds at the base of the stem (Keeley and Zedler 1998).

Pitch pine is found in elevations up to about 1300 m (Little 1995). The oldest living specimen was recorded at 375 years (Pederson 2009), but the species can live up to 450 years (Gucker 2007). Comparable in size to the shortleaf, pitch pines grow to about 25 m in height and 1 m in diameter. Pitch pine is known to hybridize with shortleaf pine in the southern Appalachians. The needles measure up to 15 cm long and are most often bundled in threes. Cones are 3–7 cm long with a thin, sharp spine on the ends of the scales, and are sometimes serotinous. The bark is dark gray, thick and rough. Often the boles have epicormic sprouts emerging from the sides, a feature characteristic of pitch pines and useful in their identification. Pitch pine saplings and seedlings can exhibit basal resprouting after fire (Keeley and Zedler 1998).

Table Mountain pine is more often found at higher elevations than the other pines, where it competes more successfully on bare mountain ridges (Little 1995). This relatively smaller tree grows to an average height of 6–12 m and 0.3 to 0.6 m in diameter. The bark is dark gray, thick and furrowed. Needles are 3–6 cm long and usually occur in bundles of two. The substantial 5 to 9 cm -long cones have large spines and remain attached to the tree for many years. The cone protects the pine seeds until they are released by fire (Keeley and Zedler 1998).

Virginia pine is considered an early successional species because of its fast growth and ability to colonize old fields (Little 1995). It is commonly found at 30 to 762 m ASL. The trees grow 9–18 m in height and 0.3 to 0.5 m in diameter. Needles are bundled in twos, and are 4 to

7.5 cm in length. The bark is thinner and flakier than other yellow pine species in the southern Appalachians. Cones are 4–7 cm long. Virginia pines are adapted to regenerate in areas after a large disturbance, such as stand-replacing fire, and the cones are frequently serotinous (Keeley and Zedler 1998).

Southern pine beetles are a major cause of yellow pine mortality in the southeastern United States. A large attack can overwhelm even strong, previously healthy pines (Reeve 1997). Trees that are stressed by drought or injury are more vulnerable to beetle infestation (Kloeppel *et al*. 2003). Pine bark beetle outbreaks have positive-feedback interactions with wildfire (Gibson and Negron 2009). Fire can injure trees, making them more susceptible to beetle infestation. In turn, beetle-killed trees can provide fuel that influences future fires. A balance of fire and beetle activity may increase diversity and productivity in forests which would allow a faster response to disturbance (de Groot and Turgeon 1998).

Studies conducted prior to 1980 (Leuschner 2002) indicated that in the southeastern U.S., dead trees were slow to decay and fall. This reduced contribution to accumulated ground debris so that the snags did not provide substantial fuel for wildfires. Over the course of my research in GSMNP, storms and wind events have knocked down most, if not all, of the numerous dead pines across the study area. Under severe drought conditions, this large quantity of woody debris could potentially fuel a higher-severity fire. In the absence of fire, stands in this condition favor shade-tolerant hardwood regeneration over pine (Knebel and Wentworth 2007).

Yellow pines have many characteristics that assist survival and regeneration in the presence of fire (Agee 1998). Thick bark insulates the living cambial layer from high temperatures and protects it from damage. Harmon (1980) found that bark thickness increases towards the base of trees located in GSMNP, which would better protect them from ground-level fires. Many pines also self-prune their lower branches, which increases the distance of living branches from the ground. Others have serotinous cones, such as Table Mountain pine, that safeguard seeds for extended periods. The seeds are eventually freed from the cone after fire melts the resin that seals it; thus, the release is timed so that the seeds are more likely to fall on bare mineral soil, which is more hospitable for germination (Agee 1998). Another feature of some yellow pines, epicormic sprouting, allows for the replacement of branches that were lost to fire. Some younger pines have the ability to resprout from the root collar if the primary stem is damaged (Keeley and Zedler 1998). Oaks found in association with pines also show adaptations that allow them to withstand fires (Van Lear and Brose 2002), such as thick bark and the ability to repeatedly resprout.

Pines are typically found in communities with a high oak component (Abrams 1992), with the exception of the harshest habitats. Many of these stands have anthropogenic origins (Vose *et al.* 1995). Humans used fire to clear the landscape for centuries prior to the 1930s (Delcourt and Delcourt 1997). Suppression of fire in recent decades has altered forest composition and dynamics. Abrams and Orwig (1996) determined that both oak and pine recruitment have suffered in the absence of fire across the eastern U.S.

Restoration of pine-oak ecosystems is complex. Various treatments are under investigation including mechanical removal of trees, prescribed burning, and combinations of the two techniques. Vose *et al.* (1995, 1999) found that fell-and-burn treatment was more costly and removed more nitrogen (a necessary component of plant growth) from the ecosystem than stand-replacing burns, while each method was able to regenerate pine. In another study, carbon and nitrogen loss were both minimal after low-intensity fire, but there was a significant reduction in coarse woody debris and forest litter (Hubbard *et al.* 2004). Single low-intensity fires may not be sufficient, however, to restore pine-oak stands after extended periods of fire suppression (Harrod *et al.* 1998). Single fires also allow for resprouting of competitive species (Kuddes-Fischer and Arthur 2002), such as red maple (*Acer rubrum* L.), that can hinder the regeneration of oaks and pines. Restoration may require combinations of mechanical removal and fire, and varying levels of fire intensity. My research provides information on historical fire frequency and seasonality that will be useful for planning and implementing maintenance of post-restoration stands in GSMNP using prescribed burning.

### 1.5 Background to Fire Regimes

A fire regime describes the spatial and temporal activity of fire at a site. Several variables can be measured to characterize a fire regime, including fire type, fire frequency, areal extent of the fire, and seasonality of the fire (Morgan *et al*. 2001, Schuler and McClain 2003, Taylor and Skinner 2003, DeWeese 2007, Feathers 2010). Three general types of fire are: ground fires, surface fires, and crown fires, the latter also known as stand-replacing fires (Graham *et al*. 1999, Flannigan *et al*. 2000, Stanturf *et al*. 2002, Speer 2010). Ground fires smolder within the organic layer of soil, sometimes for many years. These are typically found in areas that have thick and organic-rich soil, such as that in a peat bog. Surface fires are often found in pine ecosystems.

They burn frequently and may kill smaller trees, but these fires generally leave mature trees alive. Crown fires burn up into the canopy and cause high mortality rates in trees of all sizes. Trees within certain pine ecosystems, such as lodgepole forests, are adapted to such fires (Axelson *et al*. 2009). These pines have serotinous cones that are tightly sealed with resin and typically require high temperatures to release the seeds. Because crown fires kill trees rather than scarring them, the fire record has to be determined by examination of the forest stand age structure (Kipfmueller and Baker 1998, Huckaby *et al*. 2001, Speer 2010). Stands that experience low- to moderate-severity fires contain trees of many age classes, while those that have experienced a high-severity fire are even-aged or have trees that are in only a few age classes (Fulé *et al*. 2003, Taylor and Skinner 2003, Whitlock *et al*. 2004).

Fire frequency is a measure of how often a fire occurs within a given area and time frame. Seasonality refers to the time of fire occurrence within the annual growth/dormancy cycle. In temperate climates, annual tree rings generally progress from a lighter and less-dense earlywood that has thin tracheid (xylem cell) walls to a darker and dense latewood as growth slows down and eventually ceases for the year. If the fire scar is directly upon the sharp boundary between the previous and current annual rings, it is likely a dormant season fire. If a few earlywood cells are present between the scar and the ring boundary, then the fire occurred very early in the growing season. If the scar is in the darker latewood, then the fire was later in the growing season (Baisan and Swetnam 1990, Taylor and Skinner 2003).

Several statistics can be used to describe the range of fire interval data including: Mean Fire Interval (MFI), Weibull Modal Interval (MOI), Weibull Median Interval (MEI), Standard

Deviation (SD), Coefficient of Variation (CV), Minimum Fire Interval (MAX), Maximum Fire Interval (MIN), Lower Exceedance Interval (LEI), Upper Exceedance Interval (UEI), and Maximum Hazard Interval (MHI). The MFI is the average length of the fire intervals, with MIN and MAX being the shortest and longest interval lengths, respectively. MOI, another measure of central tendency, is the fire interval that contributes the largest amount of area under the probability density function curve for the Weibull distribution. The MEI represents the 50th percentile of the fitted distribution (Grissino-Mayer 2001). It is a measurement of the frequency in which fire would occur in the stand, and provides gives a more robust result than calculating the mean. The Weibull distribution is useful for fire history studies because it can model positively skewed distributions and is not strongly affected by outliers (Grissino-Mayer 1999). The LEI and UEI are the intervals associated with the 12.5 and 87.5 percentiles of the Weibull distribution, respectively. Intervals at the outer edges of the distribution are considered to be unusually short or long (Grissino-Mayer 2001). The MHI is derived from the Weibull hazard function and represents the theoretical maximum fire interval that an ecosystem can sustain before a fire event becomes highly probable based on the preceding fire intervals in the distribution (Grissino-Mayer 1999). The standard deviation (SD) and coefficient of variation (CV) are measures of dispersion about the mean of the fire interval distributions. The CV provides a measure of the homogeneity of fire frequency over time; the lower the CV, the more homogenous the intervals (Grissino-Mayer 1995).

### 1.6 Wildfire History from Yellow Pines in the Southeastern U.S.

Several wildfire studies have been conducted in stands of Table Mountain pine (TMP), a species endemic to the southern Appalachians. Williams and Johnson (1990) used stand age structure to detect recruitment pulses of TMP at three sites on Brush Mountain in Southwestern Virginia. The pines at all sites presented a bimodal age distribution. The most recent peak was in the 10-year age class, and the earlier peaks ranged from 45 to 80 years (approximately 1910 to 1945). Evidence of fire was found at the sites, but the authors did not link age structure to particular fire events.

DeWeese (2007) conducted a comprehensive study over four sites in the George Washington/Jefferson National Forests in southwestern Virginia that combined fire-scar records from living and dead pines, primarily TMP, with stand dynamics data from vegetation plots. The record of fire events extended from 1694 to 1994, with most fires occurring between the mid-1700s and the 1930s. The Weibull median fire return interval ranged from 1.8 years to 3.3 years if including all scarred trees and from 4.1 years to 8.0 years when at least 10% of the trees sampled were scarred for each event. The majority of fires occurred in the dormant or early in the growing season. All sites showed some degree of bimodal distribution of the pine age structure, with the most recent peak centered on the 1940s. Earlier peaks varied by site and were centered between 1881 and 1920. The large, most recent pulse of pine regeneration was linked to widespread fires in the decade prior to 1935. Age-diameter graphs provided by DeWeese clearly showed links between fire events and pine establishment at each site, as well as the establishment of numerous hardwood trees following fire suppression.

In Great Smoky Mountains National Park (GSMNP), Armbrister (2002) examined TMP-dominant stands at five sites that extended across the north-central portion of the park. This study also combined records from fire-scarred pine sections and data from vegetation plots. Because of collection restraints (only handsawing was allowed) and a lack of quality samples, only 17 cross-sections were used in the fire history analysis. Prior to the 1930s, the Weibull median fire return interval was 6.8 years, indicating the regular occurrence of wildfire on the landscape. Fire suppression on the landscape was evident in the scar-free outer rings of the samples. Species inventories showed mountain laurel (*Kalmia latifolia* L.), an ericaceous shrub that is often associated with pines on xeric sites, to be dominant in the understory. The age structure of TMP at all sites peaked in the 60- to 70-year class. This placed establishment during the mid-1930s.

An earlier research project conducted by Harmon (1980) in GSMNP used samples of fire scars from several yellow pine species distributed across the western end of the park to examine the change in fire regime after park establishment. Wedge-shaped samples were removed from 43 trees and a total of 115 scars were recorded, the oldest of which dated to ca. 1856. Harmon was restricted to collecting samples with a handsaw, which constrained his ability to access the oldest scars in the central portion of standing trees. From 1855 to 1940, the mean fire interval was 12.7 years on south-facing slopes, which in the northern hemisphere, tend to be warmer and drier than northern slopes. Very few fires were recorded between 1910 and 1940.

In a study of four upland yellow pine stands located in Tennessee, South Carolina, and Georgia, Brose and Waldrop (2006) collected cores and cross-sections that were analyzed for the primary purpose of detecting canopy releases caused by disturbances. Fire-scarred trees were not targeted, but if scars were found in the samples, they were used to date fire events. At each site, two to six fires were detected between 1900 and 1949. Only one or two were found after 1950. All of these studies suggest that fire had been a regular feature on the southern Appalachian landscape prior to suppression.

### 1.7 Relevant Fire Research on Southern Appalachian Yellow Pines

To provide for optimal restoration of pine communities, it is important to understand under which conditions the trees will germinate and survive. A series of related studies have been performed to determine the fire intensity at which Table Mountain pine will regenerate. Prescribed burns were conducted in Table Mountain/yellow pine stands in northern Virginia, Georgia, South Carolina, and North Carolina (Welch *et al.* 2000, Waldrop *et al.* 2002, 2003), which produced four levels of fire intensities: low, medium-low, medium-high, and high. Fire intensity refers to the energy output of the fire and is associated with temperature as well as duration of heating (Keeley 2008). Post-burn observations of pine regeneration were made in the first growing season. Yellow pine seedlings were abundant in areas burned at each intensity level, indicating that less-intense fires (*i.e.* cooler temperatures or shorter burn time) were sufficient to release seeds from the serotinous cones. The roots of the seedlings were able to penetrate relatively thick litter and duff layers (up to 9 cm) to reach mineral soil. However, follow-up monitoring of seedling survival was not performed. It was predicted by the authors that the pine sprouts would experience high mortality from competition with resprouting hardwoods, and from being shaded under the dense canopy cover.

Knowledge of pine growth and the relationship to climate is needed to understand how the communities will respond to change. Using dendrochronology, tree rings can be measured and the standardized series analyzed against temperature, precipitation, drought indices, and other climate variables. While trees in the East are considered less sensitive to variation in these factors than those in the more arid West, it is possible to carry out dendrochronological studies in the southern Appalachian Mountains through careful site selection (Stokes and Smiley 1996). Trees growing on slopes or at the edge of their ecological boundaries should be more responsive than those that reside in valley bottoms or in the center of their ranges.

Copenheaver *et al.* (2002) measured growth and climate relationships of yellow pines at upper (520 m ASL) and middle (350 m ASL) slope positions on a mountain in the western portion of the Virginia Piedmont. Tree-ring chronologies were developed from 20 pitch pines and 20 Virginia pines at each position. The trees at both positions showed a similar response to climate; growth was negatively correlated with previous year late-fall temperatures and mid-summer precipitation, but positively correlated with early-fall precipitation. The small difference in elevation between the sites did not notably affect the response of the pines to climate; trees on the upper slope and on the mid-slope displayed similar correlation patterns between the radial growth and the monthly temperature or precipitation data. However, the upper slope vegetation was more diverse as determined by comparing species importance values (in this study, the sum of relative frequency, relative density, and relative dominance).

A study of loblolly pine (*Pinus taeda* L.) in northern Georgia (Grissino-Mayer *et al.* 1989) used cores from 20 trees that were predicted to be climatically-sensitive and were randomly chosen from habitats within a 1256 km$^2$ area. The resulting tree-ring chronology was analyzed against monthly temperature and precipitation data for the local region. Published tree-ring statistics for loblolly pine were not available at the time, so comparisons were made with shortleaf pine. Loblolly pine was faster growing and less sensitive to climate compared to reference shortleaf statistics, but significant correlations were still found between loblolly pine growth and climate variables. Growth was most strongly and positively related to current summer precipitation, and negatively to current summer temperatures. They also found a negative association with previous summer temperatures and late-summer precipitation.

A later study of shortleaf pine performed in the same geographical area used samples collected from 31 trees at three sites (Grissino-Mayer and Butler 1993). Ring series data from all sites were pooled into one chronology, which was then analyzed against monthly and seasonal climate variables. Sensitivity of the chronology was low for the species, but still within the acceptable range. Results showed significant positive growth correlations with current summer precipitation, and significant negative correlation with previous summer temperature; comparable to the loblolly response in the 1989 study. A study in central North Carolina examined both shortleaf and loblolly pine species, and found that shortleaf pine was more sensitive to spring temperatures than loblolly pine (Friend and Hafley 1989). Growth of each species was positively correlated with high spring temperatures and high soil-water levels in late summer of the current year.

My comprehensive study of yellow pine and pine-oak communities in GSMNP complements research done in other locations in the southern and central Appalachian Mountains (Lafon *et al*. 2009, Aldrich *et al*. 2010, DeWeese *et al*. 2010). A thorough analysis of fire history and vegetation at each of three, distinct sites in the park will allow for comparison between forest stands, and will also provide information regarding common factors over the study area as a whole.

### 1.8 Relevant Climate Studies in the Eastern U.S.

Temperature is a primary climate variable that influences the radial growth of trees (Fritts 2001, Speer 2010), especially in sites where moisture is not a limiting factor (Briffa *et al.* 2001). It also drives growth at treeline, where temperature sensitivity of the trees is greater (Jacoby and D'Arrigo 1989, Davi *et al.* 2003). Oak growth in the southern Appalachian Mountains (Speer *et al*. 2009), and more specifically in GSMNP (White *et al*. 2011), exhibited a negative association with summer temperatures. Yellow pine growth in GSMNP had a positive relationship with winter temperatures, suggesting that warmer winters increase growth (Grissino-Mayer *et al*. 2007, Biermann 2009). A notable decline in the correlation between temperature and radial growth since the 1960s has been documented in a number of studies (Johnson *et al.* 1988, Briffa *et al.* 1998, D'Arrigo *et al.* 2008, Biermann 2009), however, controversy exists as to the cause or existence of this divergence phenomenon (Esper and Frank 2009, Loehle 2009).

In temperate zone trees, the timing of bud break in the spring season and of dormancy in the fall is also affected by temperature (Kozlowski and Pallardy 1997). Shoots and new leaves, or flowers, depending on the species, develop along the trunk or branches during bud break when temperatures have become consistently warm enough after winter to trigger new growth. In the fall, radial growth slows, then ceases. Deciduous trees lose their leaves prior to dormancy, but pines retain their needles and are able to photosynthesize and store carbohydrates outside of the growing season (Kozlowski and Pallardy 1997).

Precipitation is another climate variable that frequently has a strong correlation with radial growth (Fritts 2001, Speer 2010), especially in xeric locations such as the southwestern United States (D'Arrigo and Jacoby 1991, Grissino-Mayer 1995, Salzer and Kipfmueller 2005, Stahle *et al.* 2009). In the southern Appalachian Mountains, oak growth showed a strong positive relationship with precipitation during current-year June and July (Speer *et al*. 2009). Oak trees in GSMNP additionally showed a positive growth response to increased precipitation during the previous fall (White 2007, White *et al*. 2011). Studies of yellow pine growth in GSMNP showed a significant, but weak, positive correlation with winter and spring precipitation (Grissino-Mayer *et al*. 2007, Biermann 2009).

Drought indices are closely tied with both temperature and precipitation. The Palmer Drought Severity Index (PDSI) is a monthly index that indicates the severity of wet and dry conditions, and the Palmer Hydrologic Drought Index (PHDI) is a monthly index used to assess long-term moisture supply. Because PHDI takes into account moisture storage in the soil, it responds more slowly to dry conditions than does PDSI. The values for both indices usually fall between –6 (dry) to +6 (wet), but occasional values of –7 or +7 are seen. Significant positive relationships between PDSI and tree growth have been found in the western United States (Meko *et al.* 1993, Cook *et al.* 1999, Woodhouse and Brown 2001). In the central Appalachian mountains, growth of Table Mountain pine (TMP) trees was significantly, positively correlated with PDSI and PHDI in the prior-year fall and in the current-year summer months, indicating that increased moisture during these times led to increased annual growth (DeWeese 2007, DeWeese *et al.* 2010). Oak growth in the central and Southern Appalachian Mountains, and in GSMNP, had a positive relationship with the drought indices, primarily during the current summer months, suggesting that growth was enhanced by increased moisture and cooler temperatures during the growing season (White 2007, Speer *et al*. 2009, White *et al*. 2011).

Most instrumental climate data are only available for the previous 50 years, or so. Some measurements extend for the past century, but missing data may occur and the data tend to be unreliable. To study past climate conditions beyond the century mark, it is necessary to use proxies such as ice cores, lake sediments, and tree rings. These proxies record the environmental conditions in which they were produced. For example, they capture chemical or isotope changes over time (Miller *et al*. 2006), the presence of pollen (Delcourt and Delcourt 1980), shifts in microscopic organism assemblage (Duigan and Birks 2000), or charcoal incorporated into the strata (Whitlock and Larsen 2001). The width of each layer can also provide clues to the environment (Dean *et al*. 2002). When the proxies are calibrated against known environmental conditions, they can be used to extend the climate record back in time. Tree ring records can then be analyzed against the proxies to determine climate-growth relationships. Cook *et al.*

(1999) used 388 tree ring chronologies from across North America to create a gridded network of average summer (June–August) PDSI values. The dataset was expanded in 2004 to include additional chronologies, from which a 286-point 2.5 degree grid was made that covered most of the continent (Cook *et al*. 2004).

Climate fluctuations are related to shifts or oscillations within the hemispheric air masses, and also to changing sea surface temperatures. Movement or changes in location-linked high and low pressure centers modify wind patterns which then alter the flow of warm or cold air, and any moisture associated with the air. These dynamics influence the growth of trees, and also wildfire regimes with regard to frequency, severity, and spatial extent across North America (Ali *et al*. 2009).

The North Atlantic Oscillation (NAO) is a measure of sea level atmospheric pressure fluctuations between an area of typically low pressure over Stykkisholmer (or Akureyri, 63° N, 23° W), Iceland (known as the Icelandic Low) and an area of typically high pressure over Ponta Delgadas, Azores (38° N, 26° W, referred to as the Azores High) (D'Arrigo *et al*. 1993, Goodkin *et al*. 2008). The NAO generally cycles every 1.7 to 7 years and affects westerly winds and storm tracks across the northern Atlantic Ocean, especially during November to April (Hurrell *et al.* 2003, National Oceanic and Atmospheric Administration (NOAA) 2010). When pressure differences are great (*i.e.* positive phase), the eastern United States experiences warmer winters, as westerly winds increase across the ocean and warm, moist air is brought up from the Gulf of Mexico and the tropical Atlantic (Yin 1994, Greatbatch 2000, Stenseth *et al.* 2003). Opposite patterns are generally observed during the negative phase. Occasionally, a complete reversal of pressure occurs, leading to cold winters in Europe and in the eastern United States. From 1925 to 1970, NAO values trended toward a low pressure gradient or negative phase (D'Arrigo *et al*. 1993). Cook *et al*. (1998) used tree-ring records from eastern North America and northwestern Europe to reconstruct the NAO from 1701 to 1980. The dataset was later extended through 2001 (Cook *et al*. 2002). Winter NAO values correlate significantly with tree growth in the eastern U. S. (Cook *et al.* 1998), suggesting that warmer winters increase growth. Yellow pine trees in GSMNP had a significant positive correlation to January and February NAO values (Grissino-Mayer *et al.* 2007, Biermann 2009).

The East Atlantic Oscillation (EA) is similar to the NAO, except the pressure poles (approximately 55° N, 20–35° W and 25–35° N, 0–10° W) are shifted southward and the oscillation has a subtropical link. The positive phase is associated with below-average temperatures in the southern United States from January through May (Barnston and Livezey 1987, Nesterov 2009, NOAA 2010). Since the 1950s, the subtropical pole anticyclone (high pressure center) has gained strength, and is associated with increased precipitation in the northeastern United States (Henderson 2000). I am unaware of dendrochronology research in the eastern United States that has included the EA; however, at least one study was conducted in Europe using Norway spruce (*Picea abies* (L.) Karst.), but the results were inconclusive (Makinen *et al*. 2003).

The Atlantic Multidecadal Oscillation (AMO) is defined by sea surface temperature (SST, Kaplan series) variability in the northern Atlantic Ocean, and it affects air temperature and rainfall in the Northern Hemisphere. It is driven, in part, by the multidecadal fluctuations of the NAO (Kerr 2000). Distinct cool and warm phases each last 20–40 years and have an overall cycle length of 65–80 years. In the warm (positive) phase, rainfall is abundant in Florida and the Pacific Northwest, but decreases elsewhere in the United States. Hurricanes are also more likely to occur (Kerr 2005). Conditions are reversed during the cool (negative) phase, and streamflow (precipitation) increases in the southern Appalachian Mountains (Tootle *et al*. 2005). Longleaf pine (*Pinus palustris* Mill.) and slash (*Pinus elliottii* Engelm.) pines collected in southern Georgia were used in a study that compared oxygen isotope concentrations within portions of annual growth rings to AMO fluctuations (Miller 2005). The ratio of stable oxygen isotopes deposited by precipitation, and absorbed into the trees, provides evidence for climate and atmospheric circulation trends. Earlywood levels were negatively correlated to AMO from 1876 until about 1950, after which the relationship lost strength and reversed. This switch corresponded to increased El Niño-Southern Oscillation and Pacific Decadal Oscillation effects. Latewood isotope levels exhibited no significant correlation over the analyzed time frame (1876–1997). Gray *et al*. (2004) reconstructed the AMO using tree-ring records from eastern North America, Europe, Scandinavia, and the Middle East. The index spanned 1567 to 1990. An extended cool phase was observed in the reconstructed data from 1789 to 1849, following a neutral period that began about 1700. Short oscillations occurred between 1850 and 1925 that led into an extended warm phase that lasted until about 1970 (Gray *et al*. 2004).

The El Niño-Southern Oscillation is a dual-component climate phenomenon over the tropical Pacific Ocean. El Niño refers to atypically warm sea surface temperatures that extend along the equator to the western coast of Central and South America that change in response to a shift in sea-level pressure over Indonesia. The Southern Oscillation Index measures pressure differences in the region, specifically between Darwin, Australia and the island of Tahiti (Speer 2010). In normal, non-El Niño conditions, the trade winds prohibit the warmer surface waters from flowing eastward and sea level is notably higher near Indonesia than at Ecuador (NOAA 2010). During El Niño, the trade winds weaken and allow the warm surface waters to expand eastward. This essentially smothers the cool, upwelling sea water along the South American coast, which negatively affects marine life and fisheries there. El Niño cycles bring increased moisture and cooler temperatures across most of the southern U.S., especially during the winter months (October–March; Allan and D'Arrigo 1999), resulting in decreased wildfire activity (Gramley 2005). La Niña is associated with cooler-than-normal temperatures in the equatorial Pacific Ocean. During a La Niña year, most of the southern U.S. experiences warmer and drier conditions. Wildfires that start during this cycle tend to be more severe, driven by the availability of drier fuels (Gramley 2005). La Niña is considered the "cool phase" of the oscillation, in contrast to the "warm phase" of El Niño, and occurs less frequently. El Niño episodes often occur every three to five years, but minimum and maximum intervals of two and eight years have been recorded (D'Arrigo *et al*. 2005, NOAA 2010).

The NIÑO-3 reconstruction by Cook (2000) represents annual fluctuations of the El Niño-Southern Oscillation for each winter season (December-February). It was developed using age-detrended tree-ring chronologies from Texas and Mexico that were combined with instrumental data. The period of record extends from 1408 through 1978. The trees used in this reconstruction express the strongest ENSO signal found in any tree-ring data thus far (D'Arrigo *et al*. 2005). In contrast, the instrumental NIÑO-3 index is derived from seasonal sea surface temperatures (SST) averaged over the central Pacific Ocean (5° S-5° N, 90°-150° W; Torrence and Compo 1998). Positive values of the index indicate an El Niño phase, whereas La Niña values are negative.

The Pacific Decadal Oscillation (PDO) was discovered in 1996 by fisheries scientist Steven Hare while researching the relationship between Pacific climate and Alaskan salmon cycles (Mantua 2011). This oscillation modulates the effects of ENSO on the North American continent (Biondi *et al*. 2001). Warm phase PDO (positive) is associated with below average temperatures and with above average precipitation in the southeastern United States during October through March. Cool phase PDO (negative) conditions are reversed during those same months (Mantua 2011). Between 1976 and 1999, PDO was in a cool phase that was associated with a higher incidence of El Niño events (Joint Fire Science Program 2007). To reconstruct PDO from 1661 to 1991, Biondi *et al*. (2001) used tree-ring chronologies from southern and Baja California. Large shifts of PDO phase polarity were documented at around 1750, 1905, and 1947.

Using a network of tree-ring density chronologies from North America, Siberia, and Europe, Briffa *et al*. (1998) reconstructed northern hemisphere summer temperatures (NHTMP; April-September) for 1400 to 1994. The NHD1 index was generated by dividing the hemisphere into five regions, taking the mean of the chronologies within each region, and then averaging those means. Ring density was found to increase following large volcanic eruptions, which indicated cooler temperatures. Notably colder years included 1740, 1783, 1816–1818, 1836, 1837, 1884, and 1912. A strong warm peak occurred in 1878, and temperatures between 1930 and 1960 tended to be warmer than average.

### 1.9 Organization of Dissertation

This dissertation is composed of six chapters, three of which are written as manuscripts for publication. The first chapter provides an introduction to the biogeography and ecology of yellow pine and pine-oak communities in the southern Appalachian Mountains. A review of previous studies that focused on wildfire history and dendrochronological research in these forests is also presented. A detailed description of the study area and sites is covered in Chapter 2. Chapter 3, "Yellow Pine Radial Growth Response to Climatic Variables in great Smoky Mountains National Park, Tennessee, U.S.A.," explores the response of yellow pines to changes in precipitation and temperature. Description of the development of annual tree-ring chronologies is included, along with analyses performed to discern relationships between climate and growth using data collected at nearby weather stations. Analyses cover site to regional scales. The largest research chapter in this dissertation, Chapter 4, "Fire History and Regeneration Status of Yellow Pine and Pine-Oak Stands in Great Smoky Mountains National Park, Tennessee, U.S.A., " reports on past wildfire occurrence and temporal patterns at each of three sites used in this study. Complementary stand structure analysis is also presented. Chapter 5, "Relationships between Wildfires and Climate in Great Smoky Mountains National Park, Tennessee, U.S.A.," examines short- and long-term climate interactions with wildfire events. Investigative tools include superposed epoch analysis. Chapter 6 summarizes the research, draws conclusions, and makes recommendations for future research.

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# CHAPTER 2

# DESCRIPTION OF STUDY AREA AND SITES

## 2.1 The Southern Appalachian Mountains

The Appalachian Mountains have a rich and varied history. Within their embrace, they hold rocks that predate most, if not all, of life on Earth, have remnants of towering mountains, and harbor abundant fossils from former inland seas. In their southern realm, these mountains contain areas of high plant and animal biodiversity that likely served as refugia for many species during past glacial episodes. Cycles of lifting, erosion, submersion, and faulting have created a landscape that contains many different microclimates and habitats in which both widespread and endemic species reside.

The core rock of these mountains was formed over one billion years ago when all of the continents on Earth were unified into the supercontinent Rodinia. Approximately 750 million years ago (MYA), tectonic forces pulled Rodinia apart, forming the Ocoee inland sea. Marine sediments and materials that eroded from the land accumulated in the basin until the movement of the continents brought together most of the land masses to form the supercontinent Pangaea, about 270 MYA. Proto-North America (also called Laurentia) and Proto-Africa met in a collision that uplifted enormous masses of rock, overlapping and folding them, and created the Appalachian Mountain chain. The thickness of the underlying continental crust layer of these aged mountains is similar to that of much taller ranges, such as the Himalayas, indicating that the Appalachian Mountains were more massive in the past and have undergone substantial erosion since their formation (Matmon *et al.* 2003). Approximately 240 MYA, the continents again moved apart, forming the Atlantic Ocean. The spreading movement continues today, outward from the mid-Atlantic Ridge.

The Appalachian Mountain chain extends for more than 2000 km in length, from Maine, to northeastern Alabama, and includes peaks that reach elevations greater than 2000 m ASL. The famous Appalachian Trail, revered by hikers, follows much of the length. Three regions have been designated within the range: the northern Appalachian Mountains run from Maine to New York, the central Appalachian Mountains extend from New York to Virginia, and the southern Appalachian Mountains stretch from Virginia to Alabama. The southern Appalachian Mountains are further divided into several smaller mountain ranges that include the Unaka, the Unicoi, and the Nantahala. The Great Smoky Mountains are in the middle of the Unaka Range, a large portion of which is managed as National Forest.

Physiographic provinces, as defined by the U.S. Geological Survey (USGS), are based on geologic and topographic features of the landscape. There are 25 provinces in the U.S., which are further divided into divisions and sections (USGS 2010). Seven of these provinces cover the Appalachian Highlands Region: Piedmont, Blue Ridge, Valley and Ridge, St. Lawrence Valley, Appalachian Plateaus, New England, and Adirondack. Great Smoky Mountains National Park lies with the Blue Ridge province, between the Valley and Ridge to the west and the Piedmont to the east (Moore 1994, USGS 2010).

### **2.1.1** ***Great Smoky Mountains National Park***

Great Smoky Mountains National Park (GSMNP), which straddles the state border between Tennessee and North Carolina, is the most visited national park in the United States, attracting millions of people each year. The park was officially established by Congress on June 15, 1934, but as early as 1926, parcels of land were purchased from corporations (mostly logging) and from private individuals for the purpose of conservation (Pyle 1988). In addition to being the largest natural preserve east of the Mississippi River (Young 2006), GSMNP was also designated an International Biosphere Reserve in 1976 and a World Heritage Site in 1983 (National Park Service (NPS) 2010).

Many scientists believe that when thick ice covered much of upper North America during the continental glaciation events of the Pleistocene, plant and animal species sought refuge in these mountains. Many of these species can be found only in the GSMNP today. An ambitious, collaborative project underway, known as the All Taxa Biodiversity Inventory (ATBI), seeks to catalog every life form found in the park, and to document the rare, endemic species (White 2008). GSMNP encompasses 2072 $km^2$ of land, 95% of which is forested, and a quarter of that is old-growth forest. This is the largest area of temperate broadleaf deciduous old-growth forest in North America (NPS 2010). The National Park Service provides oversight of GSMNP and is charged with preserving the natural and cultural resources within the park, while still allowing the public to benefit from these resources (NPS 2010). Sustainability and ecological restoration are major goals of park management today (Young 2006).

### 2.1.2 *Climate*

The Köppen climate classification for the southeastern United States, including GSMNP, is mesothermal humid subtropical (Köppen 1936, Kottek *et al*. 2006). This classification denotes high humidity, especially in summer, and an absence of very cold winters. A distinct dry season is also lacking. Several ocean-atmosphere teleconnections, which are relationships between sea surface temperatures and atmospheric pressure, drive cyclic changes in air temperature and precipitation in the region (National Oceanic and Atmospheric Administration (NOAA) 2010). The most well-known teleconnection, the El Niño-Southern Oscillation (ENSO), cycles every five years, on average. In the southeastern United States, ENSO brings cooler, wetter winters during the "warm" phase, but while in the "cool" phase, known as La Niña, conditions are drier and warmer than average. Other teleconnections known to influence the southern Appalachian Mountains include the North Atlantic Oscillation (NAO), the East Atlantic Oscillation (EA), and the Atlantic Multidecadal Oscillation (Enfield *et al*. 2001, Stenseth *et al.* 2002, NOAA 2010).

The southeastern United States receives a large amount of moisture from air flowing over the Gulf of Mexico, which leads to relatively high annual precipitation (Konrad 1995). The peak incidence of average annual rainfall occurs just southeast of GSMNP, toward the North Carolina/Georgia border (National Weather Service (NWS) 2010). The mountainous terrain moderates how much precipitation reaches the ground locally, as well as temperature differences from varying levels of sunlight exposure and cold air drainage; thus, microclimates within GSMNP differ based on elevation and aspect. The highest elevations of the Great Smoky Mountains are generally cooler and wetter, while the south-facing slopes are warmer and drier

(Whittaker 1956). Moving up the mountain range in elevation is somewhat analogous to travelling on a northward transect through the eastern United States and into Canada (NPS 2010), because as elevation increases, the average temperature drops and the number of species declines, as occurs with increasing latitude.

The town of Gatlinburg (35°42′ N, 83°30′ W) is located just outside the western edge of GSMNP and represents a low-elevation (486 m) site for meteorological data. The mean monthly temperature at Gatlinburg ranges from a January high/low of 11/ –2 °C to a July high/low of 31/15 °C. Gatlinburg receives 1371 mm of precipitation annually (NPS 2010). In comparison, Clingman's Dome (35°33′ N, 83°29′ W), the highest peak in GSMNP at 2025 m ASL, has a mean January high/low of 2/ –7 °C and a mean July high/low of 18/12 °C . The mean annual precipitation of 2083 mm at Clingman's Dome is much greater than that of lower elevation locations nearby (NPS 2010). Precipitation over the park, as a whole, is relatively consistent through the year, although late spring and early fall are the driest times of the year.

### 2.1.3 *Topography*

The land within GSMNP exhibits considerable topographic relief. There are 16 mountain peaks over 1830 m ASL, some of which rise 1500 m above the valleys (Young 2006). These peaks represent the highest range in the southern Appalachian Mountains (Matmon *et al.* 2003); however, most of the slopes are covered with soil and vegetation, unlike many slopes in the western United States. The mountain range bisects GSMNP from the northeast to the southwest, and demarcates the state boundary line between North Carolina and Tennessee. The headwaters for several creeks originate in these mountains, including Abrams Creek, which winds through Cades Cove and the western portion of the park, eventually flowing into Chilhowee Lake, an impounded segment of the Little Tennessee River. Cades Cove is an unusual ovoid valley that was formed by erosion that revealed younger limestone layers that had been overthrust by older sandstones (Moore 1994). GSMNP is bounded by the Little Pigeon River to the east and the Little Tennessee River (Lake Fontana) and Tuckasegee River to the south and west. (Matmon *et al.* 2003).

### 2.1.4 *Geology and Soils*

The variety of rocks found in the southern Appalachian Mountains reflects the complex history of inland seas, subsequent uplift and orogeny, and intense pressure and heat generated during the collision of large land masses 270 million years ago (Clark 2003). The terrain of GSMNP is very rugged with an elevational range of 270–2025 m ASL (NPS 2010). Three basic classes of bedrock are found within the park. The oldest bedrock class (more than one billion years old) consists of metamorphic Precambrian rocks, including gneiss, schist, and granite. The most spatially-extensive bedrock is primarily metamorphosed sedimentary late-Precambrian rocks, such as phyllite, schist, quartzite, slate, shale, sandstone, and metasiltstone. These rocks are 500 million to one billion years old. In the western portion of GSMNP, the youngest rocks are sedimentary and about 300–500 million years old. This class of rocks includes limestone, dolostone, shale, and sandstone (King *et al.* 1968, Moore 1988).

### 2.1.5 *Vegetation*

The major vegetation patterns of Great Smoky Mountains National Park are most easily understood in terms of elevation and moisture gradients. Other topographic properties that can influence the forest structure at specific sites are stream courses, slope angle, and slope aspect. Eastern Forest is dominant at low to middle elevations, and Boreal Forest prevails at the highest elevations (Whittaker 1956). The Eastern Forest type is a mix of deciduous hardwood trees and evergreen conifers, and covers most of the land surface in the park. Boreal Forest consists of cold-tolerant conifer species including spruces (*Picea* spp.) and firs (*Abies* spp.)

Forest type differentiation is guided by soil moisture and elevation. The low-elevation (274–762 m ASL) forest types in order of mesic (moist) to xeric (dry) are: cove forest, red oak-pignut hickory forest, chestnut oak-chestnut forest, chestnut oak-chestnut heath, and Virginia pine forest. At lower-middle elevations (762–1219 m ASL), the forest types are: cove forest/hemlock forest, chestnut oak-chestnut forest/red oak-chestnut forest, chestnut oak-chestnut heath/white oak-chestnut forest, and pitch pine heath/Table Mountain pine heath. The higher-middle elevation (1219–1067 m ASL) pattern is similar to that of the lower-middle elevation except that beech forest is found in the mesic areas and grassy balds appear in the most xeric locations (Whittaker 1956). The Boreal Forest at the highest elevations (above 1067 m ASL) consists of red spruce (*Picea rubens* Sarg.) and Fraser fir (*Abies fraseri* (Pursh) Poir.) in the canopy level, while the understory components vary depending on moisture availability and slope characteristics. Heath balds occupy the most xeric of the high elevation areas (Whittaker 1956). All of these vegetation communities, from low to high elevation, are undergoing some form of change.

Widespread disturbance from pathogen and insect outbreaks has greatly altered the composition of the forest over the past 80 years. The American chestnut (*Castanea dentata*

(Marsh.) Borkh.), a sizeable tree species that was historically dominant throughout the Great Smoky Mountains, was decimated by the introduction of the chestnut blight in the 1920s. The disease killed most of the chestnut trees in GSMNP by the 1930s (Pierce 2000). Hickories, oaks, and red maple were the most common species to fill the open niche created by the loss of the chestnut trees (Woods and Shanks 1959). Unfortunately, these replacement species do not provide an equally high quality of food source for wildlife.

The fungus (*Cryphonectria parasitica* (Murrill) Barr.) that causes the disease originated in Asia and was discovered in the United States in 1904 (Woods and Shanks 1959). Some of the once-regal chestnut trees stricken by the blight remain alive, but most survive as coppice arising from existing root stock. After a few years of regrowth, the tree usually succumbs again to the fungus. As early as the 1940s, efforts were underway to cross-fertilize American chestnuts with blight-resistant Asiatic chestnuts to restore this important native tree to the landscape. In September 2009, previously-transplanted, blight-resistant chestnut seedlings (that retained 94% of the *C. dentata* genes) were reported to have survived their first growing season in National Forest lands of Tennessee, North Carolina, and Virginia (Taylor 2009).

Flowering dogwood trees (*Cornus florida* L.), a once-common component of moderately-moist eastern U.S. forests are also suffering from a blight, this one caused by the fungal pathogen *Discula destructiva* Redlin. The disease (anthracnose) has spread across GSMNP since the late 1980s (Jenkins and White 2002). Dogwood mortality was found to be high across the park, especially in moist and shady sites that favor fungal growth. Interestingly, dogwood density was much higher in an area burned by a wildfire in 1976. The authors theorized that the open stand conditions hindered the fungus, and suggested that prescribed burning may be useful in maintaining the dogwood component in oak-pine forests.

Two species of adelgid (*Adelges* spp.), aphid-like insects, have also significantly affected the forest. These insects feed on the sap of specific host trees, and inject a toxin that damages the vascular system of the tree. The balsam wooly adelgid (*A. piceae* Ratzeburg) has killed vast numbers of Frasier fir in the boreal zone of GSMNP. Hemlock wooly adelgid (*A. tsugae* Annand) has spread over the eastern United States, decimating stands of eastern hemlock (*Tsuga canadensis* (L.) Carrière) and Carolina hemlock (*Tsuga caroliniana* Engelm.). Driving through the park, one can see these dead trees dotting, and sometimes covering, the landscape. Managers at GSMNP originally planned to restore disturbed forest stands, or forest stands decimated by insect outbreaks, through the process of secondary succession (Young 2006), in other words, by letting nature take its course without human intervention. Currently, park personnel are playing a more active role by using targeted pesticides and predatory beetles to address the adelgids, and also by returning fire to the landscape.

### **2.1.6** ***Wildlife***

As well as a high diversity of plants, GSMNP hosts many species of animals, some of which are found nowhere else. Over 30 species of salamanders are present, the highest number located anywhere on the North American continent. One of the larger, and more well-known, animal species is the American black bear (*Ursus americanus* L.). Its image can be found gracing many souvenirs generated for the tourist trade. In 2001, elk (*Cervus canadensis* L.*)* were reintroduced to the park after elimination from over-hunting and habitat loss. Prior to the mid-

1800s, large ungulates such as elk and American bison (*Bos bison* L.) had freely roamed the landscape. Other successful wildlife reintroductions include the river otter (*Lontra canadensis* Schreber), Peregrine falcon (*Falco peregrines* Tunstall), and three species of small fish (NPS 2010). Additional species have flourished in this protected area. White-tailed deer (*Odocoileus virginiana* Zimm.) populations swelled in Cades Cove after creation of the park. Their numbers peaked in the 1970s, then declined into the 1990s (in Webster *et al.* 2005). Wild turkey (*Meleagris gellopav* L.*)* can often be heard calling through the trees, and are commonly seen in more open areas. Occasionally, red fox (*Vulpes vulpes* L.) and coyote (*Canis latrans* Say) can also be observed.

### **2.1.7 *Land Use***

About 8000 years ago, humans first entered the area that would become Great Smoky Mountains National Park (Pierce 2000). These Native Americans practiced a hunting-gathering lifestyle and maintained several trails into the mountains from their villages along the nearby rivers. Though often romanticized and considered benign inhabitants of the land, indigenous people likely had an effect on the structure of the southern Appalachian forests. They regularly used fire as a tool to drive game during hunting and to decrease the density of understory vegetation, which enhanced visibility, including that of enemy approach. Fire was also used to clear the ground to ease collection and boost abundance of staple foods such as chestnuts and berries, and to help control pest insect populations (Pierce 2000). This activity had the unintended consequence of facilitating fire-tolerant oak and pine species in the forests (Delcourt and Delcourt 1997, 1998)

European explorers and naturalists came through the region as early as the 1500s. Hernando de Soto of Spain passed nearby on his quest for gold that took him to the Mississippi River and beyond (Pierce 2000). Later in the 1770s, naturalist William Bartram wandered nearby while exploring the southern Appalachian Mountains, and recorded in detail the plants he found and the people he met (Van Doren 1955). Within two decades, the first European settlers made their homes within what would become the GSMNP boundaries, near present day Cherokee, North Carolina (Pierce 2000, Young 2006). European settlers moved into Cades Cove in 1818 (Webster *et al.* 2005), displacing the original Cherokee inhabitants. By the 1840s, the new settlers had claimed most of the major stream valleys (Pierce 2000).

The majority of the European settlers practiced subsistence farming, allowing their hogs and cattle to roam the open woods and the grassy balds in search of forage. Cattle favored tulip poplar, which may have helped establishment of Virginia pine in grazed areas that were eventually abandoned (Pyle 1988). Both of these tree species are among the first to regenerate in strongly-disturbed areas of Eastern Forest. The lower-elevation areas near homesteads were cleared for crops. The settlers also collected herbs (some to near extinction, such as ginseng), fruits, and nuts from the forest (Pierce 2000). They continued the Native American tradition of periodically burning the forest, including the xeric south-facing slopes where blueberry (*Vaccinium* spp.) bushes were prevalent (Shields 1981). Fires were more common in the lower elevations of the mountains where most of the home sites were located (Harmon 1982). Most of the settlement on the Tennessee side of GSMNP occurred below 760 m ASL, mainly around the park periphery (Pyle 1988).

The most destructive disturbances to the Appalachian ecosystems were from mining and logging activities. Prospectors arrived in the 1850s searching for gold and silver (Clark 2003), for which they had little luck; but instead, copper was found and mined in the far southwest portion of the present-day GSMNP. Heavy logging affected much of what is now park land, especially in the late 1800s through the early 1900s. The largest, most-profitable hardwoods were targeted first, but eventually two-thirds of the original forest cover were removed (Pierce 2000). Once this protective vegetation layer was cleared, the mountainsides eroded and streams were choked with sediment. This occurred rapidly and on a large scale, exacerbated by the numerous steep slopes found in the area and by the abundant rainfall.

During the same time as these massive natural-resource-collecting operations, a movement was spreading from the western United States that called for the protection of sites that exemplified America's natural beauty. California's Yosemite Valley was the first of these sites; initially designated a state park in 1864 and then made a national park in 1906. By 1916, the Department of the Interior was responsible for 14 national parks and 21 national monuments. President Woodrow Wilson signed the bill establishing the National Park Service (NPS) in August of 1916. In managing the newly-protected federal lands, the NPS was directed "to conserve the scenery and the natural and historic objects and the wild life [*sic*] therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations" (NPS 2010).

Wealthy people were the chief consumers who traveled to see the areas of natural beauty, and to partake in their fresh air and healing waters. Trains were a primary mode of transportation. In GSMNP, railways that had been created to haul lumber out of the forest were now used to bring tourists in. The number of resorts multiplied in the southern Appalachian mountains, and a complex at Elkmont was a very popular destination for many visitors. John Oliver of Cades Cove rented out cabins to vacationers starting in 1924 (Pierce 2000).

As more people experienced the beauty of the Great Smoky Mountains, concern grew with regard to its degradation, and the realization dawned that logging provided only short-term economic gain. Author Horace Kephart and his lesser-known photographer friend, George Masa, helped to broaden the audience of the park through their writings and pictures. Two organizations, the North Carolina Park Commission and the Great Smoky Mountains Conservation Association, acquired land as early as 1926 for the purpose of protection (Pyle 1988). Finally, after much politicking, controversy, and exchange of monies, Great Smoky Mountain National Park was officially established in 1934. Over 6,600 separate tracts of land had been purchased and incorporated into the park (Young 2006).

### 2.1.8 *Wildfire*

Wildfires in Great Smoky Mountains National Park usually originate from one of two ignition sources: lightning and human activity. Native Americans occupied the southern Appalachian Mountains for thousands of years, and their regular use of fire is evident in proxy records (Delcourt and Delcourt 1997). Prior to European settlement, the Cherokee burned areas of the forest for agriculture and hunting (Pierce 2000). In 1818, settlers moved into Cades Cove (Webster *et al*. 2005), displacing the native inhabitants; they had claimed most of the major stream valleys in the area by the 1840s (Pierce 2000). The settlers also periodically burned the forest, including the stands on xeric south-facing slopes where blueberry bushes were prevalent (Shields 1981). Fires were more common in the lower elevations of the mountains, where the majority of home sites were situated (Harmon 1982).

While some fires were ignited by lightning after 1834 (post-European settlement), the majority of the fires were most likely started by the European settlers (Barden and Wood 1976). Logging activity in the early 1900s ignited many fires in GSMNP, mainly along the railways (Pierce 2000); however, the western portion of the park was exempt from much of this activity (Pyle 1988). After the official establishment of GSMNP in 1934, fire was essentially excluded from the landscape (Rock 2000). Even under a policy of suppression, occasional fires still occurred. A study by Harmon (1981) determined that between 1940 and 1979 an average of 13.3 anthropogenic fires and 2.1 lightning fires occurred each year in GSMNP. Anthropogenic fires in the park tended to be bimodal with a large peak in April and a smaller peak in November. In 1976, a lightning-caused wildfire was allowed to burn near Polecat Ridge (close to Pine Mountain) in an attempt by park personnel to encourage a policy change that would permit some fires to burn naturally (Cohen *et al*. 2007). In the 1990s, a new fire management plan was enacted, and the first official wildland fire use (WFU) wildfire was permitted to burn at Forney Ridge. The WFU plan allows wildfires that are away from the park boundary, and within certain parameters, to continue burning until naturally extinguished (NPS 2010). Between 1998 and 2006, 16 lightning-ignited fires occurred, 10 of which were managed as WFU fires (Cohen *et al*. 2007). Eleven of the fires during that time frame were in 1988, a period of extreme drought in the region (Klos *et al.* 2009). Other notable fire frequency peaks occurred in 1953 (another severe drought period) and 1963. Interestingly, a strong peak in fire activity was not recorded during the 1998–2001 drought, as might have been expected. From 1940 to 2006, the vast majority (90%) of lightning fires occurred between the growing season months of April and August, during which time storm activity increased, and peaked in May (Cohen *et al*. 2007). A similar relationship was found between fire and weather found in Ohio (Petersen and Drewa 2006). In recent years, peak lightning-related fire activity has shifted into April (Cohen *et al*. 2007).

Prescribed burning activity by park personnel increased during the 2000s (NPS 2010). Five burns were conducted in 2004, for a total of 181.5 ha. Four of the fires were set to clean up piles of brush and debris. One WFU lightning fire occurred that year; a single eastern hemlock (*Tsuga canadensis* (L.) Carrière ) burned for 35 days, and affected very little vegetation on the ground. In April of 2005, the park conducted the largest prescribed fire to date. The Hatcher fire (west of Cades Cove) covered 930.8 ha, and was set to help perpetuate the yellow pine-oak community type. Four other prescribed burns were conducted that year for a total of 987.4 ha, including several fields in Cades Cove (NPS 2010). From April to July of 2006, a lightning fire near Chilly Springs Knob was allowed to burn 369.5 ha through an oak-pine community (Cohen *et al*. 2007). Prescribed burns were conducted in April 2007 in the Stony Ridge and Arbutus Ridge watersheds and also on Wash Ridge. In May 2007, a campfire near Abrams Creek evolved into the Buck Shank fire. This WFU-managed fire burned over 364.2 ha, and we were able to photograph the smoke plume from this fire during our fieldwork. While most of the prescribed burns were conducted in spring (March–May), dormant season prescribed burns have been found to reduce leaf litter and increase populations of rare plants in GSMNP (Rock 2000).

### 2.2 Study Sites

The study area for this research is on the western edge of Great Smoky Mountains National Park, an area with highly dissected topography located between the high central mountain ridge to the east and the Great Valley of Tennessee to the west (Figure 2.1). Toward the boundary of the park, the ridges are lower in elevation and lie parallel to each other. The long line of Chilhowee Mountain is positioned between the park boundary and the Great Valley, where the city of Knoxville is located. The study sites are within Blount County, which was established in 1795, prior to Tennessee statehood.

Potential research sites were targeted after consultation with park ecologists and examination of near-infrared aerial photographs of the study area. Healthy vegetation in these images is brightly colored (often designated red in color-enhanced imagery). This technique is most helpful for locating evergreen trees when the images are taken during the winter, after the deciduous trees have become dormant and lost their leaves. The pines, which retain needles year-round, stand out on the landscape in comparison to the bare deciduous hardwoods. The locations of suitable pine-dominant stands for sampling can then be identified. Even if the photos are taken during the growing season, with practice, differences in the visual textures between pines and hardwoods can be determined. For this research, ground scouting was used to confirm site appropriateness. Site selections were based on the presence of fire-scarred yellow

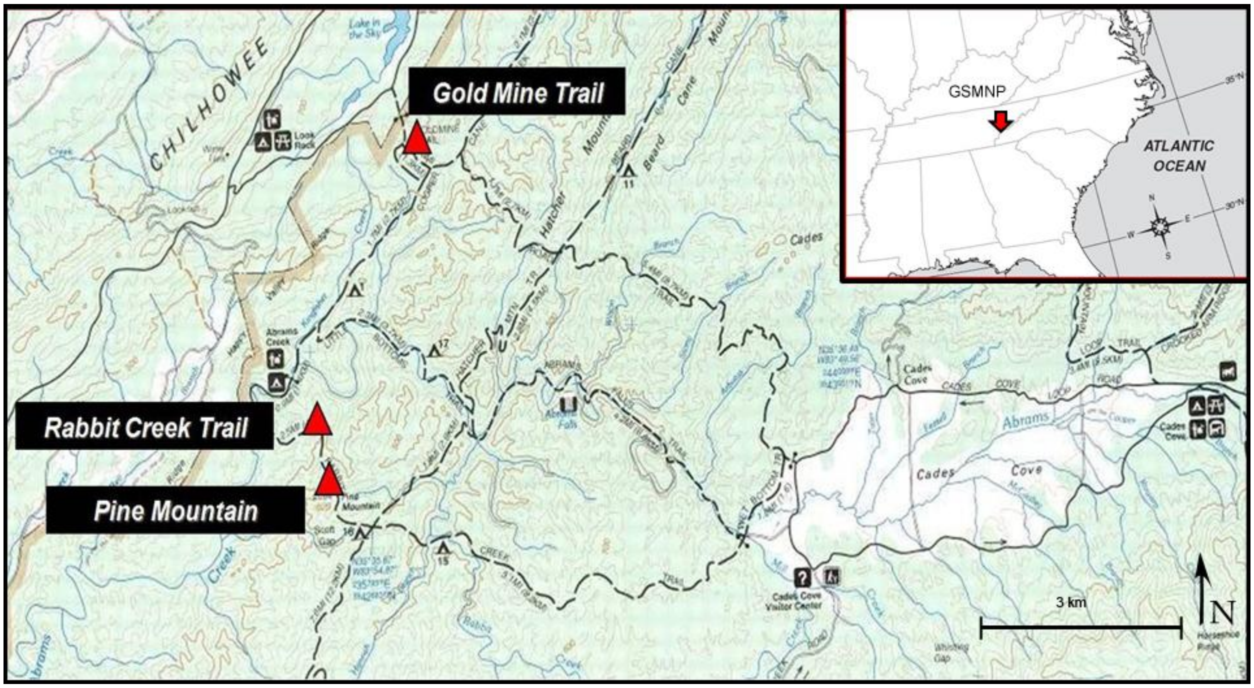

**Figure 2.1**: Map of Study Area. The three research sites are located near the western edge of Great Smoky Mountains National Park, Tennessee.

pines, and accessibility via trails or park roads over which research equipment could be transported (Figure 2.2). Two of the sites lay within the Abrams Creek watershed and one was in the Little River watershed. All sites were in areas classified by Pyle (1988) as having experienced diffuse disturbance following European settlement. Each site had experienced a small amount of logging and livestock grazing, but also had stands of large, older trees.

### 2.2.1 *Gold Mine Trail (GMT)*

Gold Mine Trail (35°38′ N, 83°54′ W, Blockhouse Quadrangle) is a short (1.3 km) spur of a trail system on the extreme western edge of the park near Look Rock campground and the Top-of-the-World community. It was originally part of a road that extended from Montvale

**Figure 2.2:** Photograph of vegetation in study area. Note catface scar feature at base of yellow pine tree. The understory was typically dense at all three study sites, and fallen pine trees were common.

Springs, a popular resort from the 1830s to the 1930s, to Cooper Road Trail (DeFoe *et al*. 2003). Cooper Road Trail was the primary road used by European settlers to access Cades Cove. It was originally established by the Cherokee, whose ancestors had inhabited the cove for several thousand years. Cooper Road was improved for wagon use in the 1830s, thereby improving transportation of supplies and products between Cades Cove and Maryville. Logging by Cades Cove residents was more intense on the eastern end of Cooper Road Trail, but the effects of this activity rapidly decrease traveling westward along the road and over the sandstone ridges. Cooper Road continues past the junction of Gold Mine Trail, through to Abrams Creek

Campground, and into Happy Valley, an unincorporated community just east of Chilhowee Mountain.

The north end of Gold Mine Trail can be accessed via a short path that extends outside of the park boundaries. Starting from the outer end of the trail and traveling deeper into the park, the trail decreases in elevation from about 609 to 536 m ASL, and it crosses three small tributaries that flow eastward into Cane Creek, a tributary of the Little River Watershed. The study site extends approximately 0.5 km from each side of the trail beginning at the park boundary and sweeps in a southerly direction down to Cooper Road Trail. The elevation range of the Gold Mine Trail site area is approximately 460 to 600 m ASL, and the site covers about 35 ha.

The forest on the eastern side of Cooper Road Trail was burned in the Hatcher Mountain prescribed fire conducted in April 2005 (Forests and Rangelands 2005). As of that date, it was the largest prescribed burn in the park's history at 2300 acres. Evidence of the fire could clearly be seen from the Gold Mine Trail junction during field work for this study. Organic debris and litter on the ground was charred, as were tree trunks. Many young, fire-intolerant trees had been killed. The burn did not directly affect our Gold Mine Trail site, or the other two study sites.

The vegetation at the Gold Mine Trail site varied from xeric pine-oak dominated stands on the ridge tops to shady rhododendron (*Rhododendron* spp.) thickets with eastern hemlocks along the stream beds. The lower canopy of the forest was primarily composed of blackgum (*Nyssa sylvatica* Marsh.), sourwood (*Oxydendrum arboreum* (L.) DC), and red maple (*Acer rubrum*

L.). Upper level canopy species include white oak (*Quercus alba* L.), shortleaf pine (*Pinus echinata* Mill.), eastern white pine (*Pinus strobus* L.), black oak (*Quercus velutina* Lam.), and mockernut hickory (*Carya alba* (L.) Nutt.). The understory contained eastern white pine saplings, red maple (*Acer rubrum* L.), serviceberry (*Amelanchier arborea* (F. Michx.) Fernald), sassafras (*Sassafras albidum* (Nutt.) Nees), striped maple (*Acer pensylvanicum* L.), blueberries (*Vaccinium* spp.) buffalo nut (*Pyrularia pubera* Michx.), and galax (*Galax urceolata* (Poir.) Brummitt). Large rhododendron and mountain laurel (*Kalmia latifolia* L.) shrubs were also present. These plants can readily resprout from their roots after a major disturbance and fill in the understory, out-competing tree seedlings (Plocher and Carvelle 1987, Elliott *et al*. 1999). A small number of flowering dogwood trees were noted during the fieldwork, all unhealthy. Some large, old trees remained on the landscape, but many of the mature yellow pines had died from recent beetle outbreaks and fell during wind and storm events over the course of this study. A few mature Virginia (*Pinus virginiana* Mill.) and pitch pine (*P. rigida* Mill.) trees were still present at the site. Eastern hemlocks were common along the trail, usually in the shadier and moist areas, but they were showing signs of woolly adelgid infestation.

The area surrounding Gold Mine Trail may have been owned by farmers in the late 1920s, and was documented as containing old-growth trees when the park was established (Pierce 2000). Much of the westernmost portion of the park was owned by the Morton Butler Lumber Company, with the exception of a few private in-holdings inside the lumber tract and around the edges (Harmon 1982). According to Pierce (2000), the Morton Butler tract remained essentially unlogged. The age of some of the trees sampled at our site indicate that this area did escape intensive logging, and that it was not cleared for agriculture.

### 2.2.2 *Rabbit Creek Trail (RCT)*

Rabbit Creek Trail is part of a network of trails that were originally used by the Cherokee to travel between their villages along the Little Tennessee River and Cades Cove (DeFoe *et al*. 2003). By the 1830s, European settlers were using the trail, and the Civilian Conservation Corps improved it to road condition a century later, in the 1930s. Rabbit Creek Trail begins near the Abrams Creek Ranger station and campground, and extends 12.5 km to the junction of Wet Bottom Trail and Abrams Falls Trail, near Cades Cove. Prior forest clearing is evident close to the ranger station, and also bordering Abrams Creek. These clearings were the fields and homesteads of Leason Hearon and Charlie Boring (DeFoe *et al*. 2003). Presently, a stone chimney and planted daffodils are the only obvious remains of a house that once stood near the creek crossing.

The site on Rabbit Creek Trail (35°36′ N, 83°55′ W, Caulderwood Quadrangle) lies at an elevation of approximately 500 to 600 m ASL. It is located near a large bend in the trail, approximately 1.5 km southeast of the Abrams Creek Ranger Station. The upper half of the 20 ha site straddles the trail for about 0.5 km along the ridgeline. The ridge increases in elevation toward the direction of Pine Mountain. The lower half of the site extends across the nose of the ridge, which points in a northeasterly direction toward Abrams Creek. Some portions of the ridge slopes are very steep. An unnamed tributary of Abrams Creek lies to the east. Contrary to expectations, several remnants of fire-scarred trees were found along the moister northeast face of the slope, an area that is now covered with many small-diameter white pines and hemlocks.

The canopy was primarily composed of eastern white pine, eastern hemlock, and red maple. Tree species having the largest diameters included white pine, pitch pine, scarlet oak (*Quercus coccinea* Münchh.), chestnut oak (*Q. montana* Willd.), and Virginia pine. Beetle-killed yellow pines were present, especially on the ridge top, and several dead trees had already fallen prior to our sample and data collection. The understory vegetation included blueberries, greenbrier (*Smilax* spp.), and mountain laurel.

### 2.2.3 *Pine Mountain (PMT)*

The Pine Mountain site (35°37′ N, 83°55′ W, Caulderwood Quadrangle) lies 250 m west of the junction of Hannah Mountain Trail and Rabbit Creek Trail, and covers approximately 20 ha. Hannah Mountain Trail was built in the 1840s by David Foute to provide a route between his resort at Montvale Springs and Gregory Bald, a scenic and open, grassy mountain top southwest of Cades Cove. The area near the trail junction, called Scott Gap, was farmed by several families, including John Boring and George Scott (DeFoe *et al*. 2003). Most of the study site is located on a three-pronged ridge, downslope from Rabbit Creek Trail and the summit of Pine Mountain (629 m), between two forks of the headwaters of Pardon Branch. Pardon Branch flows eastward to join Abrams Creek. The elevation range is approximately 500 to 600 m ASL. The north-facing and more mesic slopes supported mixed hardwood trees, including numerous oaks, and the xeric, southern slopes had more yellow pine, although much of it had been beetle-killed. The most dominant canopy species were blackgum, red oak (*Quercus rubra* L.), eastern white pine, and chestnut oak. The largest diameter trees included shortleaf pine, chestnut oak, pitch pine, red maple, Virginia pine, and red oak. The understory contained sassafras, dogwoods (diseased), blueberries, and galax.

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# CHAPTER 3

## YELLOW PINE RADIAL GROWTH RESPONSE TO CLIMATIC VARIABLES IN GREAT SMOKY MOUNTAINS NATIONAL PARK, TENNESSEE, U.S.A.

Portions of the introduction and study site descriptions in this chapter were taken from Chapters 1 and 2 of this dissertation. The use of "we" in Chapter 3 refers to the many people who assisted in the field and laboratory to make this study possible. Details can be found in the Acknowledgements section of this dissertation. Funding for this research was made possible through a Joint Fire Science Program grant authored and managed by Dr. Henri D. Grissino-Mayer, Dr. Charles Lafon, and Dr. Sally P. Horn. Essential support was also provided by the personnel of Great Smoky Mountains National Park, who gave us important permissions, access, and assistance for this study. My contributions to this research include field work, sample processing and dating, development of the chronologies, statistical analyses, and interpretation of results. This chapter will be submitted to the journal *Tree-Ring Research* for publication.

### Abstract

Historical composition changes in forest stands with a yellow pine (*Pinus* subgenus *diploxylon*) component are occurring throughout the southern Appalachian Mountains that may be related to shifts in climate. To better understand the changes, it is necessary to investigate the response of yellow pines to broad-level environmental factors over both short- and long-term time scales. Using dendroclimatic methods, we analyzed the growth response of yellow pine trees within the western portion of Great Smoky Mountains National Park to four instrumental (1940–2007) East Tennessee climate variables: total monthly precipitation, mean monthly temperature, Palmer Drought Severity Index (PDSI), and Palmer Hydrologic Drought Index (PHDI). Three atmospheric-oceanic oscillations that affect the southeastern United States were also analyzed: the North Atlantic Oscillation (NAO), the East Atlantic Oscillation (EA), and the

Atlantic Multidecadal Oscillation (AMO). Yellow pine radial growth was strongly and positively correlated with winter (January–February) temperatures during the growing season and less so with February precipitation. Growth was also significantly related to the winter NAO signal as the NAO influences winter temperatures in the region. The AMO was most associated with growth in the winter months, as well. Drought sensitivity (PDSI/PDHI) varied among the study sites, but all sites were significantly associated with PDSI in February. The EA showed minimal influence. The strong relationship with the winter signal of the analyzed variables would allow our 300-year-long tree-ring record to be used in reconstructions of climate variables beyond the instrumental records; however, divergence in the relationship between temperature and growth since the 1960s found in other studies should be considered. Further research is needed on the annual relationships between growth and the oscillations to determine how the trees respond to the long-term cyclic changes of the climate variables, and also how the oscillations interact with each other.

### 3.1 Introduction

This chapter is part of a larger research project conducted in the southern Appalachian Mountains to determine the growth response of yellow pines (*Pinus* subgenus *diploxylon*) to climate, to elucidate historical wildfire patterns on the landscape, and to reveal relationships between wildfire occurrence, climate, and human activity. The primary goal of chapter 3 is to determine the relationships between radial growth of lower-elevation (400–600 m ASL) yellow pines (*Pinus* subgenus *diploxylon*) and climate in the western portion of Great Smoky Mountains National Park (GSMNP), Tennessee.

Composition changes in forest stands with a yellow pine component are occurring throughout the southern Appalachian Mountains (Smith 1991, Vose *et al.* 1995) and within Great Smoky Mountains National Park (GSMNP), a protected area of renowned diversity (Harrod *et al.* 1998, Harrod and White 1999). The number of yellow pines has declined for at least the past century, and there has been a notable loss of larger, older trees. To better understand the changes, it is necessary to investigate the response of yellow pines to environmental factors over both short- and long-term time scales. The climate in which a forest resides is fundamental to the composition and structure of the stands. Climate fluctuates over time; long-term changes can affect forest composition, while short-term changes influence growth of the trees. Additionally, Earth is undergoing an overall warming trend that is likely associated with anthropogenic activity. The change will affect vegetation diversity (Currie 2001), migration or range expansion of plant species (Iverson and Prasad 1998, McKenney *et al*. 2007), and frequency and intensity of disturbances such as wildfires (Dale *et al*. 2001, McKenzie *et al*. 2004). Understanding how tree species respond to climate may help to forecast the fate of forest communities. Before the records contained in the old pines are lost to death and decay, the data contained in their rings need to be retrieved and examined.

### **3.1.1** ***Climate Variables***

We investigated the radial growth response of yellow pine trees to temperature, precipitation, two drought indices (Palmer Drought Severity Index and Palmer Hydrologic

Drought Index), and three atmospheric-oceanic oscillations that affect the southeastern United States: the North Atlantic Oscillation (NAO), the East Atlantic Oscillation (EA, also called East Atlantic Pattern), and the Atlantic Multidecadal Oscillation (AMO) (Enfield *et al.* 2001, Stenseth *et al.* 2002, National Oceanic and Atmospheric Administration 2010). The oscillations represent long-term climate changes, while temperature, precipitation, PDSI, and PHDI represent short-term changes. Previous-year climate data, in addition to current-year climate data, were analyzed against current year radial growth, as environmental conditions in one year often affect tree growth the following year (Fritts 2001).

Recent dendroclimatic studies of yellow pines in GSMNP indicated that radial growth is positively related to winter temperatures, suggesting that warmer winters increase growth, and that growth was weakly but positively related to winter and spring precipitation (Grissino-Mayer *et al*. 2007, Biermann 2009). Drought indices are closely tied with both temperature and precipitation. The Palmer Drought Severity Index (PDSI) is a monthly index that indicates the severity of wet and dry conditions, and the Palmer Hydrologic Drought Index (PHDI) is a monthly index used to assess long-term moisture supply. Because PHDI takes into account moisture storage in the soil, it responds more slowly to dry conditions than does PDSI. The values for both indices usually fall between –6 (dry) and +6 (wet), but occasional values of –7 or +7 are seen.

The North Atlantic Oscillation (NAO) is a measure of sea level atmospheric pressure fluctuations between the Icelandic Low (63° N, 23° W) and the Azores High (38° N, 26° W) (D’Arrigo *et al*. 1993, Goodkin *et al*. 2008). The NAO generally cycles every 1.7 to 7 years and affects westerly winds and storm tracks across the northern Atlantic Ocean, especially during November through April (Hurrell *et al.* 2003, Climate Prediction Center 2010). When pressure differences are great (*i.e.* positive phase), the eastern United States experiences warmer winters as moist air is brought up from the Gulf of Mexico and the tropical Atlantic (Yin 1994, Greatbatch 2000, Stenseth *et al.* 2003); patterns are generally reversed during the negative phase.

The East Atlantic Oscillation (EA) is similar to the NAO, except the pressure poles (approximately 55° N, 20–35° W and 25–35° N, 0–10° W) are shifted southward and the oscillation has a subtropical link. The positive phase is associated with below-average temperatures in the southern United States from January through May (Barnston and Livezey 1987, Nesterov 2009, Climate Prediction Center 2010).

The Atlantic Multidecadal Oscillation (AMO) is defined by sea surface temperature (SST, Kaplan series) variability in the northern Atlantic Ocean, and it affects air temperature and rainfall in the Northern Hemisphere. It is driven, in part, by the multidecadal fluctuations of the NAO (Kerr 2000). Distinct cool and warm phases each last 20 to 40 years, and together have an overall cycle length of 65 to 80 years. In the warm (positive) phase, rainfall is abundant in Florida and the Pacific Northwest, but decreases elsewhere in the United States. Conditions are reversed during the cool (negative) phase, and streamflow (precipitation) increases in the southern Appalachian Mountains (Tootle *et al*. 2005).

### 3.1.2 *Research Questions*

This chapter will address two primary research questions:

1) Which climate factors influence growth in the mixed-pine/pine-oak stands in the western portion of Great Smoky Mountains National Park?
2) Were there site-related differences in growth response?

## 3.2 Study Sites

The study area for this research is a region of highly dissected topography on the western edge of Great Smoky Mountains National Park, Tennessee, USA. Temperatures range from –2 to 11 °C in January and 15 to 31 °C in July. Approximately 1370 mm of precipitation falls annually. Large stands of yellow pines and oaks remain on the landscape that escaped the heavy logging prevalent in other portions of the park prior to the 1930s (Pyle 1988, Brose and Waldrop 2010), but many of the pines have more recently been affected by southern pine beetle (*Dendroctonus frontalis* Zimm.) outbreaks (Harrod *et al.* 1998, Waldron *et al.* 2008) and crowding from fast-growing, fire-intolerant tree species (Chapman *et al.* 2006).

The forest type in the western portion of the park is primarily xeric pine-oak. Three sites were selected for this study after reviewing aerial photographs and performing ground surveys: Gold Mine Trail (35°38′ N, 83°54′ W), Rabbit Creek Trail (35°36′ N, 83°55′ W, and Pine Mountain (35°37′ N, 83°55′ W). The elevation range for each site was between 460 and 600 m. The Gold Mine Trail site covered approximately 35 ha, while Rabbit Creek Trail and Pine Mountain were about 20 ha in area.

**Table 3.1:** List of sites and number of samples collected. Plot cores were from within 0.1 ha macroplots, and external cores were collected nearby. Cross-sections were wedges or disks taken from trees, snags, stumps, or logs using a chainsaw from within, and outside of, the macroplots.

| Site | Plot Cores | External Cores | Cross-Sections |
|---|---|---|---|
| Gold Mine Tr. | 13 | 73 | 45 |
| Rabbit Creek Tr. | 28 | 20 | 44 |
| Pine Mountain | 45 | 11 | 44 |
| Total Collected | 86 | 104 | 133 |

### 3.3 Field Methods

We established three 0.1 ha plots at each site. All canopy-class trees (≥ 5 cm DBH) within the plots were identified to species. Cores were collected from each live canopy tree according to standard dendrochronological procedures (Fritts 2001, Grissino-Mayer 2003). A minimum of 40 yellow pine trees were sampled per site, including cores from trees outside of, but near to, the plots and cross-sections collected with a chainsaw for related wildfire history research (Table 3.1). All samples were transported to the Laboratory of Tree-Ring Science at the University of Tennessee for processing and analysis.

### 3.4 Laboratory Methods

#### 3.4.1 *Sample Preparation*

The air-dried cores were fixed to labeled, wooden mounts with the transverse plane of the core perpendicular to the mount and then surfaced with a belt sander and progressively finer grit, from ANSI 120 grit (105–125 μm) to ANSI 400 grit (20.6–36.0 μm), so that the cells would be more visually apparent (Stokes and Smiley 1996, Orvis and Grissino-Mayer 2002). If necessary, the cores were further polished by hand with P1500 grit (9.8–12.3 μm) sandpaper. Cross-sections were either frozen at –40 °C for 24 hours, or treated with insecticide, and then allowed to dry. Fragile samples were mounted on particleboard, and all sections were downsized into thinner sections using a band saw. The sections were surfaced similarly to the cores, except the initial grit was coarser (*e.g.* ANSI 60 grit, 250–297 μm) to remove saw marks.

### 3.4.2 *Crossdating*

Tree rings on cores and cross-sections were first assigned calendar decades by counting backwards from the outermost ring, or were assigned unanchored decades if the outer year was unknown, with the aid of a stereozoom microscope according to standard dendrochronological methods (Stokes and Smiley 1996, Speer 2010). Unusually narrow or wide rings (marker rings) were noted on all samples and were used to visually confirm their crossdating to other samples. The width of the rings in each series for every core or cross-section transect was measured to the nearest 0.001 mm using a Velmex measuring system coupled with Measure J2X software.

The measurement files from Measure J2X were combined into a master ring-width series file for each study site, and then statistically analyzed in COFECHA (version 6.06) for crossdating accuracy using 40-year segments with a 20-year lag (Holmes 1983, Grissino-Mayer 2001). A flagged segment was left at its original placement if the suggested dating position was not convincing, or if it did not have an appreciably higher correlation (Grissino-Mayer 2001). Some samples had to be excluded from the master raw ring-width series file because of damage, irregular growth, or poor dating. A regional measurement file was generated by combining data from all three site files. All final measurement files used for chronology development had < 10% of the tested segments flagged in COFECHA.

### **3.4.3** ***Chronology Construction***

For each study site, the raw ring-width series were standardized using the computer program ARSTAN_41d (Cook 1985) to maximize climate-related growth patterns and to minimize differences and trends in ring widths caused by non-climatic factors such as tree size or age and fluctuations from competition or disturbance (Friend and Hafley 1989, Cook and Krusic 2007, Speer 2010). Detrending was performed primarily using linear regression lines and negative exponential curves (Grissino-Mayer *et al.* 2007). Only in rare instances were 50- or 100-year cubic smoothing splines used. These splines are often avoided when standardizing chronologies for climate analyses as they could potentially remove low-frequency climate patterns from the ring series (Cook and Peters 1981, Cook *et al.* 1990). ARSTAN_41d produced three index versions for each chronology: standard (STD), residual (RES), and ARSTAN (ARS) (Cook and Holmes 1986). The STD chronology was used for the analyses, rather than the RES or the ARS types, because preliminary analysis indicated that it had the strongest relationship to climate for the study area. The STD chronology is developed by detrending the ring series by fitting the data to a curve to remove a large part of the variance derived from factors other than climate, but it retains more of the low-frequency trends than the RES chronology form (Grissino-Mayer 1995)

### 3.4.4 *Climate Data*

The NCDC has defined climate divisions in the United States based on the statistical analysis of climate patterns, but also take into account state borders, agricultural boundaries, and major topographic features (Consortium for Atlantic Regional Assessment 2010). Divisional data that represent the broader climate variability in the region were used rather than individual weather station data, which may be influenced by microclimatic changes at the station site (Blasing *et al*. 1981, Speer *et al*. 2009). The study area for this research lies within the Eastern Tennessee division (coded as "4001") and the data are derived from averages of weather observations recorded at stations within the division. Datasets for mean monthly surface air temperature, total monthly precipitation, PDSI, PHDI, NAO, and EA were downloaded from the NCDC (2010). Data for the AMO index (unsmoothed from the Kaplan SST V2) were downloaded from the NOAA website (Kaplan *et al.* 1998, NOAA 2010). The data for temperature, precipitation, PSDI, and PHDI are for division 4001. The NAO, EA, and AMO are hemispheric-wide phenomena.

### 3.4.5 *Statistical Analyses*

Correlation analysis used SAS® version 9.2 to explore the relationship between yellow pine growth and climate at all three sites, and for the study area as a whole, using the detrended individual site chronologies and a combined regional chronology (SAS 2008). Temperature, precipitation, PDSI, PHDI, and AMO were analyzed over the period 1940–2006, while NAO and EA were analyzed over the period 1950–2006. The climate variables analyzed included all months during the current year's growth, as well as months from the previous growing season beginning May of the previous year. Months through December of the current year were included because previous studies indicated that warmer winters may enable trees to continue growing past the average dormancy cutoff of early November (Biermann 2009, NPS 2010). Tree growth for the current year is influenced by conditions that affect uptake and processing of nutrients during the previous dormant season and growing season of the prior year, so months from the preceding year (May–December) were also included in the analyses (Grissino-Mayer and Butler 1993, Fritts 2001, Ford and Brooks 2003). After the initial correlation tests were run for individual months, consecutive months that showed a significant relationship to growth were grouped by adding the monthly values and the groups were then analyzed to determine if the trees were responding strongly to particular seasons (Grissino-Mayer 1996, Stahle *et al.* 2009, DeWeese *et. al* 2010, White *et al.* 2011).

After the preliminary correlation analysis data investigation, the detrended chronologies were run against the temperature and precipitation data (1940–2006) using response function analysis in DendroClim2002 (Biondi and Waikul 2004). Response function analysis is a more robust analysis that minimizes multicollinearity of the variables, thus better representing the relationship between tree growth and climate (Biondi 1997, Wimmer and Grabner 1997). Specifically, this analysis separates out the effects of the related variables temperature and precipitation on tree growth. DendroClim2002 uses bootstrapped confidence intervals to test for significance (Efron 1979, Guiot 1991).

## 3.5 Results

### 3.5.1 *Chronology Results*

Each of the three site chronologies exceeded 200 years in length (Table 3.2). The interseries correlation, an indicator of crossdating quality, ranged from 0.51 to 0.54. Average mean sensitivity values, a measure of year-to-year variability of the ring widths, were 0.27–0.28. First-order autocorrelation ranged from 0.68 to 0.74. The chronologies each had distinctive narrow and wide marker rings that were markedly different in width from average width rings in the series (Table 3.3). Several of the marker rings were common to all of the chronologies. Evidence of a century scale oscillation is present in each of the chronologies, but least so at Rabbit Creek Trail.

#### 3.5.1.1 ***Gold Mine Trail (GMT) Chronology***

For the Gold Mine Trail chronology (Figure 3.1A), most of the series were derived from shortleaf pines. The oldest sample collected at the site dated back to 1684, but the early rings were very complacent and could not be included in the chronology. A narrow ring in 1994 (Table 3.3) may have been related to an ice storm in February of that year (NCDC 2010). The narrowest ring was 1714 (–6.015 SD, prior to standardization), but sample depth was only two segments for that year, so this may be anomalous. Notable multi-year spans of narrower-than-average ring widths occurred in the mid-1710s, early-1770s, mid-1890s, and mid-1980s (Figure 3.1A). The widest ring occurred in 1723 (2.503 SD), but again, sample depth was low (n=3). Prior to 1739, low sample depth (n<10) makes that entire section less reliable.

**Table 3.2:** Descriptive statistics for each of the four chronologies constructed.

| Site | Number of Series | Period of Record | Interseries Correlation | Mean Sensitivity | First-Order Autocorrelation |
|---|---|---|---|---|---|
| Gold Mine Trail | 198 | 1697–2006 | 0.54 | 0.27 | 0.74 |
| Rabbit Creek Trail | 87 | 1779–2007 | 0.53 | 0.28 | 0.68 |
| Pine Mountain | 99 | 1742–2006 | 0.53 | 0.27 | 0.71 |
| Regional | 368 | 1697–2007 | 0.51 | 0.27 | 0.72 |

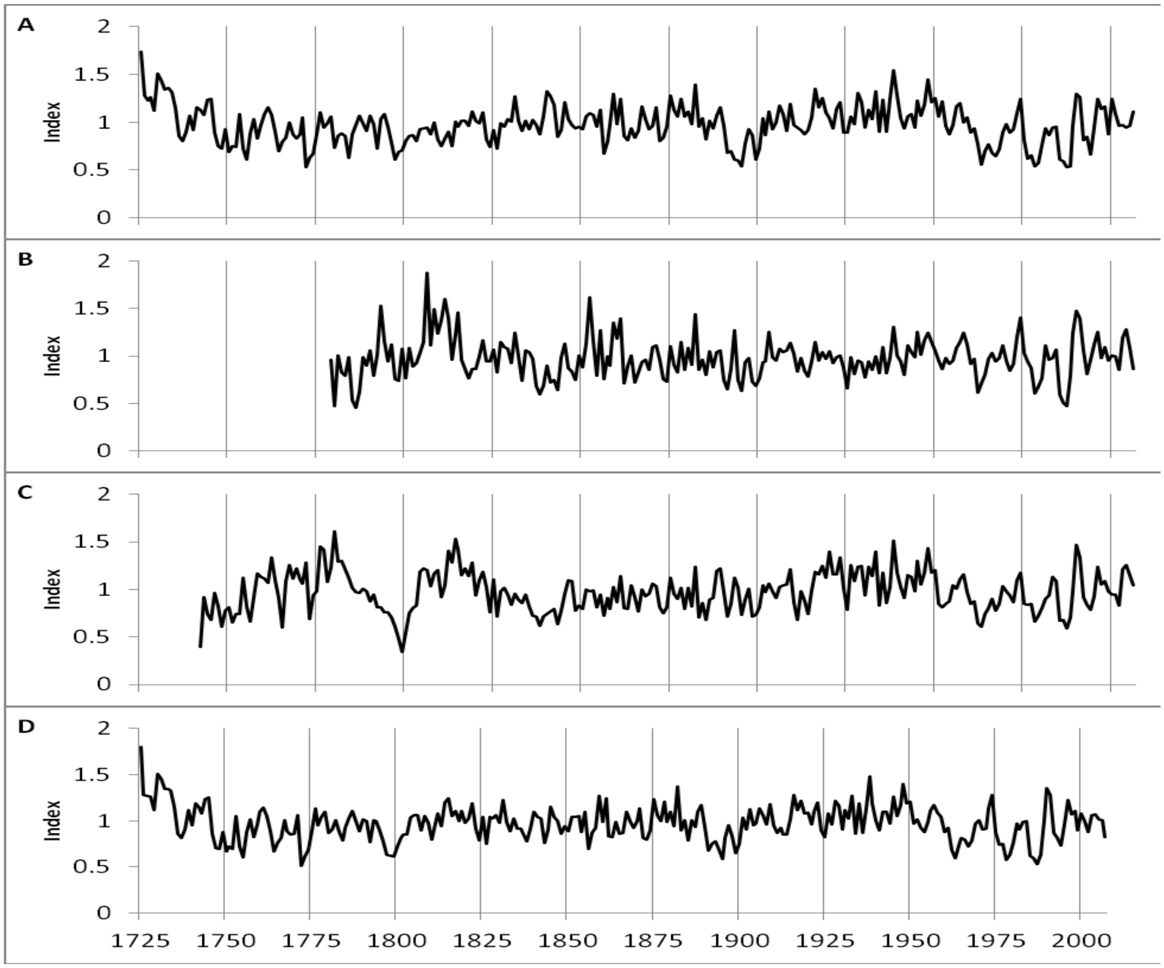

**Figure 3.1:** Standardized chronologies shown for the years 1725 through 2006.
**A)** Gold Mine Trail (GMT), **B)** Rabbit Creek Trail (RCT), **C)** Pine Mountain Trail (PMT), **D)** Regional (ALL). GMT and ALL were truncated at 1725 for comparison purposes. Y-axis is mean ring width index.

**Table 3.3:** Marker rings found in each site chronology. Underlined years indicate marker rings common to all sites.

| GMT Narrow | RCT Narrow | PMT Narrow | GMT Wide | RCT Wide | PMT Wide |
|---|---|---|---|---|---|
| 1994 | 2002 | 2002 | 1991 | 1991 | 1991 |
| 1987 | 1987 | 1987 | 1990 | 1990 | 1990 |
| 1963 | 1986 | 1963 | 1974 | 1974 | 1974 |
| 1936 | 1985 | 1962 | 1973 | 1938 | 1948 |
| 1899 | 1978 | 1936 | 1948 | 1893 | 1938 |
| 1895 | 1963 | 1934 | 1938 | 1882 | 1920 |
| 1894 | 1962 | 1925 | 1916 | 1861 | 1909 |
| 1893 | 1941 | 1914 | 1889 | 1859 | 1889 |
| 1872 | 1925 | 1911 | 1882 | 1852 | 1882 |
| 1856 | 1895 | 1885 | 1861 | 1831 | 1847 |
| 1826 | 1891 | 1873 | 1859 | 1822 | 1846 |
| 1824 | 1874 | 1856 | 1831 | 1806 | 1814 |
| 1797 | 1865 | 1843 | 1761 | 1793 | 1780 |
| 1784 | 1862 | 1826 | 1753 | 1784 | 1762 |
| 1774 | 1856 | 1824 | 1745 | 1781 | 1743 |
| 1773 | 1843 | 1810 | 1744 | 1779 | |
| 1772 | 1838 | 1800 | 1723 | | |
| 1755 | 1826 | 1799 | 1722 | | |
| 1747 | 1818 | 1798 | 1711 | | |
| 1738 | 1813 | 1775 | 1710 | | |
| 1737 | 1798 | 1774 | 1704 | | |
| 1736 | 1797 | 1773 | 1697 | | |
| 1726 | 1787 | 1765 | | | |
| 1718 | 1786 | 1756 | | | |
| 1717 | 1785 | | | | |
| 1715 | 1780 | | | | |
| 1714 | | | | | |
| 1701 | | | | | |
| 1700 | | | | | |

#### 3.5.1.2 *Rabbit Creek Trail (RCT) Chronology*

Most of the samples in the Rabbit Creek Trail chronology (Figure 3.1B) were Virginia pine, followed by pitch pine. Narrow and wide marker rings are listed in Table 3.3. The narrowest ring occurred in 1786 (–3.565 SD). Multi-year spans of lower-than-average ring widths occurred in the mid-1780s, early 1960s, and mid-1980s (Figure 3.1B). The widest ring occurred in 1806 (2.29 SD). Sample depth was below ten prior to 1820.

#### 3.5.1.3 *Pine Mountain (PMT) Chronology*

The Pine Mountain chronology (Figure 3.1C) was developed from a mix of pitch pine, Virginia pine, and shortleaf pine. Narrow and wide marker rings are shown in Table 3.3. The years 1798–1800 were very narrow; 1799 was extremely narrow (–4.05 SD before standardization). Sample depth for these three years was 15, so should have been sufficient for providing a realistic record of reduced growth in the trees. Other multi-year narrow rings were found in the mid-1770s and mid-1980s. The widest ring occurred in 1780 (2.238 SD, n=8). Prior to 1783, the sample depth dropped below ten.

#### 3.5.1.4 *Regional Chronology (ALL)*

The regional chronology was developed from the crossdated series from GMT, RCT, and PMT (Figure 3.1D). Sample depth dropped below ten prior to 1741. Several narrow rings were common across the study area, for example 1826, 1856, 1963, and 1987. Common wide rings occurred in 1882, 1938, 1974, 1990, and 1991.

### 3.5.2 *Climate Response Results*

#### 3.5.2.1 *Gold Mine Trail (GMT)*

Pine growth at Gold Mine was positively correlated with January (r = 0.47, P < 0.001) and February (r = 0.40, P < 0.001) temperatures (Figure 3.2). When the temperature variables were combined (Jan-Feb), the correlation was even stronger (r = 0.54, P < 0.001) (Table 3.4). October temperature was also positively correlated to growth (r = 0.25, P < 0.05), but the relationship was somewhat weaker. Weak, but significant, correlations were also found for February (r = 0.25, P < 0.05) and December (r = 0.28, P < 0.05) precipitation (Figure 3.3). In the response function analysis, both January and February temperatures remained significant (P < 0.05), but precipitation did not.

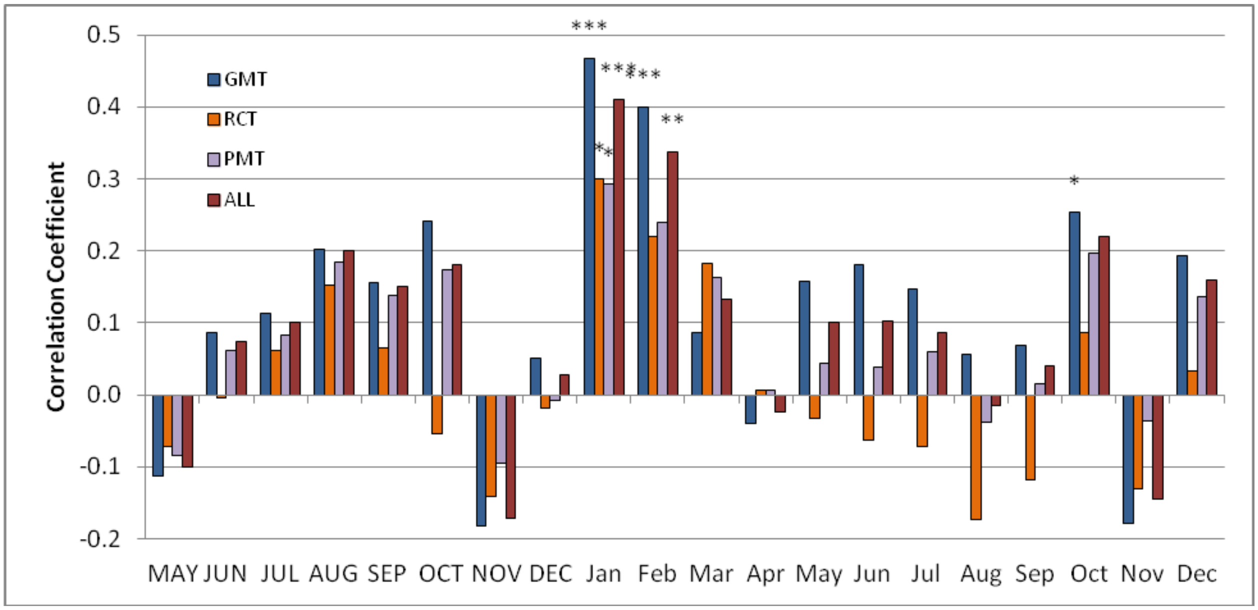

**Figure 3.2:** Correlation results for temperature and pine growth at each site and the combined study area. Months in the previous year are capitalized. Significance is indicated by * (P < 0.05), ** (P < 0.01), and *** (P < 0.001).

**Table 3.4**: Top five correlation results for pine growth versus monthly and seasonal climate variables. Results are shown for each site (Gold Mine Trail, Rabbit Creek Trail, and Pine Mountain) and for the regional chronology (ALL). The East Atlantic Oscillation was not included in this table because of lacking significant association. Correlation coefficients are designated CC. Capitalized months are from the year prior to the current growing season. Significance is indicated by * ($P < 0.05$), ** ($P < 0.01$), and *** ($P < 0.001$).

| | **Temperature** | | **Precipitation** | | **PDSI** | | **PHDI** | | **NAO** | | **AMO** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **Month(s)** | **CC** | **Month(s)** | **CC** | **Month(s)** | **CC** | **Month(s)** | **CC** | **Month(s)** | **CC** | **Month(s)** | **CC** |
| GMT | Jan-Feb | 0.54 *** | Dec | 0.28 * | Feb | 0.34 ** | None | None | Jan-Feb | 0.45 *** | NOV | 0.44 *** |
| GMT | Jan | 0.47 *** | Feb | 0.25 * | Feb-Mar | 0.30 * | n/a | n/a | Jan | 0.37 ** | OCT-NOV | 0.43 *** |
| GMT | Feb | 0.40 *** | n/a | n/a | Feb-Apr | 0.29 * | n/a | n/a | Feb | 0.37 ** | SEP-NOV | 0.42 *** |
| GMT | Oct | 0.25 * | n/a | n/a | Feb-May | 0.29 * | n/a | n/a | NOV | -0.28 * | AUG-NOV | 0.41 *** |
| GMT | n/a | n/a | n/a | n/a | Jan-May | 0.29 * | n/a | n/a | Jun | -0.29 * | SEP-DEC | 0.41 *** |
| RCT | Jan-Feb | 0.33 ** | Dec | 0.35 ** | Feb-Dec | 0.52 *** | Dec | 0.46 *** | Jan-Feb | 0.37 ** | OCT-NOV | 0.26 * |
| RCT | Jan | 0.30 * | May | 0.33 ** | Mar-Dec | 0.52 *** | Jun-Dec | 0.46 *** | Feb | 0.34 ** | NOV | 0.26 * |
| RCT | n/a | n/a | Feb | 0.31 * | Apr-Dec | 0.52 *** | May-Dec | 0.46 *** | Jan | 0.27 * | SEP-NOV | 0.26 * |
| RCT | n/a | n/a | SEP | 0.29 * | Dec | 0.52 *** | Jul-Dec | 0.46 *** | OCT | -0.33 * | OCT | 0.26 * |
| RCT | n/a | | n/a | n/a | May-Dec | 0.52 *** | Apr-Dec | 0.45 *** | | | AUG-NOV | 0.26 * |
| PMT | Jan-Feb | 0.33 ** | Dec | 0.31 * | Dec | 0.43 *** | Dec | 0.35 ** | Jan-Feb | 0.37 ** | OCT-NOV | 0.33 ** |
| PMT | Jan | 0.29 * | Feb | 0.30 * | Feb-Dec | 0.41 *** | Jul-Dec | 0.35 ** | Jan | 0.30 * | SEP-NOV | 0.32 ** |
| PMT | n/a | n/a | May | 0.27 * | Mar-Dec | 0.40 *** | May-Dec | 0.35 ** | Feb | 0.30 * | AUG-NOV | 0.32 ** |
| PMT | n/a | n/a | n/a | n/a | Apr-Dec | 0.40 *** | Jun-Dec | 0.35 ** | OCT | -0.31 * | NOV | 0.32 ** |
| PMT | n/a | n/a | n/a | n/a | Feb-Aug | 0.40 *** | Apr-Dec | 0.35 ** | n/a | n/a | OCT | 0.32 ** |
| ALL | Jan-Feb | 0.47 *** | Dec | 0.32 ** | Dec | 0.39 ** | Dec | 0.31 * | Jan-Feb | 0.43 ** | NOV | 0.39 ** |
| ALL | Jan | 0.41 *** | Feb | 0.30 * | Feb | 0.39 ** | Feb-Dec | 0.29 * | Feb | 0.36 ** | OCT-NOV | 0.38 ** |
| ALL | Feb | 0.34 ** | n/a | n/a | Feb-May | 0.37 ** | Apr-Dec | 0.29 * | Jan | 0.34 * | SEP-NOV | 0.37 ** |
| ALL | n/a | n/a | n/a | n/a | Feb-Jun | 0.37 ** | Mar-Dec | 0.29 * | n/a | n/a | AUG-NOV | 0.36 ** |
| ALL | n/a | n/a | n/a | n/a | Feb-Aug | 0.37 ** | May-Dec | 0.29 * | n/a | n/a | OCT-DEC | 0.36 ** |

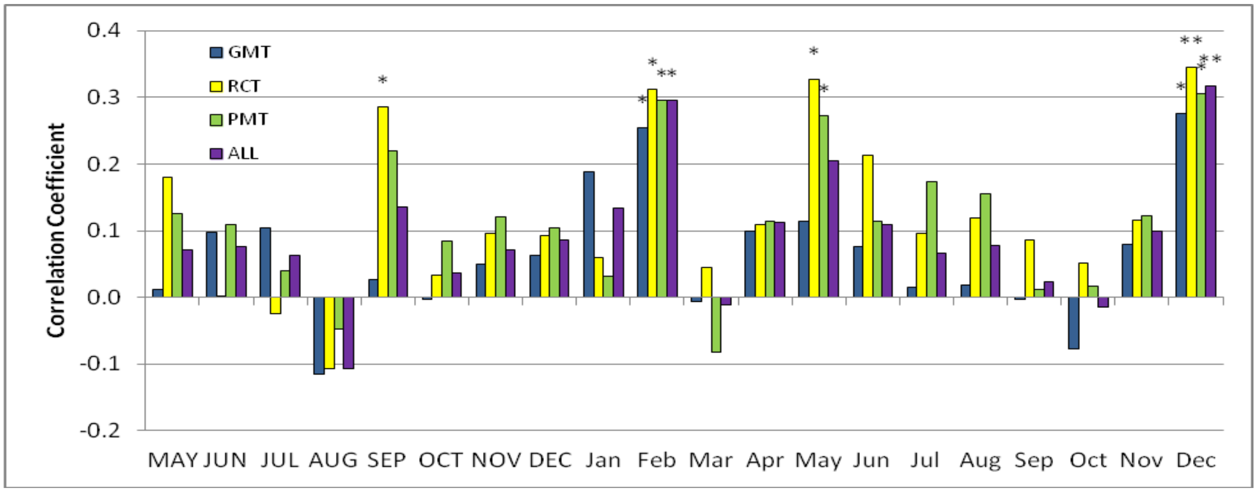

**Figure 3.3:** Correlation results for precipitation and pine growth at each site and the combined study area. Months in the previous year are capitalized. Significance is indicated by * (P < 0.05) and ** (P < 0.01).

Analyzing the tree growth-drought relationship, February PDSI had the strongest correlation (r = 0.34, P < 0.01), of the analyzed months, followed by March PDSI (r = 0.25, P < 0.05), April PDSI (r = 0.24, P < 0.05), May PDSI (r = 0.25, P < 0.05), and December PDSI (r = 0.28, P < 0.05) (Figure 3.4A). Several seasonalized month groupings spanning January through May were also significantly positive for PDSI (Table 3.4). This suggests that winter and spring drought decreases yellow pine growth at Gold Mine. Interestingly, none of the monthly values for PHDI were significantly correlated with growth.

Pine growth was significantly and positively correlated with January NAO (r = 0.37, P < 0.01) and February NAO (r = 0.37, P < 0.01) (Figure 3.5A). Combining the two month variables strengthened the relationship (Jan-Feb, r = 0.45, P < 0.001). NAO also has a significant negative relationship with growth for the prior-year November (r = –0.28, P < 0.05) and the current-year June (r = –0.29, P < 0.05).

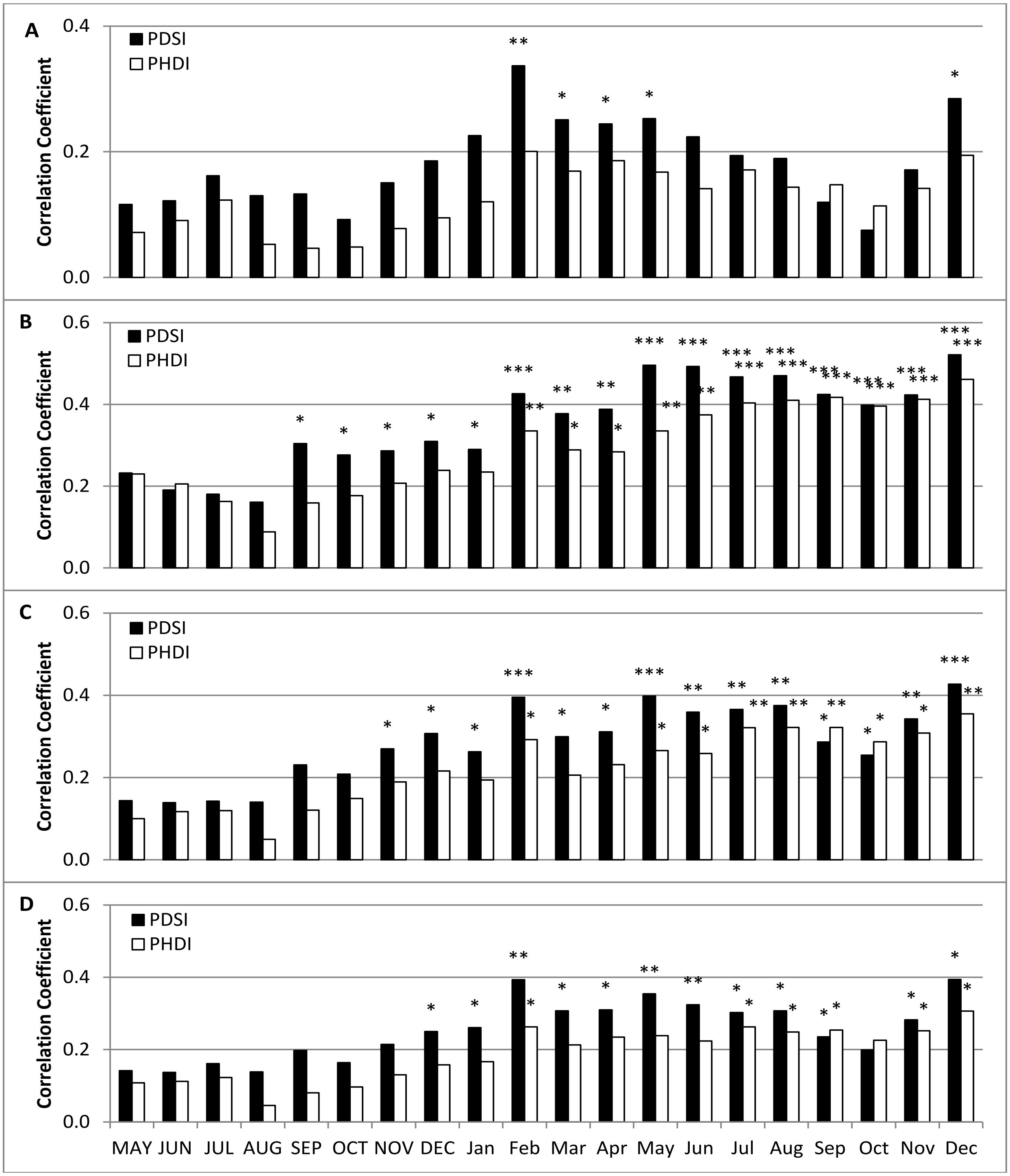

**Figure 3.4:** Correlation results for PDSI and PHDI against pine growth at each site and the combined study area. **A)** GMT, **B)** RCT, **C)** PMT, **D)** Regional (ALL). Months in the previous year are capitalized. Significance is indicated by * ($P < 0.05$), ** ($P < 0.01$), and *** ($P < 0.001$).

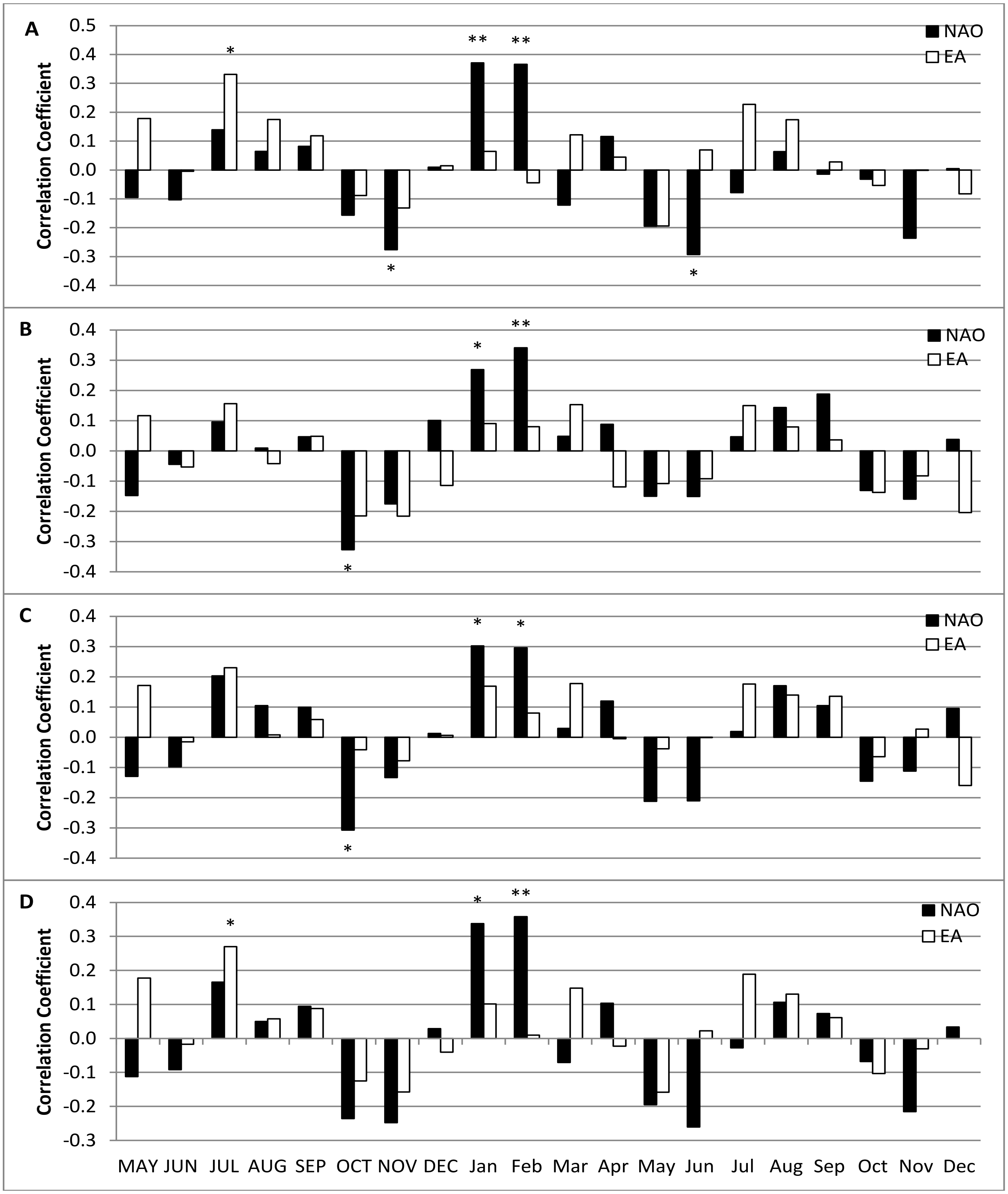

**Figure 3.5:** Correlation results for NAO and EA against yellow pine growth. **A)** GMT, **B)** RCT, **C)** PMT, **D)** Regional (ALL). Months in the previous year are capitalized. Significance is indicated by * ($P < 0.05$) and ** ($P < 0.01$).

EA (the "southward-shifted NAO") correlated only with prior-year July growth ($r = 0.33$, $P < 0.05$). All of the months for AMO were positively correlated with yellow pine growth, but the current-year summer months of May, June, and July were not significant. The strongest relationship was found with the prior-year fall (*e.g.* Sep-Nov, $r = 0.42$, $P < 0.001$), followed by a combination of late summer and fall of the prior-year (*e.g.* Jul-Nov, $r = 0.41$, $P < 0.001$) (Table 3.4). Prior-year November AMO was the most highly correlated month ($r = 0.44$, $P < 0.001$).

#### 3.5.2.2 ***Rabbit Creek Trail (RCT)***

The pines at Rabbit Creek responded positively to warmer winter temperatures (Figure 3.2). Both January and February temperatures were associated with growth, but only January was significant ($r = 0.30$, $P < 0.05$). The combined Jan-Feb temperature variable was also significant ($r = 0.33$, $P < 0.01$). Growth and precipitation were correlated in four separate months (Figure 3.3): February, May, and December of the current year ($r = 0.31$, $P < 0.05$; $r = 0.33$, $P < 0.01$); and $r = 0.35$, $P < 0.01$, respectively) and September of the previous year ($r = 0.29$, $P < 0.05$) Response function analysis indicated that only January temperatures and December precipitation were significant ($P < 0.05$). At RCT, the majority of months tested for both PDSI and PHDI were positively correlated to growth (Figure 3.4B). The PDSI correlation was significant for prior-year September through the current-year December, but was most strongly correlated during the summer, May ($r = 0.50$, $P < 0.001$) through August ($r = 0.47$, $P < 0.001$), in individual month analysis. For PHDI, February through December of the current year correlated positively with ring width, and showed a peak in strength during late summer and early fall.

Pine growth at RCT had a positive relationship with NAO in January ($r = 0.27$, $P < 0.05$) and February ($r = 0.34$, $P < 0.01$) (Figure 3.5B), but the combined Jan-Feb variable was not as strongly correlated ($r = 0.37$, $P < 0.01$) at this site (Table 3.4). Growth was negatively correlated with NAO values for the previous October ($r = –0.33$, $P < 0.05$) (Figure 3.5B). No significant association between growth and EA was found. The relationship with AMO correlated significantly only during the fall months of October and November (both $r = 0.26$, $P < 0.05$).

#### 3.5.2.3 *Pine Mountain (PMT)*

Pine growth at Pine Mountain correlated significantly with January temperature ($r = 0.29$, $P < 0.05$) (Figure 3.2). A positive relationship with February temperature was present, although it was not significant. The combined January-February variable was significant ($r = 0.33$, $P < 0.01$) (Table 3.4). Growth was also positively correlated with precipitation in February ($r = 0.30$, $P < 0.05$), May ($r = 0.27$, $P < 0.05$), and December ($r = 0.31$, $P < 0.05$) (Figure 3.3). Precipitation was not significantly associated with growth in the response function analysis, but January temperature was significant ($P < 0.05$). For PDSI, all of the months from the previous November through the current December were positive and significant (Figure 3.4C). The most highly correlated individual months were February ($r = 0.39$, $P < 0.001$), May ($r = 0.40$, $P < 0.001$), and December ($r = 0.43$, $P < 0.001$). PHDI values were correlated with growth in February ($r = 0.29$, $P < 0.05$) and the months of May through December.

January and February NAO values were positively correlated to growth (both $r = 0.30$, $P < 0.05$) (Figure 3.5C), while the combined January-February variable had an even stronger relationship ($r = 0.37$, $P < 0.01$) (Table 3.4). October NAO was negatively correlated ($r = –0.31$, $P <$

0.05) with growth. No significant relationship with EA was present. Monthly AMO values from the previous July through November were positively and significantly correlated with growth, as were September, November, and December of the current year. The prior November and October showed the strongest monthly relationship (both r = 0.32, $P < 0.01$).

#### 3.5.2.4 *Regional Composite (ALL) Chronology*

Pine growth for the combined study area had a strong relationship with January and February temperature (r = 0.34, $P < 0.01$ and r = 0.41, $P < 0.001$, respectively) (Figure 3.2). When these were combined, the strength of the relationship increased (r = 0.47, $P < 0.001$) (Table 3.4). For precipitation, the months of February (r = 0.30, $P < 0.05$) and December (r = 0.32, $P < 0.01$) were positively correlated with growth (Figure 3.3). Response function analysis indicated no significance for precipitation, but January temperature was significantly related to growth ($P < 0.05$). For PDSI, the previous December through current December monthly values, with the exception of October, were significantly correlated (Figure 3.4D). February and current December PDSI were the strongest individual months (both r = 0.39, $P < 0.01$). Fewer months for PHDI were correlated than for PDSI, and the relationship was weaker. February PHDI was the only early month showing significance (r = 0.26, $P < 0.05$); later significant months were July through September, and then November and December.

Pine growth for the study area was positively correlated with NAO values for January (r = 0.34, $P < 0.05$) and February (r = 0.36, $P < 0.01$), again most strongly for the combined January-February variable (r = 0.43, $P < 0.01$) (Figure 3.5D). For EA, July of the previous year was correlated (r = 0.27, $P < 0.05$). Monthly AMO values for the prior-year May through prior-year

December were significantly and positively correlated with pine growth across the combined study area. Current-year February, September, November and December AMO were also significantly correlated. Prior-year November AMO had the strongest relationship ($r = 0.39$, $P < 0.01$) of the individual months, as did October-November for the combined months (Table 3.4).

## 3.6 Discussion

### 3.6.1 *Chronology*

All four chronologies spanned at least 200 years. The Gold Mine Trail chronology spanned 310 years (1697–2006) and is one of the longest yellow pine chronologies generated so far for GSMNP. Most of the yellow pine trees at GMT were shortleaf pines. Pine Mountain had a mix of shortleaf pines, pitch pines, and Virginia pines. Rabbit Creek was primarily Virginia pine and had the shortest chronology length (87 series). Shortleaf pines typically live longer than Virginia pines, so this likely contributed to the length of the chronology at Gold Mine Trail. The average interseries correlation (or correlation with the master series) for the three site chronologies was 0.53, which indicated that the chronologies crossdated well, and that much of the ring variability resulted from changes in one or more climate variables. Each individual (site and regional) chronology was above 0.50, and exceeded the minimum target of 0.40. A value of 0.50 is considered to be very high for southeastern yellow pines (Grissino-Mayer 2001). Chronologies below the target value of 0.40 are generally responding to individual or stand-level disturbance, such as wind throw or insect damage, or may be complacent (not responding at all). Average mean sensitivity values for the chronologies, a measure of year-to-year variability of the ring widths, were intermediate (0.27–0.28), but still adequate for trees in the southern Appalachian Mountains, which have a tendency to be more complacent than their western U.S. counterparts (Grissino-Mayer 2001). Mean sensitivity values between 0.15 and 0.20 are common in the southeastern United States. First-order autocorrelation values, prior to standardization, for the sites ranged from 0.68 to 0.74, indicating a strong relationship between current-year growth and climatic conditions in the previous year. These values are typical for pine trees growing on moderate sites, compared to values from those trees growing on harsher sites such as very sandy soils or rocky outcrops. After filtering, the autocorrelation of the site chronologies averaged near zero (–0.007).

Several distinct narrow and wide marker rings were found for the same years across all of the chronologies, again indicating a response by the pines in the study area to a common climate signal. While some variability was found in the descriptive statistics among the three site chronologies, it was minimal with the exception of length. This suggests that the differences between the sites did not greatly influence the trees' response to climate. However, to acquire the longest ring and climate response record, shortleaf pines should be targeted over the other pines. Also, shortleaf pine samples tended to have clearer rings than the other pine species, with fewer areas of density fluctuations that could have been confused with actual ring boundaries and inappropriately measured.

### 3.6.2 *Climate Analyses*

Mean monthly temperatures for East Tennessee (division 4001) exhibit a typical temperate bell curve (NCDC 2010). The coldest months, December–January, average 4.4 °C.

May through October averages above 15.5 °C, with an average peak in July near 26.7 °C. Pine growth at all sites and for the regional chronology was significantly and positively correlated to January temperature. Pines at Gold Mine Trail were the most responsive of the sites to January temperature, and GMT was also the only site that showed a significant correlation to February temperature. However, when temperatures for both January and February were merged into one variable, correlations with growth at all individual sites were significant, and the strength of the response was greater for the combined variable than for any individual month.

Warmer winter temperatures are associated with wider rings and increased annual growth. Sustained winter temperatures above the 4.4 °C average prior to the growing season could allow the trees to initiate cambial growth earlier in the year, and to grow for a longer period. Conversely, cold winters would delay radial growth while the tree would continue to use up nutrients for basic maintenance and metabolic processes. Cold soil temperature in winter can inhibit pine photosynthesis and growth, more so than air temperature, as water uptake by roots is limited (Jurik *et al*. 1988, Rundel and Yoder 1998). The pines at all sites were also positively correlated with October temperature, but only Gold Mine Trail was significant. A milder fall would lengthen the growing season, similar to a warmer spring.

A comparable pattern of correlations was found in several pine chronologies developed and analyzed by Biermann (2009), and also in a chronology developed using Table Mountain pine samples collected in GSMNP by Armbrister (2002), which was later analyzed by Grissino-Mayer *et al.* in 2007. Each of my sites additionally showed negative correlations between growth and both previous- and current-year November temperatures, although these were not significant. A warmer previous November could have depleted nutrients that would have been stored for the following growing season, thereby decreasing current year growth. Rabbit Creek Trail was the only site that exhibited a negative relationship with summer temperatures; however, none of the values were significant. It could be that the Virginia pines were more susceptible to water stress during these typically hot months than shortleaf pine, pitch pine, and Table Mountain pine. Virginia pines belong to a different subsection (*Contortae*) of New World diploxylon pines than do the other pine species (*Australes*) (Price *et al*. 1998), and this species responds more strongly to drought (often associated with warmer temperatures) in less xeric sites than other pines (Orwig and Abrams 1997).

Monthly precipitation and temperature in East Tennessee are related to each other throughout the year. The association is strongest in February, but also in January, May, and July. Late fall and winter associations are positive (*i.e.* warmer temperatures with increased precipitation), while spring through early fall are negative (*i.e.* warmer temperatures with decreased precipitation). No clear seasonal relationship was evident between growth and precipitation, although February was positively correlated at all sites. Monthly total precipitation averages in East Tennessee are relatively high from January through March (approximately 12.7 cm), followed by a decline through June. A distinct peak appears in July, when average precipitation is 15.2 cm, which is followed by a decline ending in October, typically the driest month of the year. Average precipitation slowly increases through November and December. Extra moisture in February could have enhanced photosynthesis and carbohydrate production, providing extra nutrients during the active growth season. At Rabbit

Creek Trail and Pine Mountain, tree growth was also significantly correlated with May precipitation. These two sites had drier ridge top areas and the trees were further away from active streams than at Gold Mine Trail, thus were more moisture-limited. Correlation values for winter precipitation and growth were lower at all sites than those for temperature. Response function analysis confirmed that temperature is more influential than precipitation for the regulation of pine growth at all sites, primarily in January.

East Tennessee is subject to intermittent droughts compared to other regions in the United States, mainly in the western states, that experience frequent droughts. The average Palmer Drought Severity Index values for the area since 1940 fluctuate, on an approximate 1- to 3-year basis, between 4.0 (wet) and –4.0 (dry). Notable wet years occurred in 1973–1974, 1994, and 2003. At all sites, wide rings were produced in 1973, 1974, and 2003, while GMT and PMT showed a narrow ring in 1994. Blount County experienced ice storms in 1994 (NCDC 2010) and the trees were probably damaged, reducing the growth for that year. Notable drought years occurred in 1941, 1954, and 1986–1988. Ring width was narrower than average at all sites. The most extreme response occurred in the mid-1880s when the degree of diminished growth exceeded all other years for all sites.

The pines of Rabbit Creek Trail had the strongest relationship with both PDSI and PDHI, indicating that RCT is the most drought sensitive of all sites. The highest correlations found in the analyses were at Rabbit Creek Trail and Pine Mountain during the summer and fall months. However, all three study sites had a strong, significant relationship with February PDSI. Gold Mine Trail also had weak but significant correlations for PDSI during some later months, but interestingly, this was the only site to not show a significant relationship with PHDI. Gold Mine Trail may not be as susceptible to drought as the other two sites because of the stream tributaries crossing the site. The higher proportion of Virginia pine in the tree population at Rabbit Creek Trail is the probable cause of the elevated response at that site to the lack of available moisture. Conifers, such as pines, tend to produce new wood throughout the entire growing season if sufficient moisture is present, rather than exhibiting a burst of growth like many deciduous hardwoods, making them more susceptible to late-season droughts (Hanson and Weltzin 2000). This may explain the extension of the significant relationship between growth and PDSI/PHDI through the fall and into December at both the RCT and PMT sites. When PDSI values were seasonalized, the strongest correlations at all sites were with combinations that retained the February component. As seen with the individual month data, pines at GMT responded primarily to spring moisture, while pines at RCT and PMT responded to moisture availability through the whole current year. Pines at Rabbit Creek Trail and Pine Mountain also showed a significant, but weaker relationship to PDSI in the previous fall.

The NAO considerably influences winter temperatures in the southeastern United States. When the gradient increases between the pressure poles, and the index values increase, warm, moist air flows up from the Gulf of Mexico and over the study area. The NAO has been unusually strong during the 20th century (Cook *et al.* 2002). In my analysis, NAO index values for January and February were positively and significantly correlated to growth at each site and to the regional chronology. The combined Jan-Feb variable had the strongest relationship (ALL, $r = 0.43$, $P < 0.01$). The strong positive correlation between winter NAO and tree-ring width is not surprising in light of the growth relationship of yellow pines in the study area with winter temperature and precipitation.

Notable peaks of positive NAO winter values occurred in 1954, 1957, 1962, 1974, 1984, 1989, but only 1957 and 1974 were associated with above-average wide rings in the chronologies. Negative NAO peaks occurred in the winter months of 1955, 1960, 1963, 1966, 1969, 1979, 1985, and 1987. Of those years, 1963, 1979, 1985 and 1987 were associated with very narrow rings. The significant negative correlation of pine growth to prior fall season months (GMT with Oct, RCT/PMT with Nov) is similar to the relationship between growth and November temperature at the sites, but is dissimilar with October temperatures or with precipitation in either month. Notable peaks of fall season NAO positive values occurred in 1978 and 1986. Both years correspond to very narrow rings in the site chronologies. There is also a very strong positive NAO peak in November 1993. Pines at Gold Mine Trail and Pine Mountain both had narrow marker rings the following year (1994) that may have been related.

In general, the ring width patterns followed the winter trends of NAO, but between 1963 and 1990, the relationship seemed much tighter than years before and after. Two other recent studies in GSMNP also found significant relationships between yellow pine growth and January and February NAO (Grissino-Mayer *et al.* 2007, Biermann 2009). Table Mountain pines growing in southwest Virginia appeared to respond similarly to the NAO signal, as well (DeWeese 2007).

The East Atlantic Oscillation exerted little influence on growth of yellow pines in the study area. The overall patterns of EA correlations with growth were similar to the NAO, but much weaker. The correlations were generally positive in winter and summer, and were negative in spring and fall. Gold Mine Trail was the only site with pines that showed any significant relationship with EA (Jul, $r = 0.33$, $P < 0.05$). Positive peak EA Julys were in 1953, 1967, 1981, 1988, 1994, 1998, and 2003. The first three peaks were associated with below-average growth the following year; however, none were notable marker rings. Negative peaks in the July EA occurred in 1966, 1976, 1983, 1987, and 1993. Those years were also associated with negative growth at GMT, but the peaks were greater in amplitude. This would indicate that a warmer previous July affects ring width more than a cooler previous July.

The East Atlantic Oscillation primarily affects temperatures in the southeastern United States during the months of January through May. As EA values increase, temperatures decrease. Of those months, May EA and May temperatures are the most related for East Tennessee, and July, only weakly so. However, July EA is positively related to July precipitation. The increased precipitation during July would ease the moisture stress for the pine trees in that hot summer month. Because the previous July EA is significantly related to radial growth, it is probable that the extra moisture availability allowed for better photosynthesis function and for the storage of carbohydrates that could be used for growth starting in the following spring.

The Atlantic Multidecadal Oscillation, a driver of precipitation in East Tennessee, is related to the NAO. Warm phase (positive) brings more rain, and cold phase (negative) brings less. From 1963 through 1995, AMO was in a negative phase, while the majority of average annual NAO values were positive. The lowest peak AMO values occurred from 1972 to 1976, when the study area received several consecutive years of abundant precipitation. Very wide tree rings were recorded at all of the sites for 1973 and especially 1974. From 1940 through 2006, winter season AMO peak amplitude fluctuation was much greater than the other seasons, *e.g.* positive and negative peaks for the winter season often exceeded +5.0 and –5.0, whereas other seasons ranged primarily between +4.0 and –4.0. While significant associations between AMO and growth varied by site throughout the year, pine growth at all study sites was significantly related to January and February AMO. Gold Mine Trail had the strongest association throughout the year (all $r > 0.20$), and showed significant correlations with all months analyzed with the exception of the current May–July. Current summer months were not significant for any of the chronologies. The highest AMO correlations at each site were with October and November of the previous year. GMT had the strongest relationship of the sites ($r = 0.40$, $P < 0.001$ and $r = 0.40$, $P < 0.001$). Pines at Rabbit Creek Trail were the least responsive to AMO of the sites, only showing a weak correlation for October and November (both $r = .26$ $P < 0.05$), but not for other months.

### 3.7 Conclusions

Until the 1930s, the southeastern United States was basically ignored with regard to dendrochronological studies (Hawley 1938), the perception being that environmental conditions were not stressful enough for trees to register a quality climate signal. To date, the number of studies performed in this region is still much fewer than in the western U.S. My research shows that southeastern yellow pines in crowded, mixed-species stands do provide valuable climate information, and that winter temperatures prior to the growing season are a principal factor in pine growth across the study area, and possibly over the southern Appalachian Mountains in general. The NAO strongly influences winter temperature fluctuations; the positive phase brings milder winters and an earlier start to the growing season. Precipitation still plays a role in ring width formation in the western GSMNP, significantly in February and in May. Summer precipitation (May–August) was more important for growth at Rabbit Creek Trail and Pine Mountain, than at Gold Mine Trail. Overall, winter conditions controlled by both NAO and AMO influenced growth across the study area. Droughts, however, may have masked the longer-term climate signals at specific sites. Additional analyses, and perhaps data collection, would be needed to determine if the site-related differences in growth response are because of site-specific moisture limitation, or derive from the varying proportions of pine species that were sampled at the sites that may have different physiological responses to the same climate stimuli.

Because tree growth at my sites has a strong relationship with the NAO index, my chronologies can be used to strengthen reconstructions of NAO values and perhaps improve the ability of climate scientists to forecast fluctuations of the NAO. The NAO influences storm tracks across the Atlantic Ocean, which then affects human activities such as shipping, fishing, and offshore oil drilling (Goodkin *et al.* 2008, Hurrell and Deser 2009). Because the NAO and other oscillations influence each other, a multivariate analysis should be conducted to further explore the interrelationships of the different climate variables with each other, and with the chronologies.

This study used instrumental data available from 1940 to 2007. Divergence in the relationship between temperature and tree growth since the 1960s has been noted in a number of studies (Johnson *et al.* 1988, Briffa *et al.* 1998, D'Arrigo *et al.* 2008, Biermann 2009); however, controversy still exists as to the cause of this phenomenon (Esper and Frank 2009, Loehle 2009. Further investigation of the long-term relationship between pine growth in the western portion of GSMNP and climate proxies is explored in another of our studies, to be published separately.

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# CHAPTER 4

# FIRE HISTORY AND REGENERATION STATUS OF YELLOW PINE AND PINE-OAK STANDS IN GREAT SMOKY MOUNTAINS NATIONAL PARK, TENNESSEE, U.S.A.

Portions of the introduction and study site descriptions in this chapter were taken from Chapters 1 and 2 of this dissertation. The use of "we" or "our" in Chapter 4 refers to the many people who assisted in the field and lab to make this study possible. Details can be found in the Acknowledgements section of this dissertation. Funding for this research was made possible through a Joint Fire Sciences Program grant authored and managed by Dr. Henri D. Grissino-Mayer, Dr. Charles Lafon, and Dr. Sally P. Horn. Essential support was also provided by the personnel at Great Smoky Mountains National Park, who gave us important permissions, access, and assistance for this study. My contributions to this research include field work, sample processing and dating, development of the chronologies used for dating the samples, determination of fire events, statistical analyses, and interpretation of results. This chapter will be submitted to the journal *Forest Ecology and Management* for publication.

## Abstract

Compositional shifts in southern Appalachian forests may be related to changes in the historical wildfire regime. Policy to suppress fires on public lands was enacted in the 1930s, but relatively little is known about wildfire history prior to and during European settlement in the southeastern United States. Using dendroecological methods, we examined the historical fire regime of lower-elevation (400–600 m ASL) mixed yellow pine-hardwood stands in the western portion of Great Smoky Mountains National Park, one of the few locations in the region that has older forests. Three sites were selected for which we developed yellow pine chronologies against which fire-scarred cross-sections were dated. Stand age structure and, stand composition were determined using three vegetation plots at each site. Fires in the all-scarred class during the period of reliability (about 1828 to 1934) occurred once every 1.7 to 2.4 years. More-widespread fires occurred, on average, once every 4.2 to 7.3 years. Temporal analysis indicated changes in the fire regime over the 300-year record. Prior to European settlement (1700–1834), fires occurred every 6 to 12 years and occurred during the dormant or early-growing season. From 1834 to 1934, fire activity increased to one fire every 1.7–2.3 years, but retained the same seasonality. After fire suppression policy enactment and the establishment of the park in 1934, wildfire frequency declined to 6.5–8.8 years, and shifted later in the growing season. In the 1700s and 1800s, tree establishment was generally infrequent and was primarily composed of oaks and yellow pines. Mixed hardwood numbers notably increased at all sites after 1910, but tapered off after 1970. Eastern white pine and red maple were common in the canopy-class (≥ 5 cm DBH) at all sites. Other dominant species included eastern hemlock, blackgum, chestnut oak, white oak, and sourwood, varying by site. The yellow pine composition of the canopy-class trees was primarily Virginia pine, followed by pitch pine, shortleaf pine, and Table Mountain pine. Establishment peaked in the 1930s. Regeneration of yellow pines was negligible. The seedling- and sapling-classes were dominated by eastern white pine, red maple, and scarlet oak across the sites. Relationships were evident between the fire regime changes, vegetation shifts, and human activity. Results from this study can be used by scientists to better understand fire-adapted ecosystems undergoing change, and also by land managers to evaluate and implement restorative treatments.

### 4.1 Introduction

This chapter is part of a larger research project conducted in the southern Appalachian Mountains to determine the growth response of yellow pines (*Pinus* subgenus *diploxylon*) to climate, to elucidate historical wildfire patterns on the landscape, and to reveal relationships between wildfire occurrence, climate, and human activity. The primary goal of chapter four is to determine the historical fire regime as recorded in the tree-ring record and associated vegetation in climate in lower-elevation (400–600 m ASL) mixed pine/pine-oak stands from the early 1700s to the present in the western portion of Great Smoky Mountains National Park (GSMNP), Tennessee.

The pine-oak forest type has shown historical decline in the southern Appalachian Mountains (Smith 1991, Harrod *et al.* 1998, Harrod and White 1999, Vose *et al*. 1999), which may adversely affect overall vegetation diversity (Waldrop *et al*. 2003), native wildlife (Trani 2002, Chapman *et al.* 2006, Spaulding and Rieske 2011), and the availability of natural resources and services for humans (Christensen *et al.* 1996). The lack of recurrent wildfire events on the landscape is a probable factor in this compositional shift (Hubbard *et al.* 2004, Dumas *et al.* 2007). Policy to suppress fires on public lands in the United States was enacted in the early 20th century, and was very successful by the 1930s and 1940s. Since then, our understanding of disturbance ecology has vastly increased. In fire-adapted ecosystems, fire assists yellow pines (*Pinus* subgenous *diploxlyon*) in adequately competing against hardwoods through clearing excessive duff and debris, especially hardwood material (Williams *et al*. 1990); revealing mineral soil for improved germination and growth (Groeschl *et al.* 1993, Cain and Shelton 1994, Waldrop and Brose 1999, Stambaugh *et al*. 2007); exposing the forest floor to more light; and opening resinous cones to release the seeds (South and Buckner 2003). Suppression of fire promotes crowded understory and midstory vegetation conditions, and stresses the trees through increased competition for resources (McDonald *et al*. 2003). The composition of many pine and pine-oak communities appears to be shifting toward fire-intolerant species such a red maple (*Acer rubrum* L.) and eastern white pine (*Pinus strobus* L.) (Abrams 1992, 1998).

Public land managers now use prescribed fire as a method to restore ecosystem processes to a pre-suppression state in communities with yellow pine components (Brose *et al.* 2001, Whitlock *et al.* 2003, Fulé *et al.* 2005, NPS 2010), and to manage for endemic and rare species (Rock 2000, Hoss *et al*. 2008). To successfully use this technique, the historic fire regime of the target area should first be determined (Mutch 1992, Sutherland *et al*. 1995, Fulé and Covington 1996, Wright and Agee 2004) to gain an improved understanding of vegetation response to the presence and absence of fire (Arthur *et al*. 1998, Elliott *et al*. 1999, Welch *et al* 2000, Fulé *et al*. 2005, Huisinga *et al*. 2005). A blanket restoration prescription cannot be used across a region; different ecosystems require different management plans (Dellasala *et al.* 2004, Floyd *et al*. 2004, DeWeese 2007).

Fire regimes have been more thoroughly studied in the western United States where large wildfires are prevalent (Arno and Sneck 1977, Dieterich 1983, Floyd *et al.* 2004, Grissino-Mayer *et al.* 2004, Miller *et al.* 2009), although fire frequency is actually higher in the southern U.S. (Gramley 2005). The role of fire in ecosystems in the southeastern United States has more recently gained attention (Harmon 1980, Armbrister 2002, Waldrop *et al.* 2003), and continuing research in this region is needed. Our study investigates the current status of lower-elevation (400–600 m ASL) yellow pine stands and their associated vegetation communities in Great Smoky Mountains National Park (GSMNP). Dendrochronology and standardized vegetation survey techniques were used in our research to date fire events to the exact year of occurrence, to determine changes in stand composition and age, and to measure accumulated duff levels. We provide a detailed history of the fire regime of these stands prior to Euro-American colonization (ca. 1834), during settlement of the Great Smoky Mountains (1834–1934), and after the official establishment of the park in 1934.

GSMNP was selected for this research because it is one of the few locations in the region with forest stands that are old enough to have preserved a long record of past wildfire events (Harmon 1980, Harrod and White 1999). The park encompasses 2072 $km^2$ of land, of which 95% is forested, and of that, about 25% is old-growth forest (has not undergone large-scale disturbance for at least several centuries). GSMNP is also a protected area of rich diversity and beauty, and was designated an International Biosphere Reserve in 1976 and a World Heritage Site in 1983 (NPS 2010). Results from this study can be used by scientists to better understand fire-adapted ecosystems undergoing change (Skinner and Chang 1996), and also by park managers to help evaluate and implement restorative treatments to better preserve the protected landscape for current and future generations.

In the southern Appalachians, pine or pine-oak ecosystems typically occupy the more xeric sites, often located on southwest-facing slopes. Pine species native to the region are: shortleaf pine (*Pinus echinata* Mill), pitch pine (*P. rigida* Mill.), Virginia pine (*P. virginiana* Mill.), and Table Mountain pine (*P. pungens* Lamb.) (Vose *et al*. 1995, Vose *et al*. 1999, Welch *et al*. 2000). Shortleaf, pitch, and Virginia pines are found in the low- to mid-elevation ranges. Table

Mountain pine primarily occupies the higher ridges (Waldrop and Brose 1999), but can occasionally be found at slightly lower elevations.

A non-lethal fire can injure the living cambial layer that lies just beneath the bark of a yellow pine (Lachmund 1921, Smith and Sutherland 2001, Speer 2010), aided by flammable resin within the bark (Verrall 1938, Kilgore and Taylor 1979, Guyette and Cutter 1991, Neumann and Dickmann 2001, Huffman 2006). As the injury heals, it leaves a resinous scar in the annual growth ring, and the overlying bark often sloughs off. A tree that has been successively burned by fire, but not killed, forms a triangular "catface" feature near the base that consists of scar ridges where the cambium and bark were not able to fully close over the injured area (Figure 4.1). Once sapwood has been exposed, a yellow pine tree is more vulnerable to the next fire (Lachmund 1921, McBride 1983). This makes the pine more likely to record milder fires that may not scar trees fully protected by a layer of bark surrounding the bole (Figure 4.1). Oaks (*Quercus* spp.) and other hardwoods also scar, but they are more difficult to use in fire studies because the wood does not preserve as well and it has a higher incidence of intra-annual ring variability that hinders successful dating of the fire scars (Taylor and Skinner 2003, Guyette *et al*. 2006).

**Figure 4.1:** Photographs of fire-scarred tree and of processed sections. **A**) Fire-scar catface on living yellow pine in study area, after wedge sample removed by chainsaw. **B**) A fire-scarred sample after sanding and crossdating. Individual scars from fire events are labeled with calendar year. Annual growth bands are light (earlywood) and dark (latewood) striations. Insect galleries are also present. **C**) Cross-section showing the "20th century curl" from fire suppression following years of frequent fire events that left scar records in the wood.

The annual rings of southeastern yellow pines tend to have clearly defined boundaries and consistent intra-annual ring width in undamaged portions of the tree (Hoadley 1990). They also respond well to fluctuations of climate variables (*e.g.* temperature and precipitation) that give the ring series in each tree the distinct patterns that allow samples from multiple trees to be crossdated against each other (Friend and Hafley 1989, Grissino-Mayer *et al.* 1989, Copenheaver *et al.* 2002, Biermann 2009). Crossdated ring series collected from living trees can be assigned calendar years because the date of the outer ring is known. These anchored series are used to form chronologies against which other series measured from samples for which the outer ring, or year of death, are not known (*e.g.* logs and remnant wood) can be dated. To date fire-scarred sections from non-living trees, it is desirable, and often necessary, to develop a site-specific chronology from the same species.

To extend the fire record and examine fire regime changes between pre- and post-park conditions, Harmon (1980) took wedge-shaped samples from 43 yellow pine trees located on the western side of GSMNP. A total of 115 scars were recorded, the oldest of which dated to about 1856. Harmon was restricted to collecting samples with a handsaw, which constrained his ability to access the oldest scars in the central portion of standing trees; therefore, some of the earliest records were unavailable. From 1855 to 1940, the mean fire interval (*i.e.* average number of years between fires) was 12.7 years. Very few fires were recorded by the trees between 1910 and 1940, likely because of reduced frequency of fire on the landscape during suppression.

Two decades later, Armbrister (2002) examined fire-scar records and vegetation data collected from Table Mountain pine (TMP)-dominant stands at five sites distributed across the north-central portion of the park. Prior to the 1930s, the average fire interval was 6.8 years. Lack of fire from suppression was evident in the scar-free outer rings of the samples (*e.g.*, the "20th century curl," Figure 4.1C). Mountain laurel was dominant in the understory of the stands. The age structure of TMP at all sites peaked in the 60- to 70-year class. This placed tree establishment during the mid-1930s.

This chapter will address these research questions:

1) What was the historical fire regime on the lower-elevation landscape of Great Smoky Mountains National Park over the past three centuries?
2) Did the fire regime change over time, and can these changes be attributed to human activity?
3) Do the age structure and stand composition data reflect changes in the stand that are related to changes in the fire regime for the area?
4) Is pine regeneration favored under the current conditions?

## 4.2 Study Sites

To locate optimal sites to conduct this fire history research, we consulted with park personnel familiar with the ecology and vegetation community types found within GSMNP. After reviewing near-infrared aerial photographs of the study area, we targeted stands containing large pine trees that had been observed to have, or were strongly suspected of having, evidence of past wildfires. Three sites were selected that met these criteria, all of which were located on the drier western side of the park, within an area of highly-dissected topography: Gold Mine Trail (35°38′ N, 83°54′ W), Rabbit Creek Trail (35°36′ N, 83°55′ W), and Pine Mountain (35°37′ N, 83°55′ W). The elevation range for each site was between 460 and 600 m. The Gold Mine Trail site covered approximately 35 ha, while Rabbit Creek Trail and Pine Mountain were about 20 ha in area.

Each site had been classified by Pyle (1988) as having diffuse disturbance in the past, while still retaining many large and old trees. Areas of diffuse disturbance may have experienced small, frequent fires, livestock grazing, or small logging operations, but they were exempt from the large-scale damage and intense fires associated with corporate logging. All three study sites had numerous mature pines (and some hardwoods) that exhibited distinct catface scars, many with multiple ridges, at the base of the trees that were indicative of prior low-severity fire events. Fire scars were found not only on standing pines (living and dead), but also on stumps, logs, and remnant wood that had weathered away to the harder, resin-saturated core of the tree. Many of the mature yellow pine trees had died from recent beetle outbreaks and fell during wind and storm events over the course of this study. The understory in the stands was typically dense with saplings and younger trees, most of which were fire-intolerant hardwoods.

### 4.3. Field Methods

Field data and samples were collected from 2005 to 2008. Three 20 x 50 m (0.1 ha) macroplots were established at each site, for a total of nine. All canopy-class trees (≥ 5 cm DBH) in the plot were identified to species, and at least two cores were collected with an increment borer near the base (~30 cm above ground level) of each living tree (Grissino-Mayer 2003), preferentially parallel to the slope contour to avoid reaction wood (Speer 2010). When possible, two cores were collected synchronously by passing the increment borer through the full diameter of the tree, bark to bark. Some mid-story species were excluded from coring because they were unlikely to reach canopy height, for example, dogwood (*Cornus florida* L.) and sassafras (*Sassafras albidum* (Nutt.) Nees). To ensure sufficient sample depth for reliable yellow pine chronologies, at least 40 trees were cored per site. If fewer than 40 trees were sampled from the combined three macroplots, more yellow pine cores were extracted from trees located externally to, but nearby, the macroplots. Some of the trees included were snags (dead, but standing). The external cores were used only for developing chronologies and not for stand history analysis. All cores were placed in labeled paper straws for transport. Two 10 x 20 m subplots within each macroplot were inventoried for sapling (> 0.5 m height and < 5 cm DBH) composition. Seedlings (< 0.5 m height) were inventoried in 1 x 20 m belt transects that originated on the 0 m, 20 m, and 40 m points of the 50 m boundary of the macroplot, and that passed through the macroplot on a line parallel to the short sides (20 m sides) of the rectangle.

Across each site, samples were gathered using a targeted method because of the limited quantity and quality of fire-scarred pines (Stambaugh and Guyette 2004), a technique that has been shown to be statistically valid (Van Horne and Fulé 2006). The samples were collected using a chainsaw to remove cross-sections from snags, logs, remnant wood, and a few selected living trees (Arno and Sneck 1977). Hardwood species were not sampled for fire history because they are more difficult to work with and more likely to be decayed than pines. The fires recorded by the pines, and the age structure of trees in the plots, represent the regime experienced by the hardwoods mixed in the stands.

Duff thickness was measured at six locations across each macroplot. Each measurement was taken at a random location along every 10 m line running perpendicular to the long edge

(50 m) of the macroplot. Loose leaf litter was brushed away by hand and a trowel was used to remove a plug of soil. The depth of the organic layer above mineral soil was measured to the nearest half-centimeter.

## 4.4 Laboratory Methods

### 4.4.1 *Sample Preparation*

The tree cores were dried, removed from the paper straws, and glued onto labeled wooden core mounts (Stokes and Smiley 1996). The mounted cores were then sanded with progressively finer grit, starting with ANSI 120 grit (105–125 μm) and finishing with ANSI 400 grit (20.6–36.0 μm), to enhance the visibility of the annual rings (Orvis and Grissino-Mayer 2002). If necessary, the cores were further polished by hand with P1500 grit (9.8–12.3 μm) sandpaper. Cross-sections were either treated with insecticide or frozen at –40 °C for 24 hours to kill destructive insects. After drying, the wood samples were cut into thinner sections with a band saw and then sanded to enhance the ring visibility. If the section had deep saw marks on the surface, the initial sanding grit was coarser (*e.g.* ANSI 60 grit, 250–297 μm) than that used on the cores. Fragile samples were mounted on particle board with wood glue before processing.

### 4.4.2 *Cores and Crossdating*

Samples that retained the outer bark collected from living trees were penciled with a system of dots that represented calendar decades, starting at the outer ring (Stokes and Smiley 1996). Samples that had no bark, or were from long-dead trees, were penciled with X's at every tenth ring, starting at the interior of the core. Unusually wide or narrow marker rings were noted and compared between cores. The ring series were measured to the nearest 0.001 mm using a Velmex station coupled with Measure J2X software. Crossdating was confirmed by COFECHA version 6.06P, using 40-year segments lagged by 20 years, and a critical correlation coefficient threshold of 0.37 (Holmes 1983, Grissino-Mayer 2001a). Cores for which the calendar dates were unknown were dated against the living cores. Standardized chronologies were generated from the crossdated cores for each site using ARSTAN (Cook 1985), against which the fire-scarred sections were later dated. Macroplot cores from other conifers and hardwoods were ring-counted to calculate age and year of establishment because many of the species sampled had complacent rings or high intra-annual ring variability, making crossdating difficult, if not impossible. If pith (tree center) was not present in the cores, establishment dates were estimated using ring curvature and concentric circle locators (Applequist 1958, Larson 2005). If the inner rings of the core lacked curvature, the innermost ring date provided a minimum (as-old-as) age for the tree (Soulé and Knapp 2000).

### 4.4.3 *Wildfire Dating and FHX2*

The sanded cross-sections and wedges were visually inspected, and marker rings and individual scar positions noted. Penciled transects were drawn perpendicular to the annual rings and across the wood (inner to outer). The transect lines were preferentially made through areas having the clearest ring series and the least amount of damage from insect galleries, rot, or enlarged rings adjacent to the scars. Often, two transects were measured on each sample to increase the chances of obtaining a datable ring series. Decadal rings were marked in pencil. The ring widths for each fire sample were measured using the Velmex station and Measure J2X software. The sample was dated against the site chronology both visually and using COFECHA. Higher-quality ring series were added to the site chronology to improve sample depth, and to extend the record back in time. Several of the cross-sections had longer ring records than the cores.

Each fire scar was then assigned a calendar year according to its association with an annual ring and the date recorded on the sample in permanent marker. Seasonality was determined by the intra-annual position of the fire scar (Baisan and Swetnam 1990). Five seasonal positions were used in this study: dormant (D) was directly on the sharp boundary between annual rings; early-earlywood (E) was in the first third of the earlywood; middle-earlywood (M) was in the second third of the earlywood, late-earlywood (L) was in the last third of the earlywood, and latewood (A) was in the latewood (Baisan and Swetnam 1990, Grissino-Mayer 2001b, DeWeese 2007). If the season of a scar could not be determined, it was designated "U." Non-fire injuries were also noted. The timing of a fire event results in different effects on the landscape and vegetation. Dormant season burns tend to clear more debris from the forest floor, while growing season burns tend to injure, or kill, more young trees (Brose and Van Lear 1998, Dey 2002).

Fire-scar years and seasons, along with inner and outer dates for each sample, were entered into FHX2 and FHAES (Grissino-Mayer 2001b, http://frames.nbii.gov/fhaes), complementary software packages used to statistically analyze and graph fire history data. To ensure statistical robustness for the fire calculations, recorder and non-recorder years were documented for each sample (Grissino-Mayer 2001b). Recorder years represent the rings formed in subsequent years after a fire when the injury is unhealed and the tree more likely to scar again. Non-recorder years represent years before the first fire event or when rot or weathering has removed the wood necessary to determine whether or not a fire had occurred. The statistical analyses were performed only over segments of recorder years. I analyzed specific date ranges for each site designated as the Period of Reliability (POR) (Grissino-Mayer 1995, Arabas *et al*. 2006). The POR was bracketed by 1) the first year when at least two samples were scarred at the site, and by 2) 1934, the official year of park establishment and the approximate commencement of fire suppression. The POR aids in comparing fire regime results across sites (Riccius 1998). Using FHX2/FHAES, I created a fire chart and chronology for each study site. The fire data for all three sites were then combined to represent the fire history for whole study area.

I used 10 statistics to describe the range of fire interval data that were calculated using the 2-parameter Weibull distribution: Mean Fire Interval (MFI), Weibull Modal Interval (MOI), Weibull Median Interval (MEI), Standard Deviation (SD), Coefficient of Variation (CV), Minimum Fire Interval (MAX), Maximum Fire Interval (MIN), Lower Exceedance Interval (LEI), Upper Exceedance Interval (UEI), and Maximum Hazard Interval (MHI).

Three established classes of fire data were analyzed for each site, and also for the combined (regional) data: all-scarred, 10%-scarred, and 25%-scarred (Grissino-Mayer 1996, DeWeese 2007, Fulé *et al*. 2009). The all-scarred class included all fires that occurred within the target date range. The 10% analysis was used to reduce the influence of small “spot” fires by requiring that the fires analyzed represent at least 10% of the recorder trees within the date range. The 25% class analysis was used to indicate when the most widespread fires occurred.

A temporal analysis was conducted for each site by comparing the fire statistics generated by FHX2/FHAES for the all-scarred class (min=1) for three periods: Pre-settlement (the beginning of the fire history record through 1834), Settlement (1835–1934), and Suppression (1935–2007/2008). The Cherokee were the primary inhabitants of GSMNP and its surrounding environs until the early 1800s. European settlers had moved into Cades Cove and into most of the river valleys in the area by 1834. The park was officially established in 1934 after which many residents were moved off the land and fire suppression was prevalent. There were not enough 10%- and 25%-scarred class fire event data to analyze for all three periods, so only the all-scarred class results will be presented.

### **4.4.4** ***Stand History***

For a thorough understanding of the fire regime, it is necessary to complement the fire-scar analysis with age-structure analysis (Mann *et al*. 1994, Miller and Rose 1999, Taylor and Skinner 2003, Aldrich *et al*. 2010). Examining the age structure and stand composition provides data about fires that may not have been captured in the fire-scar analysis, and it also provides information about past, current, and potential future vegetation composition. Cohorts of even-aged trees indicate either a large disturbance (*e.g.* a higher-severity fire) or a significant change in the disturbance regime (*e.g.* suppression of wildfires).

Age diameter graphs were generated from the macroplot core data using the year of establishment plotted against the diameter (cm) of the tree at breast height (~1.4 m). These graphs present the relationship between tree size and tree age for canopy species at each study site, and also show cohort establishment. The trees were categorized into five groups: hardwoods, yellow pines, oaks, white pine, and hemlock. This grouping improved visual differentiation between fire-adapted species and fire-intolerant species. Comparing the age diameter graphs to the fire history charts allowed for determination of associations between fire events, or lack of, and establishment of the trees.

The seedling-, sapling-, and canopy-class data from each site were used to generate bar graphs of stem count percentages for tree species that had the greatest number of individuals at the site. The graphs present the species that were common in each class, the current composition of the mature trees, and which species were likely to dominate the stand in the future. Importance values were calculated to determine which species were dominant at each site using the canopy-class data. The importance percentage calculation takes into account the total stem count for each species across all three macroplots (0.3 ha) at a site and the dominance, which is the basal area ($m^2$/ha) divided by 0.3 ha. Importance values were also calculated for the combined site data to represent the study area as a whole. The canopy-class importance values provide a better understanding of which species were actually more dominant at the site by including size of the trees (basal area) in addition to stem numbers, while the stem count percentages allow for comparison between the three vegetation classes (canopy, sapling, and seedling). Two yellow pine age structure graphs were created using the combined core data from all nine macroplots (*i.e.* all three study sites or 0.9 ha total). One graph presents yellow pine establishment by decade for each site, as calculated by stem count percentage. The other graph illustrates the stem number of each yellow pine species that established per decade for all sites combined.

## 4.5 Results

### 4.5.1 *Wildfire Results*

#### 4.5.1.1 *Gold Mine Trail (GMT)*

Sections from 44 trees were crossdated against the site chronology and included in the fire history analysis at Gold Mine Trail (Table 4.1). The oldest sample spanned 324 years (1684–2007) and was collected from a living, fire-scarred tree. It was only after the sample wedge was removed and dated that this tree was determined to be the oldest living shortleaf pine on record in the U.S., even though it was smaller in diameter than many other yellow pines at the site. GMX307 was still alive and standing as of 2008. The tree had a large, deep catface scar at its base, but unfortunately, much of the fire scar record had worn away from weather and insects. It did, however, record the earliest documented fire at Gold Mine Trail (1728).

**Table 4.1:** Sample number and years for fire-scarred samples from each study site. Period of reliability (POR) is delimited by the first year with a minimum of two samples scarred and the year of GSMNP founding (1934). Statistical analyses were performed on the data within the POR.

| Site | Number of Crossdated Samples | Earliest Fire | Latest Fire | Span of Ring Record | Period of Reliability | Length of POR |
|---|---|---|---|---|---|---|
| Gold Mine Trail | 44 | 1728 | 1968 | 1684–2007 | 1820–1934 | 115 |
| Rabbit Creek Trail | 36 | 1763 | 1992 | 1700–2008 | 1838–1934 | 97 |
| Pine Mountain | 36 | 1727 | 1976 | 1710–2007 | 1827–1934 | 108 |

The period of reliability (POR) for the fire record at GMT was 1820–1934. Between 1850 and 1930, wildfires regularly occurred throughout the stand (Figure 4.2). Several fires were widespread (*e.g.* 1903, 1908, and 1919), but the fire documented in the greatest number of samples (n = 21) took place in 1929. The majority of wildfires that burned in the stand (61.7%) were early (E) in the growing season or during the dormant (D) period just prior to the growing season (Table 4.2). The 1929 fire occurred much later in the growing season compared to most of the other wildfires, and was also the last major wildfire to occur in the stand. Only a few, isolated scars appeared in the GMT tree-ring record after 1930, the most recent one in 1982. Many of the yellow pine trees included in the fire history established between 1860 and 1880. Synchronous deaths of about one-third of the trees occurred around the year 2000.

The mean fire interval (MFI) for the all-scarred class was 2.07 years, and the Weibull Modal Interval (MOI) and Weibull Mean Interval (MEI) were 0.87 and 1.76 years, respectively (Table 4.2). Minimum and Maximum Fire-free intervals for this class ranged from 1 to 10 years. The Lower Exceedance Interval (LEI) and Upper Exceedance Interval (UEI) were 0.52 and 3.93 years. The Maximum Hazard Interval (MHI) was 1.44 years. The 10%-scarred class presented similar results for the MFI (2.60 years), MOI (2.17 years), MEI (0.99 years), LEI (0.63 years), and UEI (4.98 years). The fire-free intervals for the 10%-scarred class also ranged from 1 to 10 years, and the MHI was 3.64 years. For the 25%-scarred class, the values (years) doubled for the MFI (4.95), MOI (4.21), MEI (2.26), LEI (1.31), and UEI (9.19). The fire-free intervals spanned 1 to 13 years. The MHI value was much greater than the other two classes at 27.86 years.

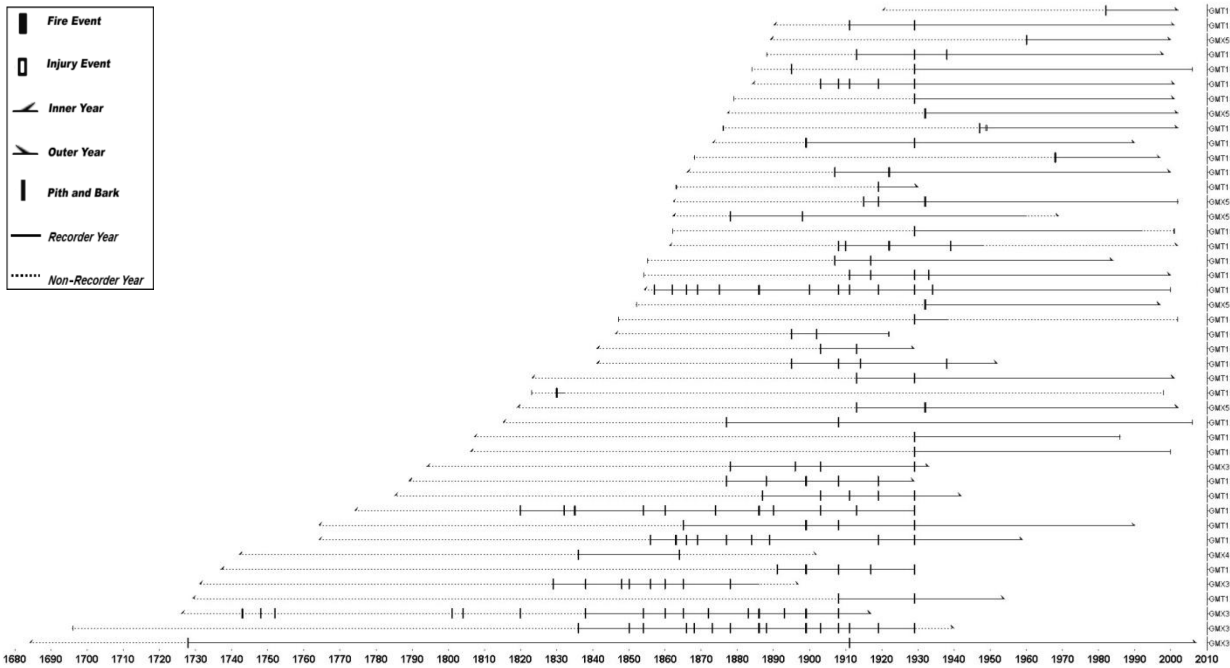

**Figure 4.2:** Crossdated fire chronology for Gold Mine Trail. Individual tree records are presented on horizontal lines (solid = recorder years, dashed = non-recorder years), with an identification code at right. Each solid vertical bar is a fire event. Trees recording the same event (*e.g.* 1929) indicate that the fire had a wider spatial distribution. A near absence of fire is evident after suppression policies were enacted in the 1930s. The period of reliability (first year when two samples were scarred) at GMT is 1820–1934.

The temporal analysis of GMT wildfires revealed notable changes in the number of fires, the return intervals, and the burn seasons for the three periods examined (Table 4.3). The Pre-settlement Period (1684–1834) showed an interval of 7.3 to 11.6 years (MEI/MFI) and ten fires, while the Settlement Period (1835–1934) displayed a much shorter interval between fires (MEI=1.7, MFI=1.9 years) and 52 fires. Despite the large differences between the intervals, the majority of fires in both periods occurring during dormancy or early in the growing season (66.7% and 61.3% D/E). Fires in the Suppression Period (six in 1935–2007) were again widely spaced in time (7.9–8.8 years, MEI/MFI), but they tended to burn later in the growing season (40% D/E).

**Table 4.2:** Descriptive statistics for fire-scarred samples from each study site during the period of reliability. The period of reliability (POR) is bounded by the first year at least two samples were scarred and the year of GSMNP founding (1934). DE = Dormant/Early growing season, MLA = Middle to Late growing season. Results are shown for three fire classes (all, 10%, and 25%).

| Statistic | Gold Mine Trail | | | Rabbit Creek Trail | | | Pine Mountain Trail | | |
|---|---|---|---|---|---|---|---|---|---|
| Total number of fires for site | 145 | | | 92 | | | 126 | | |
| Number and percentage DE fires | 79 61.7% | | | 58 84.1% | | | 83 83.8% | | |
| Number and percentage MLA fires | 49 38.3% | | | 11 15.9% | | | 16 16.2% | | |
| **Class** | **All** | **10%** | **25%** | **All** | **10%** | **25%** | **All** | **10%** | **25%** |
| Total Number of Intervals | 55 | 43 | 22 | 48 | 25 | 10 | 43 | 32 | 13 |
| Mean Fire Interval | 2.07 | 2.60 | 4.95 | 1.92 | 3.12 | 5.60 | 2.40 | 2.97 | 7.31 |
| Weibull Modal Interval | 0.87 | 0.99 | 2.26 | 1.44 | 1.34 | 5.50 | 1.45 | 1.66 | 5.29 |
| Weibull Median Interval | 1.76 | 2.17 | 4.21 | 1.79 | 2.64 | 5.19 | 2.14 | 2.61 | 6.74 |
| Standard Deviation | 1.86 | 2.30 | 3.70 | 1.13 | 2.62 | 3.37 | 1.66 | 2.10 | 4.44 |
| Coefficient of Variation | 0.90 | 0.88 | 0.75 | 0.59 | 0.84 | 0.60 | 0.69 | 0.71 | 0.61 |
| Minimum Fire Interval | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 2.00 | 1.00 | 1.00 | 2.00 |
| Maximum Fire Interval | 10.00 | 10.00 | 13.00 | 5.00 | 10.00 | 10.00 | 8.00 | 10.00 | 15.00 |
| Lower Exceedance Interval | 0.52 | 0.63 | 1.31 | 0.74 | 0.80 | 2.12 | 0.76 | 0.89 | 2.71 |
| Upper Exceedance Interval | 3.93 | 4.98 | 9.19 | 3.22 | 5.88 | 9.42 | 4.27 | 5.35 | 12.38 |
| Maximum Hazard Interval | 1.44 | 3.64 | 27.86 | 1.17 | 6.33 | 12.06 | 2.03 | 3.86 | 22.95 |

**Table 4.3:** Temporal comparison of fire intervals and seasons by site. Analyses performed in FHAES on All-scarred class, minimum of 1 scarred sample. Pre-settlement = beginning of site record–1834, Settlement = 1835–1934, Suppression = 1935–end of site record. MFI = Mean Fire Interval, MEI = Weibull Median Interval, Season D/E = Percentage of wildfires occurring during dormancy and early in the growing season.

| | Gold Mine Trail (1684-2007) | | | | Rabbit Creek Trail (1700-2008) | | | | Pine Mountain Trail (1710-2007) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Period | No. of Fires | MFI | MEI | Season (% D/E) | No. of Fires | MFI | MEI | Season (% D/E) | No. of Fires | MFI | MEI | Season (% D/E) |
| Pre-settlement | 10 | 11.56 | 7.29 | 66.7 | 10 | 7.89 | 6.08 | 87.5 | 11 | 10.3 | 6.53 | 83.3 |
| Settlement | 52 | 1.94 | 1.68 | 61.3 | 49 | 1.92 | 1.79 | 84.1 | 42 | 2.32 | 2.06 | 83.7 |
| Suppression | 6 | 8.8 | 7.88 | 40 | 8 | 8.14 | 6.76 | 62.5 | 7 | 6.67 | 6.46 | 44.4 |

#### 4.5.1.2 *Rabbit Creek Trail (RCT)*

The fire-scarred samples were more difficult to date at Rabbit Creek Trail than samples from the Gold Mine Trail and Pine Mountain sites because of lower quality from degradation (*e.g.* rot and insects). Most of the samples collected were from remnant wood, with only a few taken from living trees. Ultimately, the ring series and scar records from 36 trees were crossdated and included in the fire history, spanning from 1700 to 2008 (Table 4.1). Wildfire events were sporadic between 1763 and 1992, and usually only one or two trees recorded each fire (Figure 4.3). The fire recorded in the greatest number of trees (n = 5) occurred in 1894. The majority of documented wildfires occurred between 1800 and 1900. Fires were very infrequent after 1920. The period of reliability for Rabbit Creek Trail was 1838–1934, during which time 84.1% of the fires occurred either during dormancy or in the earliest part of the growing season (Table 4.2).

The MFI for the all-scarred class was 1.92 years, and the MOI and MEI were 1.44 and 1.79 years, respectively. The span of minimum and maximum fire-free intervals was relatively short at 1 to 5 years. The LEI was 0.74 and the UEI was 3.22. The MHI was 1.17 years for the all-scarred class. For the 10%-scarred class, the MFI, MOI, and MEI were 3.12, 1.34, and 2.64 years, respectively. Fire-free intervals ranged 1–10 years. The LEI was 0.80 years and the UEI was 5.88 years. The MHI was 6.33 years. Values for the 25%-scarred class were MFI, 5.6 years; MOI, 5.5 years; MEI, 5.19 years; LEI, 2.12 years; and UEI, 9.42 years. The minimum and maximum fire-free intervals ranged from 2 to 10 years, and the MHI was 12.06 years.

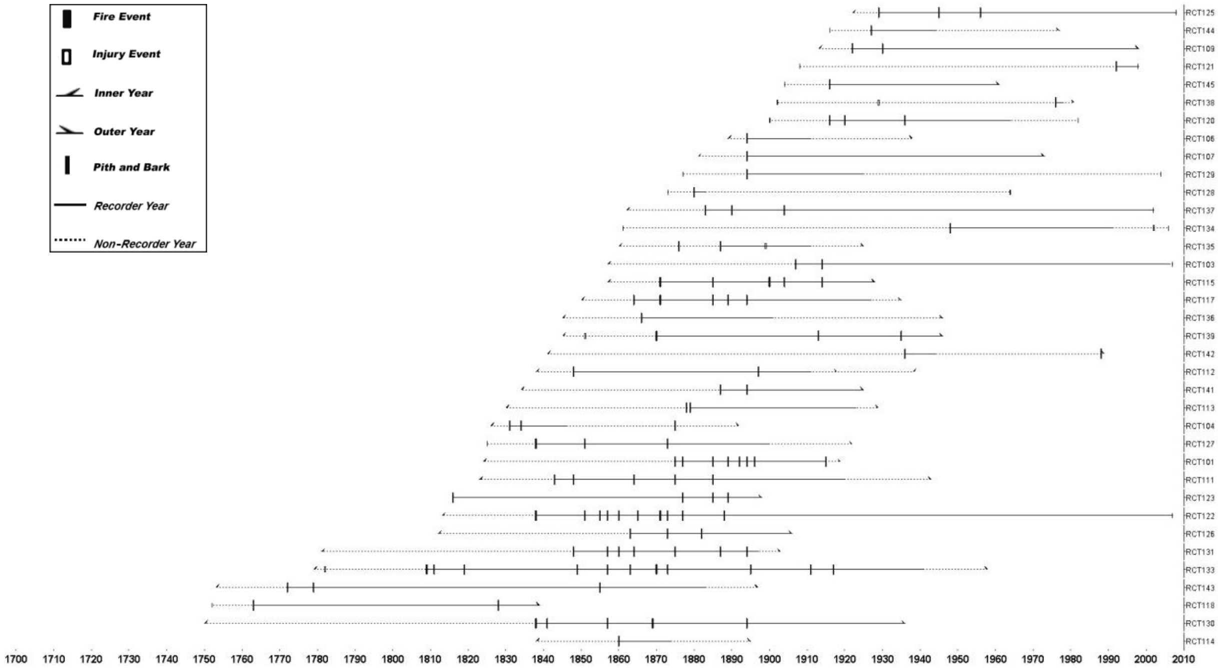

**Figure 4.3:** Crossdated fire chronology for Rabbit Creek Trail. Individual tree records are presented on horizontal lines (solid = recorder years, dashed = non-recorder years), with an identification code at right. Each solid vertical bar is a fire event. Trees recording the same event (*e.g.* 1894) indicate that the fire had a wider spatial distribution. A reduction of fire event occurrence is evident after suppression policies were enacted in the 1930s. The period of reliability (first year when two samples were scarred) at RCT is 1838–1934.

The temporal analysis revealed shifts in the number of fire events, the return intervals, and the season of burn at RCT (Table 4.3). The Pre-settlement Period (1700–1834) had intervals of 6.1 to 7.9 years (MEI/MFI) and 10 fires, and the vast majority of fires occurred during dormancy or early in the growing season (87.5%). The Settlement Period (1835–1934) produced a similar seasonality (84.1% D/E), but had much shorter intervals between fires (MEI=1.8 years MFI=1.9), and a higher incidence of fires (n=49). Fires in the Suppression Period (1935–2008) were again widely spaced in time (6.8–8.1 years, MEI-MFI) and were less frequent (n=8), as seen in the Pre-settlement period, but more of them burned later in the growing season (62.5% D/E).

**4.5.1.3** ***Pine Mountain (PMT)***

Samples from 36 fire-scarred trees were crossdated and used to generate the fire history for Pine Mountain (Table 4.1). The earliest fire occurred in 1727, and the most recent one in 1976. The ring record spanned 1710–2007. Wildfires burned regularly at PMT between 1830 and 1940 (Figure 4.4). A few fires were widespread, the most prominent of which burned in 1910 and was recorded in more than half of the trees analyzed (n = 20). The last notable fires occurred in 1922 (n = 8) and 1936 (n = 6). Records of some of the other fires were found in multiple samples throughout the site, but many of the fires at PMT were localized to one or two trees, especially early in the record and after 1940. Very few scars were found after 1950.

The period of reliability at Pine Mountain was 1827–1934. Almost 84% of the fires occurred during the dormant and very early growth seasons (Table 4.2). A widespread fire in 1900 (n = 9) burned early in the growing season, but more recent widespread fires (1910 and 1922) burned later in the growing season, as indicated by the position of the scar in many of the samples.

The MFI for the all-scarred class was 2.4 years, with the minimum and maximum fire-free interval ranging from 1 to 8 years (Table 4.2). The MOI and MEI were 1.45 and 2.14 years, respectively, with an LEI of 0.76 years and a UEI of 4.27 years. The MHI was 2.03 years. The 10%-scarred class showed similar results as the all-scarred for the MFI (2.97 years, with a minimum/maximum fire-free interval of 1 and 10 years), MOI (1.66 years), MEI (2.61 years), LEI (0.89 years), UEI (5.35 years), and MFI (3.86 years). Values increased for the 25%-scarred class. The MFI was 7.31 years and the minimum and maximum fire-free interval ranged from 2 to 15 years. The MOI and MEI were 5.29 years and 6.74 years, respectively, with an LEI of 2.71 and a UEI of 12.38 years. The MHI was 22.95 years.

The temporal analysis of PMT wildfire showed changes in the incidence, fire return intervals, and burn seasons between the three periods (Table 4.3). The Pre-settlement Period (1710–1834) had 11 fires, an interval of 6.5 to 10.3 years (MEI/MFI), and a seasonality of 83.3% D/E. Settlement Period (1835–1934) fires also primarily burned early (83.7% D/E), but displayed a much shorter interval between fires (MEI=2.1 years and MFI=2.3), and were greater in number (n=42). The return intervals of the seven fires in the Suppression Period (1935–2007) increased (6.5–6.7 years, MEI-MFI), and the fires occurred later in the growing season (44.4% D/E).

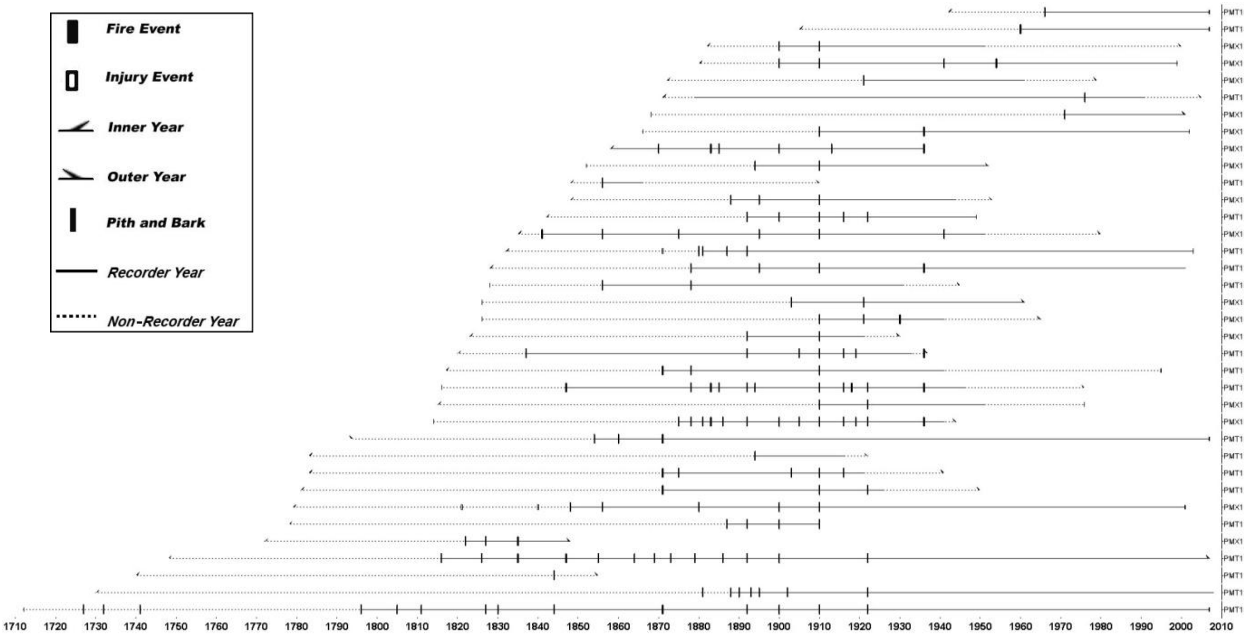

**Figure 4.4:** Crossdated fire chronology for Pine Mountain Trail. Individual tree records are presented on horizontal lines (solid = recorder years, dashed = non-recorder years), with an identification code at right. Each solid vertical bar is a fire event. Trees recording the same event (*e.g.* 1910) indicate that the fire had a wider spatial distribution. A near absence of fire is evident after suppression policies were enacted in the 1930s. The period of reliability (first year when two samples were scarred) at PMT is 1827–1934.

### 4.5.1.4 *Regional (ALL)*

Analyzing the combined fire data provided a larger-scale perspective of the historical fire activity (Figure 4.5). The Period of Reliability for the combined data was 1811–1934, and the majority of the wildfires occurred either during the dormant period or very early in the growing season (74.4%). Of the more-recent fires, 22.3% burned during the middle of the early growing season. Only 1% of the fires were recorded in the latewood of the samples. The MFI for the all-scarred class through the 25%-scarred class ranged from 1.35 to 8.43 years. The minimum fire-free interval was 1 year for all three classes. The maximum fire-free interval for the all- and 10%-scarred classes were similar (5 and 7 years, respectively), but increased to 32 years for the 25%-scarred class.

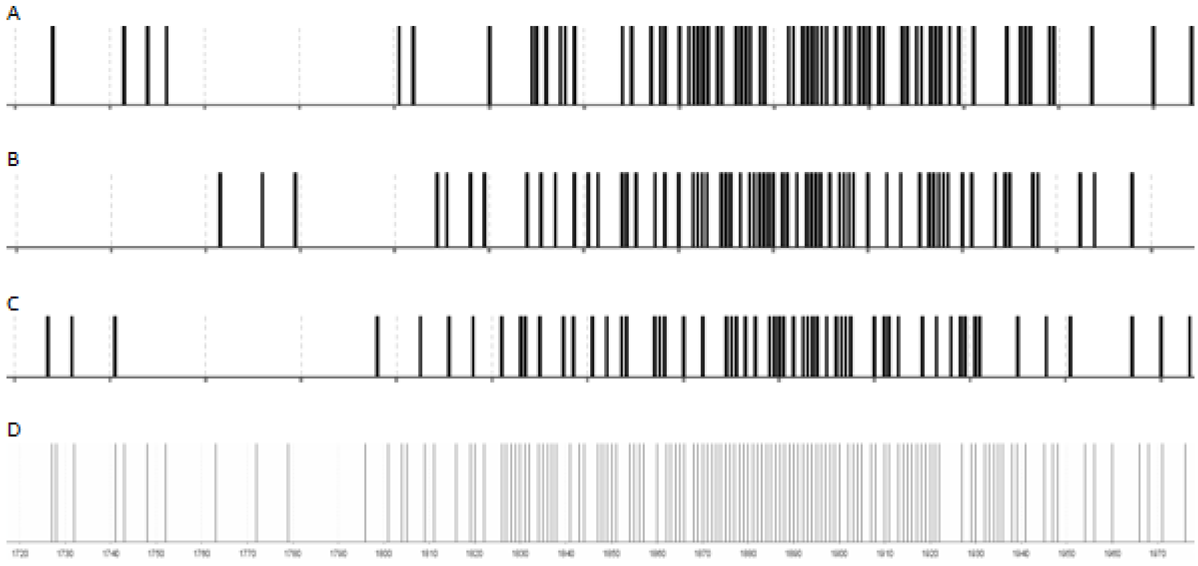

**Figure 4.5:** Composite fire chronologies for each site and for the combined site area **A**) Gold Mine Trail, **B**) Rabbit Creek Trail, **C**) Pine Mountain and **D**) combined chronologies. Each solid vertical bar represents at least one fire event that occurred that calendar year. Chronology was truncated 1720–1980 for comparison purposes.

The MEI (1 and 1.41 years), the MOI (1.26 and 1.92 years), the LEI (0.51 and 0.73 years), the UEI (2.29 and 3.66 years), and the MHI (0.54 and 1.43) were also comparable between the all- and 10%-scarred classes. For the 25%-scarred class, the MEI and MOI were 2.10 and 6.67 years, respectively. The LEI was 1.71 years and the UEI was 16.59 years. The MHI for the 25%-scarred class was > 1000 years.

### **4.5.2** ***Age Structure Results***

#### **4.5.2.1** ***<u>Gold Mine Trail (GMT)</u>***

From about 1800 through the 1920s, establishment of yellow pine, oak, and other hardwoods was low but consistent at Gold Mine Trail (Figure 4.6). In the 1930s, substantial establishment of oaks and hardwoods occurred in the stand, followed by white pine through the 1940s. Eastern hemlock arrived two decades later, during the 1960s. In the yellow pine age structure analysis, a pulse of establishment in the 1860s is evident; almost half (40%) of the yellow pines at GMT established during that decade (Figure 4.7). The majority of the trees that established prior to 1920 had relatively large diameters (> 30 cm DBH), and were primarily oaks and yellow pines (Figure 4.6). Observation of the size and form of some of the larger and older trees at the site indicated that the stands had once been more open; the trees had sizable limbs with a wide spread. Trees that established after 1930 were mainly between 5 and 25 cm DBH, with the exception of several eastern white pines and eastern hemlocks. By 1980, eastern white pines and eastern hemlocks were the only species establishing in the canopy class.

Yellow pines (n = 14) represented 5% of the canopy class trees documented in the Gold Mine Trail macroplots. Eleven trees were shortleaf pine, two trees were pitch pine, and one was

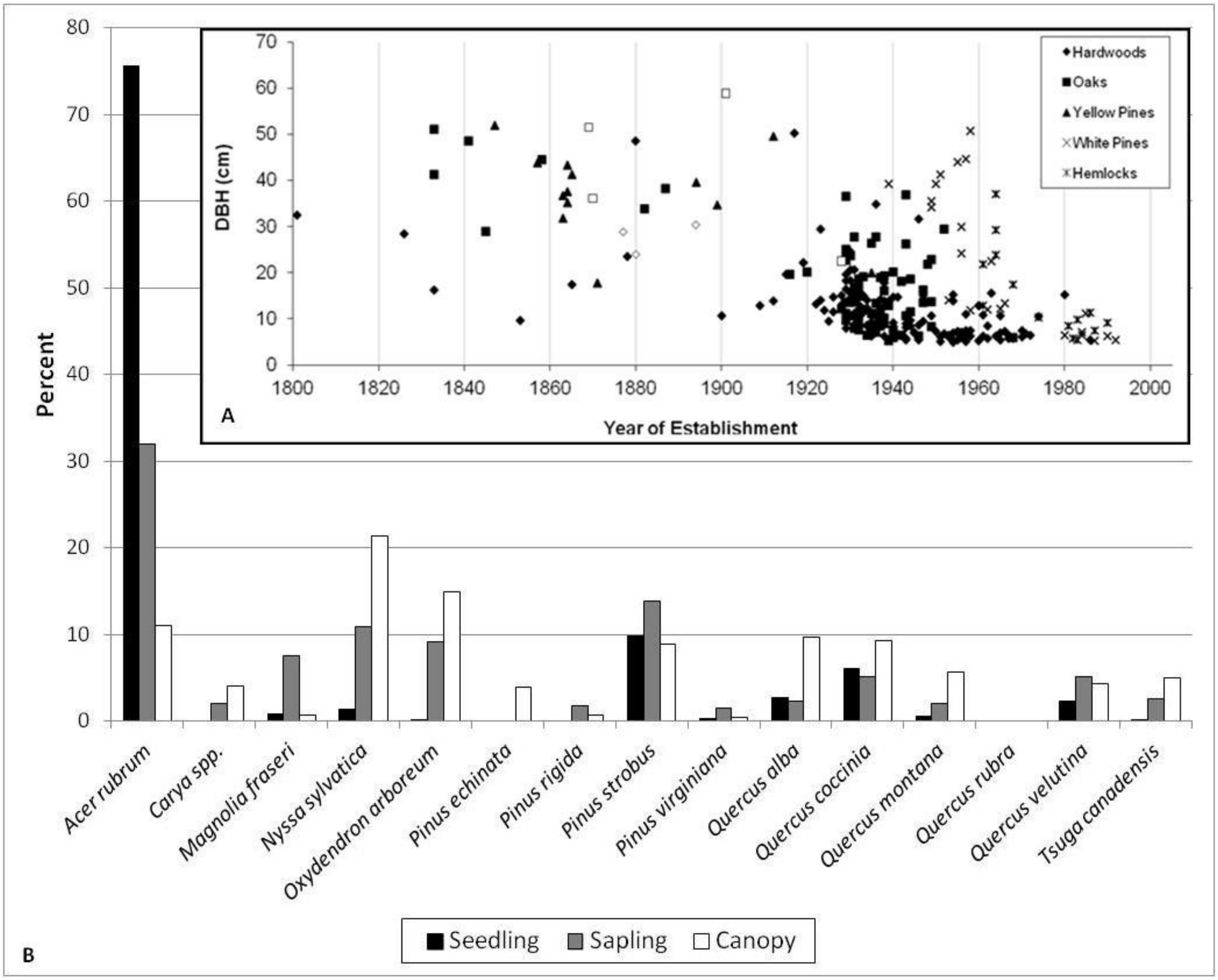

**Figure 4.6:** Age structure of five tree categories and class composition of tree species at Gold Mine Trail. **A)** This graph illustrates 1) the relationship of tree diameter against age, and 2) the relationship of establishment with fire. For example, a widespread fire event in 1929 coincided with the establishment of a large number of oaks. The cohort of yellow pines that established in the early 1860s may have established after a fire that cleared the landscape, but did not scar the surviving trees. Suppression of fire after GSMNP was established in 1934 is followed by the establishment of eastern white pine and eastern hemlock. Open symbols denote earliest dates for incomplete cores. **B)** Each species is shown with its stem count percentage within each class (seedling, sapling, and canopy). Species with negligible percentages (*e.g. Ilex opaca*) were excluded from the graph. Red maple had the highest number for the seedling and sapling classes. While the canopy percentages were more evenly distributed, blackgum and sourwood most strongly represented that class.

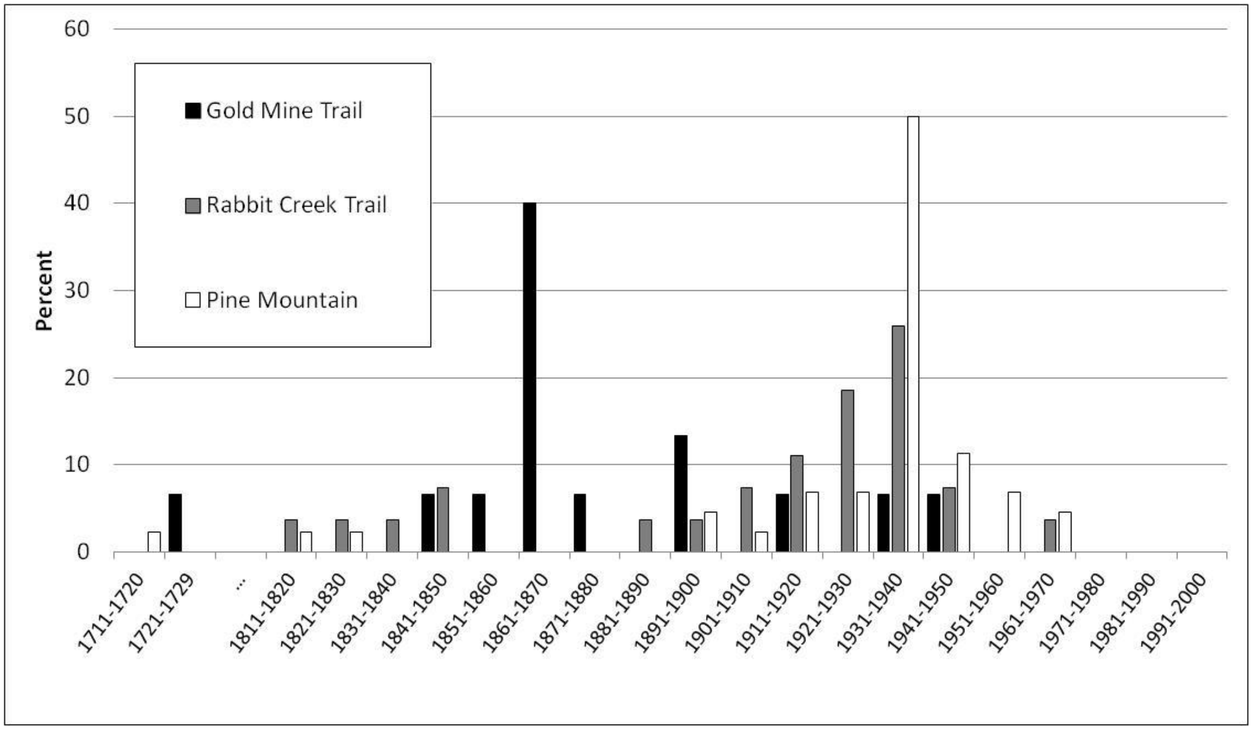

**Figure 4.7:** Yellow pine age structure by site. Most of the pine establishment at Gold Mine Trail occurred in the 1860s, whereas at Rabbit Creek Trail and Pine Mountain, the peak of establishment centered on the 1930s.

Virginia pine. Yellow pine seedlings were absent from the macroplots. Only 3% of the saplings were yellow pine, specifically Virginia pines and pitch pines.

The top five canopy-class species by importance value were blackgum (*Nyssa sylvatica* Marsh.; 13.2), white oak (*Quercus alba* L.; 12.2), eastern white pine (11.8), sourwood (*Oxydendrum arboreum* (L.) DC; 10.3), and red maple (9.5) (Table 4.4). The highest ranking species by stem count percentage were blackgum (21%), sourwood (15%), red maple (11%), white oak (10%), scarlet oak (*Quercus coccinea* Münchh.; 9%), and eastern white pine (9%) (Figure 4.6). Red maple was the most frequently found species in both the sapling and seedling classes at 32% and 76%, respectively. White pines were also numerous, comprising 14% of saplings and 10% of seedlings counted. Blackgum (11%), sourwood (9%), and Frasier magnolia (*Magnolia fraseri*

Walter; 8%) were abundant in the sapling class. The average duff depth for GMT was 5.7 cm. The macroplot average range was 2.8 to 8.3 cm, and the minimum-maximum was 1–18 cm.

#### 4.5.2.2 ***Rabbit Creek Trail (RCT)***

Very few trees in the record established prior to 1890 at Rabbit Creek Trail (Figure 4.8). These were larger (> 30 cm DBH) oaks and pines, primarily pitch pine, and a smaller eastern white pine (23 cm DBH). A cluster of oaks established between 1890 and 1910. Eastern white pine establishment also increased during those decades. Those trees ranged in diameter between 30 and 70 cm. From 1930 to 1990, numerous smaller (5–20 cm DBH) eastern white pines, eastern hemlocks, and mixed hardwoods established. Only a few oak and pine trees, predominately Virginia pine, established in that period. By 1980, eastern hemlocks were the dominant species establishing in the canopy size class.

Two distinct clusters of yellow pine trees establishment occurred at RCT (Figure 4.7). One cluster, comprised entirely of pitch pine, established in the mid-1800s. The other cluster, centered on the mid-1900s, was dominated by Virginia pine. One mature Table Mountain pine was found and sampled at the site, but it was external to the macroplots. No shortleaf pines were observed. A total of 27 yellow pine trees were documented in the RCT macroplots, of which two-thirds were Virginia pine. Pine regeneration (Virginia pine only) was limited to 2% of the sapling class and 1% of the seedlings.

**Table 4.4:** Stand composition of canopy-class trees (> 5 cm DBH) at three study sites. Three 20 x 50 m plots were inventoried at site. Underline indicates top five species at each site.

| | Gold Mine Trail | | | Rabbit Creek Trail | | | Pine Mountain Trail | | |
|---|---|---|---|---|---|---|---|---|---|
| **Species** | **Relative Density (%)** | **Relative Dominance (%)** | **Importance Value (RDn + RDm)/2** | **Relative Density (%)** | **Relative Dominance (%)** | **Importance Value (RDn + RDm)/2** | **Relative Density (%)** | **Relative Dominance (%)** | **Importance Value (RDn + RDm)/2** |
| *Acer rubrum* | 11.03 | 8.07 | 9.5 | 14.93 | 7.75 | 11.3 | 8.64 | 7.46 | 8.0 |
| *Betula lenta* | n/a | n/a | n/a | n/a | n/a | n/a | 0.33 | 0.15 | 0.2 |
| *Carya glabra* | n/a | n/a | n/a | n/a | n/a | n/a | 1.33 | 0.11 | 0.7 |
| *Carya tomentosa* | 4.27 | 8.23 | 6.3 | n/a | n/a | n/a | 1.00 | 0.32 | 0.7 |
| *Diospyros virginiana* | n/a | n/a | n/a | n/a | n/a | n/a | 0.66 | 0.92 | 0.8 |
| *Ilex opaca* | n/a | n/a | n/a | 0.60 | 0.07 | 0.3 | n/a | n/a | n/a |
| *Magnolia fraseri* | 0.71 | 0.06 | 0.4 | n/a | n/a | n/a | n/a | n/a | n/a |
| *Nyssa sylvatica* | 21.35 | 5.03 | 13.2 | 5.37 | 1.12 | 3.2 | 29.90 | 7.93 | 18.9 |
| *Oxydendron arborea* | 14.95 | 5.57 | 10.3 | 1.79 | 1.13 | 1.5 | 1.66 | 0.47 | 1.1 |
| *Pinus echinata* | 3.91 | 15.58 | 9.7 | n/a | n/a | n/a | 1.66 | 8.58 | 5.1 |
| *Pinus pungens* | n/a | n/a | n/a | n/a | n/a | n/a | 0.33 | 0.49 | 0.4 |
| *Pinus rigida* | 0.71 | 2.51 | 1.6 | 2.39 | 8.82 | 5.6 | 3.32 | 7.06 | 5.2 |
| *Pinus strobus* | 8.90 | 14.66 | 11.8 | 34.33 | 49.35 | 41.8 | 9.63 | 8.93 | 9.3 |
| *Pinus virginiana* | 0.36 | 0.27 | 0.3 | 5.97 | 9.57 | 7.8 | 15.61 | 15.88 | 15.7 |
| *Quercus alba* | 9.61 | 14.71 | 12.2 | 0.30 | 0.45 | 0.4 | n/a | n/a | n/a |
| *Quercus coccinia* | 9.25 | 9.55 | 9.4 | 2.09 | 5.26 | 3.7 | 2.33 | 2.04 | 2.2 |
| *Quercus marylandica* | n/a | n/a | n/a | n/a | n/a | n/a | 1.00 | 0.32 | 0.7 |
| *Quercus montana* | 5.69 | 7.24 | 6.5 | 6.57 | 8.70 | 7.6 | 15.28 | 31.21 | 23.2 |
| *Quercus pallustrus* | n/a | n/a | n/a | n/a | n/a | n/a | 0.33 | 0.74 | 0.5 |
| *Quercus rubra* | n/a | n/a | n/a | 0.30 | 0.05 | 0.2 | 0.66 | 3.14 | 1.9 |
| *Quercus velutina* | 4.27 | 4.84 | 4.6 | 1.19 | 1.04 | 1.1 | 3.99 | 2.89 | 3.4 |
| *Tsuga canadensis* | 4.98 | 3.70 | 4.3 | 24.18 | 6.67 | 15.4 | 2.33 | 1.37 | 1.8 |

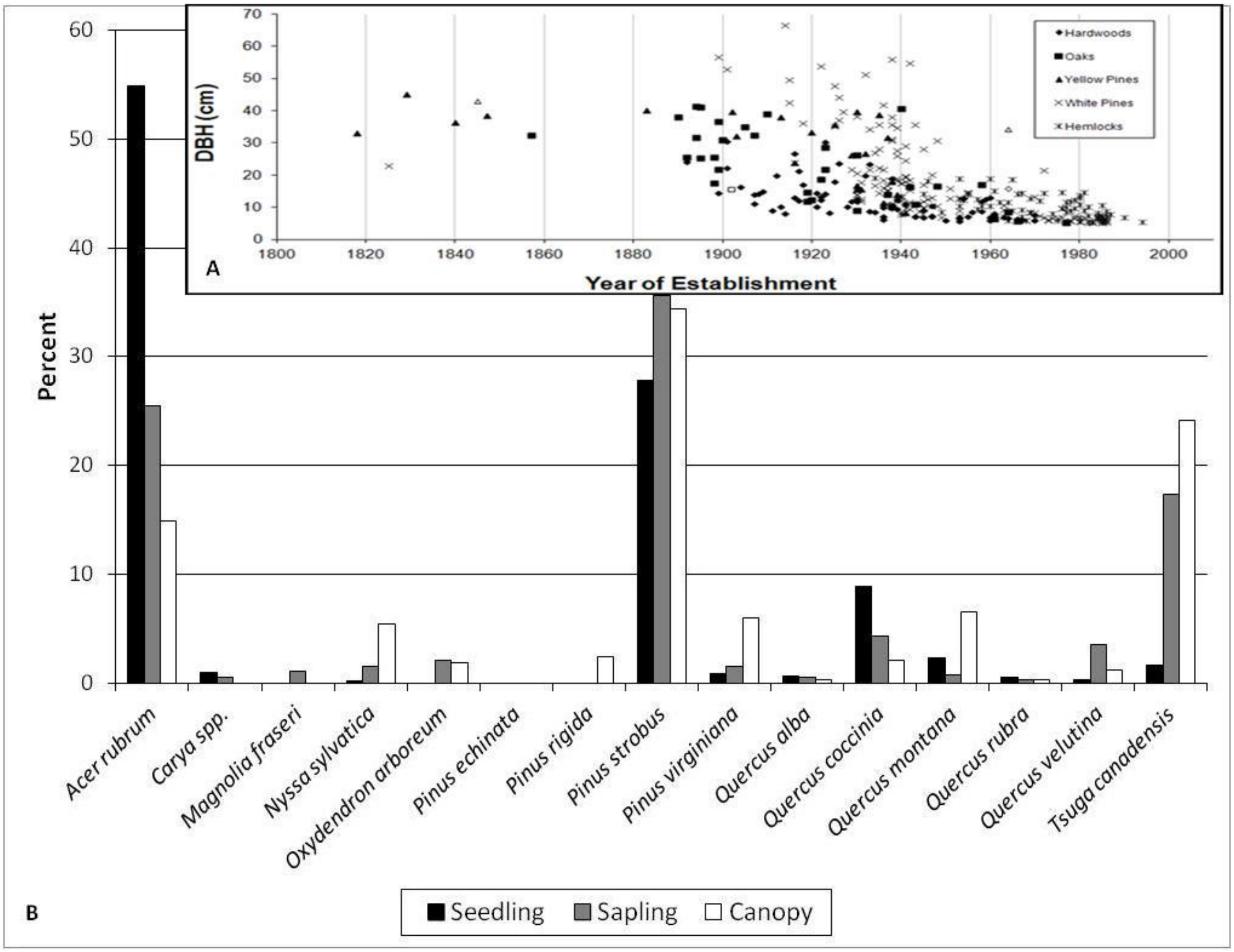

**Figure 4.8:** Age structure of five tree categories and class composition of tree species at Rabbit Creek Trail. **A)** This graph illustrates 1) the relationship of tree diameter against age, and 2) the relationship of establishment with fire. For example, numerous fire events in the 1890s coincide with oak establishment. Suppression of fire after GSMNP founding in 1934 is followed by increased eastern white pine and eastern hemlock establishment. Open symbols denote earliest dates for incomplete cores. **B)** Each species is shown with its stem count percentage within each class (seedling, sapling, and canopy). Species with negligible percentages (*e.g. Quercus rubra*) were excluded from the graph. Eastern white pine and eastern hemlock were most numerous in the sapling and canopy classes, but many of the saplings were dying from overcrowding and insect damage (*e.g.* wooly adelgid on the hemlocks) at the time of data collection.

Ranked by importance value, the composition of the canopy-class trees were primarily dominated by eastern white pine (41.8) (Table 4.4). Eastern hemlock (15.4), red maple (11.3), Virginia pine (7.8), and chestnut oak (*Q. montana* Willd.; 7.6) were also main components of the canopy. Results for the stem count percentage calculations produced the same dominant species, and the ranking was eastern white pine (34%), eastern hemlock (24%), red maple (15%), and Virginia pine (6%). Eastern white pine and red maple co-dominated the sapling (36% and 25%) and the seedling (28% and 55%) classes (Figure 4.8). Eastern hemlock (17%) was the next most-frequently documented species in the sapling class, while scarlet oak (9%) was common in the seedling class. All other species each accounted for less than 5% of the sapling and seedling classes. Duff depth averaged 5.3 cm at RCT. Macroplot averages of duff depth ranged from 4.9 to 5.5 cm. The overall duff depth range was 3–9 cm.

#### 4.5.2.3 *Pine Mountain (PMT)*

The first century of macroplot data for Pine Mountain indicated sporadic establishment of oak and yellow pine trees between 1810 and 1910 (Figure 4.9). A small cluster of hardwoods established around 1910, but the vast majority of establishment of mixed hardwoods and oaks occurred between 1920 and 1950. Eastern white pines arrived in the 1940s, followed by eastern hemlock trees in the 1950s. Yellow pine establishment was sparse until the 1930s and 1940s. Prior to 1930, most of the yellow pine trees were pitch pine, and the later ones were mainly Virginia pine (Figure 4.7). Yellow pine regeneration was negligible, representing less than 1% of seedlings and 2% of saplings. The regeneration was primarily Virginia pine.

The top five canopy-class trees ranked by importance value at PMT were chestnut oak (23.2), blackgum (18.9), Virginia pine (15.7), eastern white pine (9.3), and red maple (8.0) (Table 4.4). By stem count percentage, the prominent canopy species were blackgum (30%), eastern white pine (16%), chestnut oak (15%), and Virginia pine (10%) (Figure 4.9). Red maple composed only 8% of the canopy, but vastly dominated the percentage of seedlings (81%) and saplings (66%) counted in the macroplots. Scarlet oak (7%), black oak (6%), eastern white pine (5%) and blackgum (5%) were also represented in the saplings. Eastern white pine and chestnut oak each composed 4% of the seedling class. Duff levels at PMT ranged from 2 to 13.5 cm, and averaged 6.0 cm in depth. Average duff depth levels for the macroplots ranged from 4.5 to 7.0 cm. The overall duff depth at PMT had a range of 2 to 13.5 cm.

#### 4.5.2.4 ***Regional (ALL)***

The most dominant canopy-class species across the combined site area was eastern white pine (importance value = 22.4) (Table 4.5). Other species with high importance values included blackgum (11.4), chestnut oak (9.3), red maple (9.7), eastern hemlock (7.7), and Virginia pine (7.8). All other documented species composed less than 5% of the canopy class composition. On average, fewer than five yellow pine trees established per decade across the study area until 1910. Yellow pine establishment markedly peaked in the 1930s, primarily driven by growth at Rabbit Creek Trail and Pine Mountain. In the following decades, numbers declined sharply. Yellow pine trees that established prior to 1871 were a mix of shortleaf pine and pitch pine (Figure 4.10). In the 1900s, a dramatic shift occurred toward the faster-growing Virginia pine.

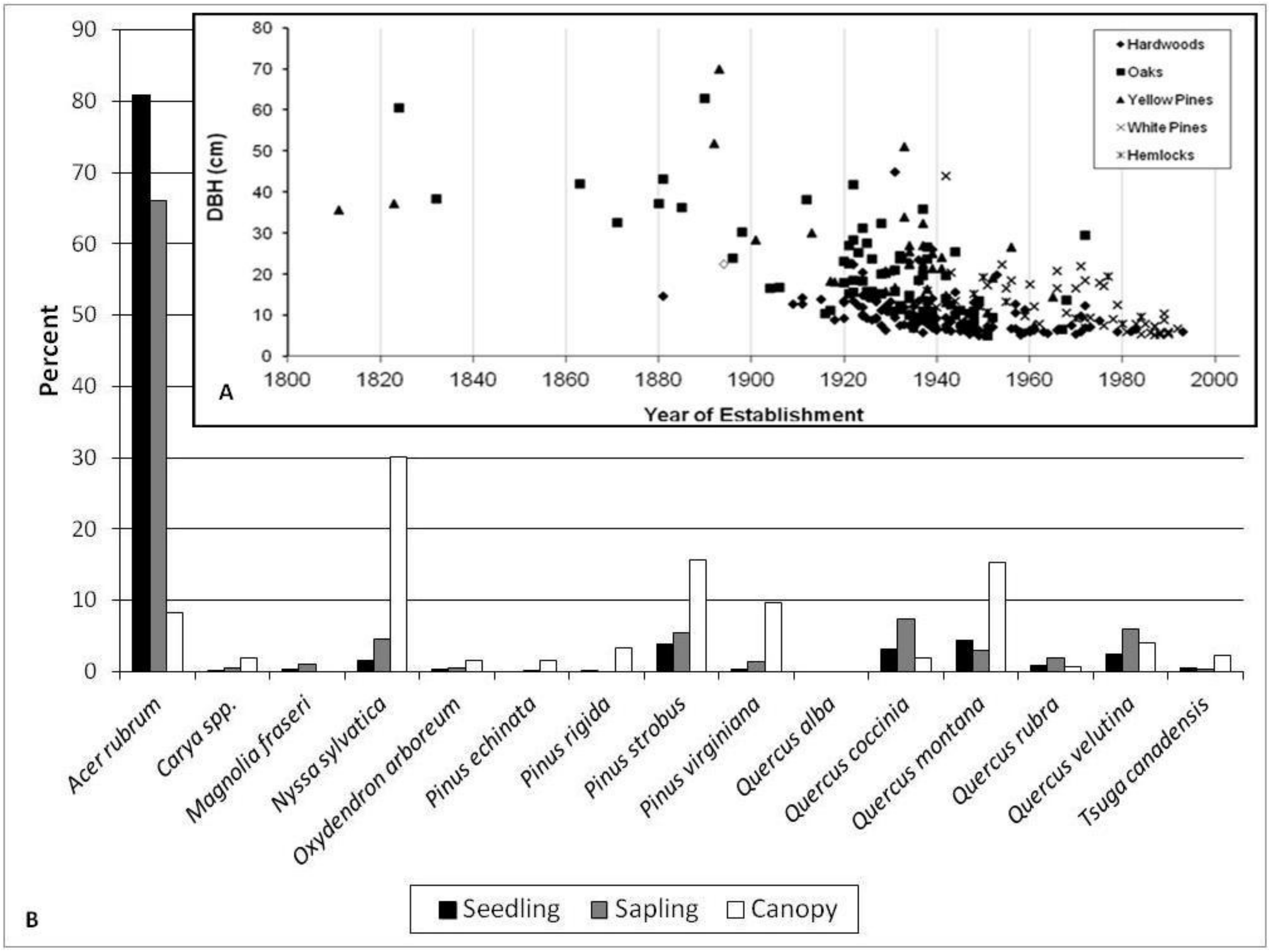

**Figure 4.9:** Age structure of five tree categories and class composition of tree species at Pine Mountain. **A)** This graph illustrates 1) the relationship of tree diameter against age, and 2) the relationship of establishment with fire. For example, the last large wildfire in 1922 coincides with increased oak establishment. Suppression of fire after GSMNP founding in 1934 is followed by eastern white pine and eastern hemlock establishment. Open symbols denote earliest dates for incomplete cores. **B)** Each species is shown with its stem count percentage within each class (seedling, sapling, and canopy). Species with negligible percentages (*e.g. Betula lenta*) have been excluded from the graph. Red maple had the highest count for the seedling and sapling classes. Blackgum, eastern white pine, and chestnut oak most strongly represented the canopy class.

**Table 4.5:** Stand composition of canopy-class trees (> 5 cm DBH) for combined study area. Nine 20 x 50 m plots were inventoried. Underline indicates top five species by importance value.

| **Species** | **Basal Area (m2/ha)** | **Stem # (total 9 plots)** | **Density (stems per ha)** | **Dominance (BA / .9 ha)** | **Relative Density (%)** | **Relative Dominance (%)** | **Importance Value (RDn + RDm)/2** |
|---|---|---|---|---|---|---|---|
| *Acer rubrum* | 21.9 | 107 | 118.8 | 24.39 | 11.77 | 7.62 | 9.7 |
| *Betula lenta* | 0.1 | 1 | 3.7 | 0.44 | 0.37 | 0.14 | 0.3 |
| *Carya glabra* | 0.1 | 4 | 14.8 | 0.34 | 1.46 | 0.11 | 0.8 |
| *Carya tomentosa* | 7.8 | 15 | 16.7 | 8.63 | 1.65 | 2.70 | 2.2 |
| *Diospyros virginiana* | 0.7 | 2 | 7.4 | 2.74 | 0.73 | 0.86 | 0.8 |
| *Ilex opaca* | 0.1 | 2 | 7.4 | 0.30 | 0.73 | 0.09 | 0.4 |
| *Magnolia fraseri* | 0.1 | 2 | 7.4 | 0.19 | 0.73 | 0.06 | 0.4 |
| *Nyssa sylvatica* | 12.2 | 168 | 186.5 | 13.56 | 18.48 | 4.24 | 11.4 |
| *Oxydendron arborea* | 6.7 | 53 | 58.8 | 7.46 | 5.83 | 2.33 | 4.1 |
| *Pinus echinata* | 21.1 | 16 | 17.8 | 23.45 | 1.76 | 7.33 | 4.5 |
| *Pinus pungens* | 0.4 | 1 | 3.7 | 1.47 | 0.37 | 0.46 | 0.4 |
| *Pinus rigida* | 17.8 | 20 | 22.2 | 19.72 | 2.20 | 6.16 | 4.2 |
| *Pinus strobus* | 75.3 | 169 | 187.6 | 83.62 | 18.59 | 26.13 | 22.4 |
| *Pinus virginiana* | 23.6 | 68 | 75.5 | 26.26 | 7.48 | 8.21 | 7.8 |
| *Quercus alba* | 13.9 | 28 | 31.1 | 15.46 | 3.08 | 4.83 | 4.0 |
| *Quercus coccinia* | 16.2 | 40 | 44.4 | 17.98 | 4.40 | 5.62 | 5.0 |
| *Quercus marylandica* | 0.3 | 3 | 11.1 | 0.96 | 1.10 | 0.30 | 0.7 |
| *Quercus montana* | 41.4 | 39 | 43.3 | 45.97 | 4.29 | 14.37 | 9.3 |
| *Quercus pallustrus* | 0.6 | 1 | 3.7 | 2.20 | 0.37 | 0.69 | 0.5 |
| *Quercus rubra* | 2.6 | 3 | 3.3 | 2.87 | 0.33 | 0.90 | 0.6 |
| *Quercus velutina* | 7.9 | 28 | 31.1 | 8.76 | 3.08 | 2.74 | 2.9 |
| *Tsuga canadensis* | 11.9 | 102 | 113.2 | 13.19 | 11.22 | 4.12 | 7.7 |

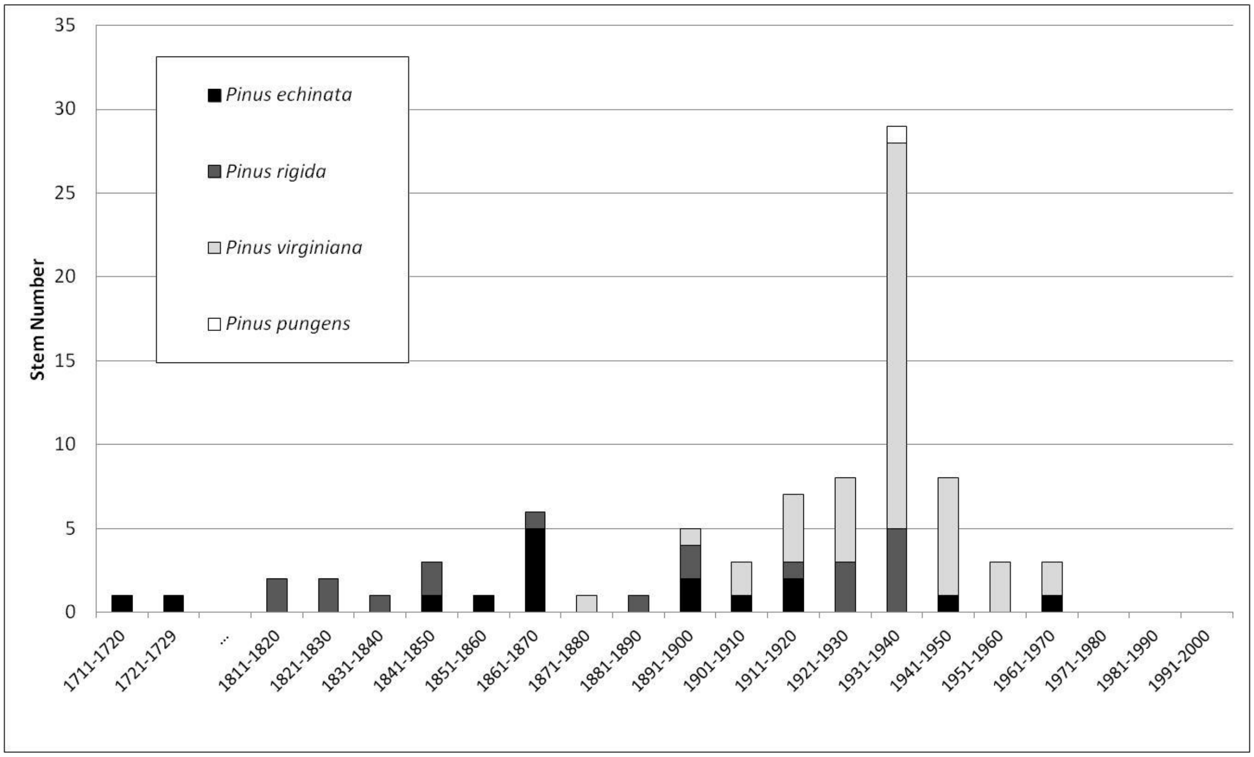

**Figure 4.10:** Yellow pine age structure by species for all three sites combined. A dramatic increase of yellow pines began in the 1900s. A composition shift that favored the faster-growing Virginia pine peaked in the 1930s.

### 4.6 Discussion

From the pines of Great Smoky Mountains National Park, we were able to retrieve over 300 years of data that provided a quality representation of wildfire history in the xeric pine-oak stands. No other study to date has as many samples or record length for the park. Fire was a regular event in the western area of the park through the 1700s and into the early part of the 1900s, although less frequently prior to European settlement. Despite the small sample size available for 1700 through 1834, the data indicate that the frequency of wildfire events during the Pre-settlement period was lower when the landscape was occupied primarily by the Cherokee. The frequency of fires declined conspicuously after suppression was enforced in the

1930s, although sporadic fires still occurred. Most of the fires were likely actively extinguished until the enactment of Wildland Fire Use policy in the late 1990s. Prescribed burning in GSMNP became more common in the 2000s, but as of 2010 had not occurred in the stands used for this research. Two known fires did, however, burn in close proximity to the study sites: Polecat Ridge in 1976–1977 near Pine Mountain, and the Hatcher Mountain prescribed burn southeast of Gold Mine Trail in 2005. One sample at Pine Mountain may have recorded the Polecat Ridge fire (1976), but the remaining study samples did not record either fire. Many of the scarred yellow pines used in this research were snags or logs, so they were unable to record more recent fires. The presence of large, dead pine debris remaining on the landscape also indicates a lack of severe fire occurrence over the recent decades.

Several of the trees used in the Gold Mine Trail fire history had died around the year 2000. This cluster of synchronous deaths was likely related to a large outbreak of bark beetles that was documented during that time. Most of the older pine samples collected from the site did not have pith dates. Center rot was common in those trees, as were insect galleries, which obscured or eliminated the affected portion of the wood. Several of the cross-sections collected from younger pine trees retained pith that indicated establishment dates between 1860 and 1880. A similar cohort of yellow pines is seen in the macroplot data. Six of those trees established in the same time frame, as did many of the yellow pines that were cored externally to the macroplots. It is probable that a moderately-severe fire moved through the site at that time, clearing and altering the landscape in favor of pine regeneration. Many of the older pines were not active recorders during that period. This is likely because they were unscarred and protected by thick and continuous bark around the base of the trunks. The trees that were recording captured several fires, and each event scarred at least three trees.

Wildfires at Gold Mine Trail were more temporally clustered than at the other sites, as indicated by the high coefficient of variation for each scar class. For example, the intervals for the all-scarred class and the 10% class varied considerably around the mean fire interval of 2.07 and 2.60 years, respectively. Also, the intervals for both classes ranged from 1 to 10 years. The Weibull results indicated a much shorter interval range, on the order of 0.5 to 4.5 years. This similarity between the two classes suggests that most fires at GMT tended to burn at least 10% of the trees, or, in other words, they spread through the stand and were not just localized spot fires. For the 25%-scarred class, the Weibull results and the traditional MFI calculation results were very similar, having average intervals of 4 to 5 years that ranged from 1 to 13 years.

The most widespread fire in the total study area occurred at Gold Mine Trail in 1929, during which 70% of the 32 recorder trees were scarred. While annual drought indices were relatively high during that year (PDSI; NCDC/TN01, Cook *et al*. 2004), indicating wetter conditions, July precipitation was below average. A lack of precipitation in conjunction with typically high July temperatures may have provided enough dry fuel for a larger fire at GMT. Gold Mine Trail is generally more mesic than RCT and PMT, with the three small creeks running across the site. If the creeks had dried up, some of the vegetation dependent on that water source could have been stressed, and added more dry fine material to the fuel base. The 1929 fire occurred during the middle of the growing season, unlike the majority of other fires in the record. Lightning fires peak in the summer (Harmon 1981), and lightning was probably the ignition source of this wildfire. The sporadic and localized fires after 1930 primarily burned late in the growing season (L/A). Many of these wildfires were likely ignited by humans because anthropogenic fires peak in the fall. Active suppression of fires would have kept them localized.

Wildfires at Rabbit Creek Trail were more frequent and less widespread than at GMT or PMT. The most widespread fire at RCT (n = 5) occurred in 1894. A large cluster of oaks in the macroplots established around the same time, as did six of the yellow pines used in the fire history, likely in response to the fire. RCT had the lowest coefficient of variation among the sites for the all-scarred class, indicating much less variability around the mean (about 2 years) in the fire intervals that ranged from 1 to 5 years; in other words, the intervals were consistently short (homogenous) across the period of record. Rabbit Creek Trail may have been used for livestock grazing, as the site was close to documented homesteads along Abrams Creek. Cattle tend to avoid eating Virginia pine, a fast-growing pioneer tree species, which may account for the higher ratio of this pine component. In addition, European setters commonly burned their pastures and the forested areas around the boundary to clear brush and promote grass or other plants suitable for grazing. This recurrent burning activity would explain the short fire intervals and frequent, localized fires. The vast majority (84.1%) of all fires occurred during dormancy or very early in the growing season. This fits with the practice of preparing pastures for livestock.

The 10%-scarred class results for RCT were comparable to those from GMT and PMT. There were also many similarities in the 25%-scarred class, with the exception of the maximum hazard interval (12.06 years) that was half the length of the other two sites. This indicates that Rabbit Creek Trail was prone to have widespread fires more frequently than the other sites

(1838–1934); however, fewer numbers of trees typically recorded widespread fires at RCT as compared to GMT and PMT.

At Pine Mountain, most of the fires (83.8%) also burned during dormancy or early in the growing season. This site was close to documented homesteads near Scott's Gap, so could have experienced fires that originated from human activity. The majority of recorder trees (n = 20) showed a widespread fire in 1910. Other notable fires at PMT occurred in 1892, 1900, and 1922. All of these fires were in the latter portion of the European settlement period. Oak establishment drastically increased around 1920, possibly in relation to the 1910 and 1922 wildfires. Both of those fires probably burned in the middle of the growing season. Other mid-growing season fires that were recorded in five or more trees occurred in 1916 and 1936. This would explain the continuance of higher levels of oak establishment until about 1940. A large cluster of yellow pine establishment also occurred between 1930 and 1945. Only a few fire scars were found after 1950 at PMT, which were probably caused by lightning. The all-scarred and 10%-scarred class results were very similar to the Gold Mine Trail results. The average fire-free interval was 1.5 to 3 years, and the range was 1 to 8 years. For the 25%-scarred class, the mean interval was the longest of all the sites at 7 years, but the range was comparable (2 to 15 years).

The temporal analysis showed clear differences in the fire statistics for all the sites across the three periods analyzed. In the Pre-settlement Period, the average interval was relatively long. Weibull median values were 6 to 7 years, while mean fire intervals were 8 to 12 years. The majority of fires occurred during the dormancy or early growth periods. Settlement Period fires occurred in the same season, but the frequency greatly increased. Intervals dropped to about 2 years for both MEI and MFI. Fires in the Suppression Period were again more widely spaced (6 to 9 years, on average), but a higher proportion occurred later in the growing season. Pine Mountain had the largest change, from 83.7% to 44.4% D/E. Rabbit Creek Trail also experienced a decline, from 84.1% to 62.5% D/E, but still the majority of fires burned early in the year. The high baseline frequency of fires at all sites prior to suppression was probably because of lightning ignitions. Harmon (1981) found that the western portion of GSMNP had a high lightning-to-human fire origin ratio.

A common pattern of tree establishment was found for all three study sites. In the 1700s and 1800s, establishment was generally infrequent and was primarily composed of oaks and yellow pines. Gold Mine Trail had the highest rate of establishment during those centuries, and Rabbit Creek Trail had the least. After 1900, overall tree establishment numbers greatly increased at all sites. The majority of canopy trees were less than 90 years old as of 2007. Gold Mine Trail and Pine Mountain both showed strong oak representation between 1920 and 1950. Mixed hardwood numbers increased at all sites after 1910, but tapered off after 1970. Eastern white pine was present early in the RCT record, the oldest dating to 1825 (183 years). This species is known to live 200 years on average and up to 450 years maximum (Virginia Big Tree Program (VBTP) 2008). Eastern white pine numbers increased at RCT after 1900, but did not substantially establish at Pine Mountain until 1940 and at GMT until 1950. Rabbit Creek Trail also harbored the oldest eastern hemlock of the study sites; it established in 1916 and was 91 years old. That age is actually quite young for an eastern hemlock, as the average lifespan is 450 years and the maximum age is 800 years (VBTP 2008). Small clusters of eastern hemlock established at GMT in the 1960s and 1980s. Only a few were found in the PMT data, mostly between 1940 and 1990. The older eastern hemlock and eastern white pine trees likely served as a seed source that boosted the regeneration of those species at RCT. The saplings were crowded and stressed, and the hemlock woolly adelgid (*Adelges tsugae* Annand) was present in the stand. Many saplings were already dying as of 2007. Pine Mountain appeared to be a much drier site than GMT and RCT, which may explain the fewer number of eastern hemlock trees there. The eastern hemlock trees at GMT were primarily in the moister areas along the streams.

Eastern white pine and red maple were the two canopy-class (≥ 5 cm DBH) species that were common across all three study sites, but had the highest importance at RCT. Eastern hemlock was important at RCT but not at GMT or PMT, whereas blackgum was important at GMT and PMT, but not at RMT. Chestnut oak was prominent at each site, but was primarily so at PMT, where it had the highest importance value of any species at the site. White oak and sourwood were only key canopy species at GMT. Virginia pine was a key canopy species at both RCT and PMT.

Seedling and sapling counts of red maple were extremely high at each site. Eastern white pine seedling and sapling counts were also high at Rabbit Creek Trail, but were moderate at Gold Mine Trail and Pine Mountain. Pioneer species, such as these, are known to have high rates of seed production and germination and many do not reach maturity. Even so, eastern white pine on the sites will likely maintain a strong presence in the stands until the upper canopy closes and the understory becomes too shaded for them. Red maple numbers will probably remain high in the midstory, where this shade-tolerant species can wait for many years until a canopy gap forms and releases it to increase growth. Gold Mine Trail showed moderate sapling counts for five other hardwood species; however, seedling regeneration was primarily limited to scarlet oak at GMT, and also at RCT. Scarlet oak has the shortest average lifespan of the oaks (80 years; VBTP 2008) and competes well on poor and sandy soils (Little 1995). Pine Mountain had low to moderate levels of oak regeneration for four species.

The trajectory over the next few decades, without intervention, is that eastern white pine and red maple will maintain a strong presence in the canopy class of trees in the study area. Oaks will remain on the landscape, but there appears to be a shift toward shorter-lived species. Yellow pines are generally in trouble. Existing mature trees that have not already been killed by beetles are at high risk. Their removal will further restrict the seed source. Seedling and sapling numbers are negligible at all of the sites. The few saplings present are primarily Virginia pine, the shortest-lived of the yellow pine species (VBTP 2008; Pederson 2009). Most of the mature Virginia pines on the sites are already over 70 years old and are soon to reach the average life expectancy of 100 years.

Excessive duff depths are one factor that can hinder yellow pine regeneration. Exposure to mineral soil is important for the germination and initial growth of yellow pines, so they can out-compete hardwoods (Williams and Johnson 1992, Groeschl *et al.* 1993). Average duff depths were very similar at all three sites, ranging from 5 to 6 cm on average. Gold Mine Trail had the deepest duff measurement (18 cm), but also the least (1 cm). Rabbit Creek ranged from 3 to 9 cm, and Pine Mountain from 2 to 13.5 cm. One study found that Table Mountain pine roots were able to penetrate littler and duff layers up to 9 cm, thick to reach mineral soil; however, follow-up monitoring of seedling survival was not done. The researchers predicted that the sprouts would have high mortality from competition with re-sprouting hardwoods and also shading by the remaining dense canopy cover (Welch *et al.* 2000, Waldrop *et al.* 2002, 2003). Duff levels of less than 7.5 cm are considered to be better for TMP regeneration (Waldrop and Brose 1999). The average duff depths at our study sites were less than the 7.5 cm threshold determined by the TMP study, but a more recent study in GSMNP (Jenkins *et al*. 2011) has concluded that less than 4 cm of duff is necessary for successful yellow pine regeneration. Additional research is needed to confirm the maximum duff depth at which lower-elevation non-TMP yellow pines will regenerate.

My findings concur with a related research project conducted at the same time as this study. At two sites in mixed-pine/hardwood stands on Cooper Road Trail northwest of Cades Cove, Feathers (2010) found mean fire return intervals ranging from 3.2 to 6.2 years. Most of the fires occurred during dormancy or early in the growing season. No pine regeneration was present in the vegetation plots. Red maple and eastern white pine were dominant species in both the seedling and sapling classes.

To maintain the pine-oak communities, wildfire would need to be returned to the landscape. Recent prescribed burns in GSMNP appear to be having a positive effect on regeneration (NPS 2010). We observed dense regeneration of yellow pine trees in the western portion of the park where burns had been conducted several years prior. Too frequent fires may prohibit survival of yellow pine seedlings (Stambaugh *et al*. 2007), however, so after a restoration burning phase, a maintenance phase should be implemented that would mimic the historic fire regime. Restoration phases are generally more intensive than maintenance phases. They can include more frequent and more severe fires to clear the accumulated woody debris and to kill excessive numbers of saplings to open the crowded understory. Once the stands are restored to a desired condition, maintenance burns are conducted at longer intervals.

Other disturbances, such as ice storms and wind-throw, open clearings in the stands in which yellow pines could possibly regenerate if there was a sufficient seed base and if hardwoods did not fill the gaps. Our data indicate that RCT and PMT may have experienced more disturbances in recent decades than GMT. Eastern white pine and Virginia pine are pioneer species and appear early in the successional sequence, both of which were prominent in the canopy class at RCT and PMT. In April 2011, an EF-4 tornado swept over GSMNP leaving a swath of felled trees across the length of the western side of the park. The path of the tornado was very close to the RCT site and may had passed directly over PMT. We have not yet conducted ground surveys to verify this.

### 4.7 Conclusions

Yellow pines provided an excellent 300-year record of fire activity in the forest stands. Distinct shifts in the fire regime correspond to changes in human occupation and policy. Wildfire events were more numerous and the return intervals were much shorter during the European Settlement period (1834–1934) than in the Pre-settlement period before and the Suppression period after. The frequency of wildfire was very similar in the Pre-settlement and Suppression periods; however, the season of burn shifted toward later in the year (*i.e.* summer) after 1934. Non-dormant season burns could help promote oak and yellow pine establishment by killing competing hardwoods (Knapp *et al*. 2009), but the stand composition analysis indicated that the yellow pines are not adequately reproducing to maintain a dominant presence in the stands under the current fire regime. The shortleaf pines show no regeneration in the stands, and the other pine species are not regenerating well. Longer-lived oak species also do not seem to be viably reproducing. The stand data clearly show a connection between a reduction of fire on the landscape after the enactment of suppression policies and an increase in eastern white pine, eastern hemlock, and mixed hardwood establishment. Lightning ignitions, while relatively high in frequency in the park, may alone not be sufficient to produce restorative burns. If the goal is to promote mixed pine stands, prescribed burning will need to be conducted. Otherwise, the numbers of mature yellow pines will continue to decline and many of the stands will likely succeed to mixed-hardwood forest.

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# CHAPTER 5

# RELATIONSHIPS BETWEEN WILDFIRES AND CLIMATE IN GREAT SMOKY MOUNTAINS NATIONAL PARK, TENNESSEE, U.S.A.

Portions of the introduction and study site descriptions in this chapter were taken from earlier chapters of this dissertation. The use of "we" or "our" in Chapter 5 refers to the many people who assisted in the field and lab to make this study possible. Details can be found in the Acknowledgements section of this dissertation. Funding for this research was made possible through a Joint Fire Sciences Program grant authored and managed by Dr. Henri D. Grissino-Mayer, Dr. Charles Lafon, and Dr. Sally P. Horn. Essential support was also provided by the personnel at Great Smoky Mountain National Park, who gave us important permissions, access, and assistance for this study. My contributions to this research include field work, sample processing and dating, development of the chronologies, determination of fire events, statistical analyses, and interpretation of results. This chapter will be eventually submitted to the journal *Fire Ecology* for publication.

## Abstract

Climate fluctuations are related to shifts or oscillations within ocean bodies, hemispheric air masses, and changing sea surface temperatures. Movements or changes in location-linked high and low pressure centers modify wind patterns which then alter the flow of warm or cold air, and any moisture associated with the air. These dynamics influence wildfire regimes with regard to frequency, severity, and spatial extent across North America; however, little is known about the relationships between wildfire and climate in the southern Appalachian Mountains. Using dendrochronological methods, we determined the fire history of lower-elevation (400–600 m ASL) mixed yellow pine stands in the western portion of Great Smoky Mountains National Park, one of the few locations in the region that has older forests. Our study examined the relationships between East Tennessee mean monthly temperature and total monthly precipitation (1895–2006); six reconstructed climate variables (Atlantic Multidecadal Oscillation,

North Atlantic Oscillation, El Niño-Southern Oscillation, Pacific Decadal Oscillation, northern hemisphere temperatures, and Palmer Drought Severity Index), 10-year wildfire frequency, and wildfire event years using correlation analysis or superposed epoch analysis. The Atlantic oscillations (AMO and NAO) were more influential on mean monthly temperature in East Tennessee than the other tested variables, while ENSO influenced total monthly precipitation. The 10-year fire frequency was most strongly associated to the AMO. The El Niño-Southern Oscillation displayed the most consistent results in the superposed epoch analysis for all sites, indicating that fire events are more likely to occur when preceded by wetter conditions in the years prior to a wildfire followed by drier conditions in the event year. Relationships between fire and climate were more evident in the period prior to European settlement (1697–1834). Anthropogenic influences may have overridden the signal in the Settlement Period (1835–1934). Nonetheless, climate (primarily precipitation) is still strongly related to fire occurrence as shown by similarities in seasonal patterns between the two, and drought influences fire probability and severity. The ability to monitor and predict climate fluctuations may help us better plan for unusual weather patterns that are not only linked with fire and drought, but also with hurricanes and other events or conditions that impact human commerce and agriculture.

## 5.1 Introduction

This chapter is part of a larger research project conducted in the southern Appalachian Mountains to determine the growth response of yellow pines (*Pinus* subgenus *diploxylon*) to climate, to elucidate historical wildfire patterns on the landscape, and to reveal relationships between wildfire occurrence, climate, and human activity. The primary goal of chapter 5 is to determine the relationships between wildfire occurrence and climate in lower-elevation (400–600 m ASL) mixed pine/pine-oak stands from the early 1700s to the present in the western portion of Great Smoky Mountains National Park (GSMNP), Tennessee.

### 5.1.1 *Climate and Wildfire*

The climate of a location is determined by interactions of solar influx, temperature, and moisture availability or precipitation averaged over a number of years. Climate guides which types of vegetation and other organisms reside on the landscape. It also strongly influences the presence and behavior of wildfires (Girardin *et al*. 2006). In consistently moist environments, fires are less likely to ignite or burn, but in dry and windy regions, fires can occur more frequently and tend to spread farther if left uncontrolled. Wildfire events have been linked with drought (Floyd *et al*. 2004, Liu 2005, Dixon *et al*. 2008), but this can be modulated by other variables such as fuel conditions (Trouet *et al*. 2010) and the season of burn (Grissino-Mayer and Swetnam 2000). During an extreme drought in 2007, at least 2000 fires had already burned 33,000 acres by June in Tennessee, statistics more typical of an entire year (Andreu and Hermansen-Báez 2008). The same year, the area burned by wildfires in North Carolina was 80% greater than the average of the two decades prior (Hoffman 2008).

Wildfire ignitions derive from both natural and anthropogenic sources and can be associated with specific times of the year. For example, if a location typically experiences strong storms in the spring, lightning ignitions could increase. Summer heat could prime conditions for a campfire spark to ignite dry vegetation nearby. Also, environmental conditions of a previous year can affect the fire potential of following years. For example, if a typically dry area experiences higher than usual precipitation levels in the year or two prior to a drought year, the increased plant biomass produced during the wet years can act as extra fuel for potential fires during the subsequent dry year(s), in essence a preconditioning for wildfire (Baisan and Swetnam 1990).

The southern U.S., in general, experiences two primary fire seasons, in the spring and in the fall, although wildfires can occur any time of the year (Gramley 2005). The spring fire season in East Tennessee begins in mid-February when temperatures begin to warm, and ends in mid-May when most of the vegetation is leafy and green (Tennessee Department of Agriculture 2012). The fall fire season starts in mid-October when the leaves fall and dry up, and ends in mid-December when cooler, moister conditions dominate. As expected by the latitudinal position of the state (approximately 35.5° N), the highest average temperatures occur in June through August, and the lowest occur in December through February (National Climate Data Center (NCDC) 2010). Precipitation peaks in March and July, and is lowest in October (Figure 5.1).

Climate fluctuations are related to shifts or oscillations within the ocean bodies, hemispheric air masses, and changing sea surface temperatures. Movement or changes in location-linked high and low pressure centers modify wind patterns which then alter the flow of warm or cold air, and any moisture associated with the air. These dynamics influence wildfire regimes with regard to frequency, severity, and spatial extent across North America

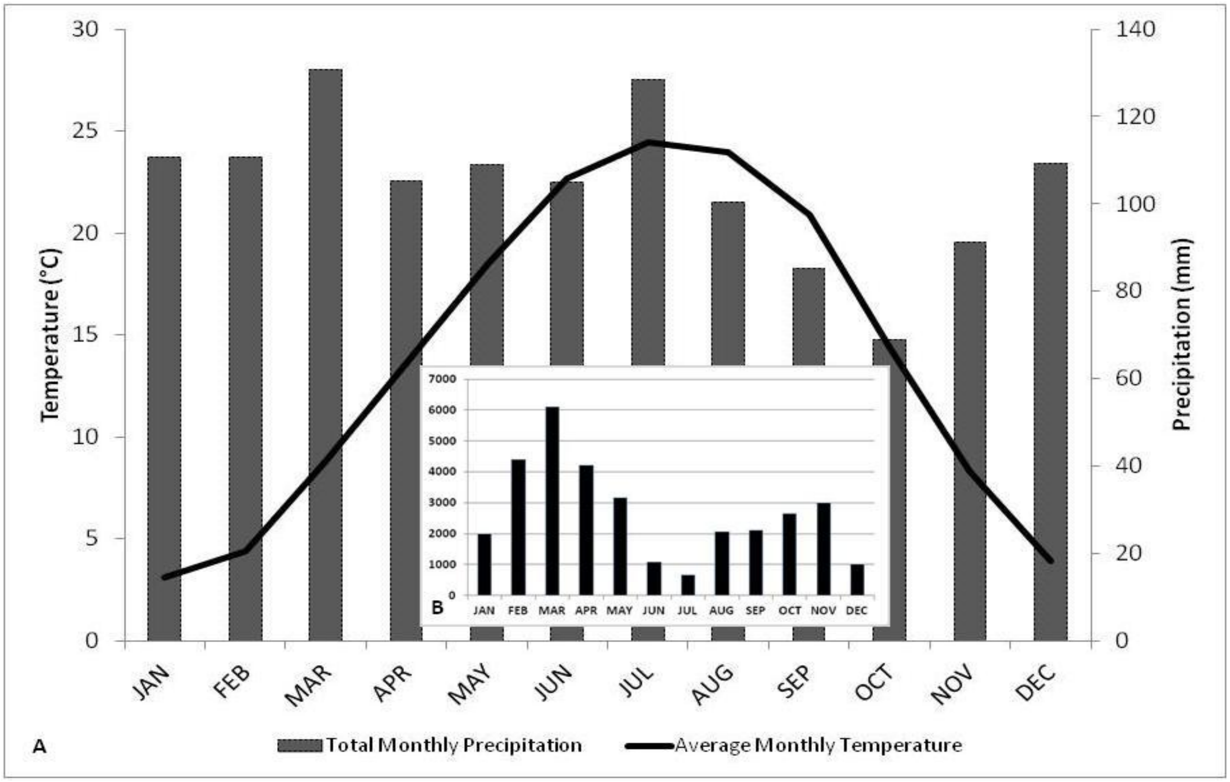

**Figure 5.1**: Monthly temperature, precipitation, and number of fires. **A)** Mean monthly temperature and total monthly precipitation for East Tennessee. Averages are shown for 1895–2006 data. **B)** Monthly number of fires in the southern United States, including East Tennessee (adapted from Gramley 2005). Fire seasons peak in the spring and in the fall.

(Ali *et al*. 2009). The ability to monitor and predict climate fluctuations may help us better plan for unusual weather patterns that are not only linked with fire and drought, but also with hurricanes and other events or conditions that impact human commerce and agriculture.

Most instrumental climate data are only available for the previous 50 years or so. Some measurements extend for the past century, but missing data may occur and the data tend to be unreliable. To study past climate conditions beyond the century mark, it is necessary to use proxies such as ice cores, lake sediments, and tree rings. These proxies record the environmental conditions in which they were produced. For example, they capture chemical or isotope changes over time (Miller *et al*. 2006), the presence of pollen (Delcourt and Delcourt 1980), shifts in microscopic organism assemblages (Duigan and Birks 2000), or charcoal incorporated into the strata (Whitlock and Larsen 2001). The width of each layer can also provide clues to the environment (Dean *et al*. 2002). When the proxies are calibrated against known environmental conditions, they can be used to extend the climate record back in time. Tree-ring records are useful for examining annual climate fluctuations because many tree species exhibit a seasonal dormancy that provides a clear demarcation between years. While a single tree typically does not have a long life span, linking living tree-ring records with those records from wood preserved in historic structures, buried in bogs, or sometimes resinous stumps or logs remaining on the landscape can extend the record hundreds, if not thousands, of years. Trees also record specific events such as wildfires, ice storms, gap formation, and insect infestations.

To ensure proper dating of tree-ring sequences and stand events, dendrochronologists use appropriate site selection and collection techniques to gather a sufficient number of samples for replication and analyses (Stokes and Smiley 1996). Ring-width measurements are recorded in a series for each tree, which are then crossdated against other samples from the site by comparison of narrow and wide marker rings, and by statistical analyses. The group of crossdated series is then converted into a single index that removes age-related trends and allows for improved evaluation against other indices. Analysis of measurements from one site provides an assessment of environmental conditions on a local scale, while combining measurements from multiple sites provides a more regional perspective. Several techniques are available with which to study the environmental conditions recorded in the trees.

### **5.1.2** ***Superposed Epoch Analysis***

Superposed epoch analysis (SEA) was originally termed "Chree Analysis" after Charles Chree who developed and used the method for his research on geomagnetism (Hudson 2009). Since then, SEA has been used to study many subjects, including volcanic forcing of climate (Adams *et al*. 2003, Hegerl *et al*. 2011), tree-ring growth and mass insect emergence (Speer *et al*. 2010), and climate and radial tree growth (Orwig and Abrams 1997, Kelly *et al*. 2002, Martin-Benito *et al.* 2008). Most research using SEA to examine climate and wildfire has been conducted in the western U.S., where the incidence of severe and widespread wildfire events is typically greater than that of other sectors of the country (Veblen *et al.* 2000, Grissino-Mayer *et al*. 2004, Taylor and Beaty 2005, Swetnam and Brown 2011). The southern U.S. (13 states from Texas to Virginia), however, leads the nation in the number of annual wildfires (Gramley 2005).

The SEA method involves taking key event years (*e.g.* volcanic eruptions or wildfires) and superimposing them on top of each other along with a set number of years prior to and following each event for which the comparison variable is known (*e.g.*, annual precipitation levels or temperatures) (Adams *et al*. 2003, Grissino-Mayer 2006). The groups of sequential years form windows that are overlain, and from which the means of the data for corresponding years around the key event are calculated and compared. Bootstrapped confidence intervals are calculated from randomly selected events from the population of observations to increase the robustness of the analysis from an often small sample size. For example, in the case of wildfire and climate, a window of 10 years starting five years before the fire can be used. The results of SEA analysis would therefore provide an average of climate conditions for each of the five years prior to the fire event, the year of the fire (zero year), and the four years after the fire, along with the significance of the relationship between the climate year and the fire year. While climate conditions after a fire could not directly influence the event, it is useful to include the post-event years to examine the general climate trend (Grissino-Mayer 2006).

### 5.1.3 *Climate Variables*

We investigated the relationship between wildfire occurrence and six climate variables that influence the southeastern United States: the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), Northern Hemisphere Temperatures (NHTMP), and the Palmer Drought Severity Index (PDSI). The relationship between wildfire and site-specific tree-ring chronologies that represent local climate conditions was also examined.

The Atlantic Multidecadal Oscillation (AMO) affects air temperature and rainfall in the Northern Hemisphere and is defined by sea surface temperature (SST, Kaplan series) variability in the northern Atlantic Ocean. It is partially driven by the multidecadal fluctuations of the North Atlantic Oscillation (Kerr 2000), and appears to modulate the strength of the El Niño-Southern Oscillation (Gray *et al*. 2004). Distinct cool and warm phases, lasting 20 to 40 years each, comprise an overall cycle length of 65 to 80 years. In the warm (positive) phase, rainfall is abundant in Florida and the Pacific Northwest, but decreases elsewhere in the United States. Conditions are generally reversed during the cool (negative) phase, and precipitation increases in the southern Appalachian Mountains (Enfield *et al*. 2001, Tootle *et al*. 2005). AMO is associated with severe drought frequency and with Atlantic hurricanes (Joint Fire Sciences

Program (JFSP) 2007). Gray *et al*. (2004) reconstructed the AMO using tree-ring records from eastern North America, Europe, Scandinavia, and the Middle East. The index spanned 1567 to 1990. An extended cool phase was observed in the reconstructed data from 1789 to 1849, following a neutral period that began about 1700. Short oscillations occurred between 1850 and 1925 that led into an extended warm phase that lasted until about 1970 (Gray *et al*. 2004).

The North Atlantic Oscillation (NAO) cycles approximately every 1.7 to 7 years and affects westerly winds and storm tracks across the northern Atlantic Ocean, especially during November to April (Hurrell *et al.* 2003, Climate Prediction Center (CPC) 2010). The NAO is a measure of sea level atmospheric pressure fluctuations between the Icelandic Low (63° N, 23° W) and the Azores High (38° N, 26° W) (D'Arrigo *et al*. 1993, Goodkin *et al*. 2008). When pressure differences are great between the high and low pressure poles (*i.e.* positive phase), the eastern United States experiences warmer winters as westerly winds increase across the ocean, and warm, moist air is brought up from the Gulf of Mexico and the tropical Atlantic (Yin 1994, Greatbatch 2000, Stenseth *et al.* 2003). Opposite patterns are generally observed during the negative phase. Occasionally, a complete reversal of pressure occurs that leads to colder winters in Europe and in the eastern United States. Cook *et al*. (1998) used tree-ring records from eastern North America and northwestern Europe to reconstruct the NAO from 1701 to 1980. The dataset was later extended through 2001 (Cook *et al*. 2002).

The El Niño-Southern Oscillation (ENSO) is a dual-component climate phenomenon over the tropical Pacific Ocean. El Niño refers to atypically warm sea surface temperatures that extend along the equator to the western coast of Central and South America that change in response to a shift in sea-level pressure over Indonesia. The Southern Oscillation Index measures pressure differences in the region, specifically between Darwin, Australia and the island of Tahiti (Speer 2010). In normal, non-El Niño conditions, the trade winds prohibit the warmer surface waters from flowing eastward and sea level is notably higher near Indonesia than at Ecuador (National Oceanic and Atmospheric Administration (NOAA) 2010). During El Niño, the trade winds weaken and allow the warm surface waters to expand eastward. This essentially smothers the cool, upwelling sea-water along the South American coast, which negatively affects marine life and fisheries there. El Niño cycles bring increased moisture and cooler temperatures across most of the southern U.S., especially during the winter months (October–March; Allan and D'Arrigo 1999), resulting in decreased wildfire activity (Gramley 2005). La Niña is associated with cooler-than-normal temperatures in the equatorial Pacific Ocean. During a La Niña year, most of the southern U.S. experiences warmer and drier conditions. Wildfires that start during this cycle tend to be more severe, driven by the availability of drier fuels (Gramley 2005). La Niña is considered the "cool phase" of the oscillation, in contrast to the "warm phase" of El Niño, and occurs less frequently. El Niño episodes often occur every 3 to 5 years, but minimum and maximum intervals of 2 and 8 years have been recorded (D'Arrigo *et al*. 2005, CPC 2010).

The NIÑO-3 reconstruction by Cook (2000) represents annual fluctuations of the El Niño-Southern Oscillation for each winter season (December–February). It was developed using age-detrended tree-ring chronologies from Texas and Mexico that were combined with instrumental data. The period of record extends from 1408 through 1978. The trees used in this reconstruction express the strongest ENSO signal found in any tree-ring data thus far (D'Arrigo *et al*. 2005). The instrumental NIÑO-3 index is derived from seasonal SSTs averaged over the central Pacific Ocean (5° S–5° N, 90°–150° W) (Torrence and Compo 1998). Positive values of the index indicate an El Niño phase, whereas La Niña values are negative.

The Pacific Decadal Oscillation (PDO) was discovered in 1996 by fisheries scientist Steven Hare while researching the relationship between Pacific climate and Alaskan salmon cycles (Mantua 2011). This oscillation modulates the effects of ENSO on the North American continent (Biondi *et al*. 2001). Warm phase PDO (positive) is associated with below average temperatures and with above average precipitation in the southeastern United States during October through March. Cool phase PDO (negative) conditions are reversed during those same months (Mantua 2011). Between 1976 and 1999, PDO was in a cool phase that was associated with a higher incidence of El Niño events (JFSP 2007). To reconstruct PDO from 1661 to 1991, Biondi *et al*. (2001) used tree-ring chronologies from southern and Baja California. Large shifts of PDO phase polarity were documented at around 1750, 1905, and 1947.

Using a network of tree-ring density chronologies from North America, Siberia, and Europe, Briffa *et al*. (1998) reconstructed northern hemisphere summer temperatures (NHTMP; April–September) for 1400 to 1994. The NHD1 index was generated by dividing the hemisphere into five regions, taking the mean of the chronologies within each region, and then averaging those means. Ring density was found to increase following large volcanic eruptions, which indicated cooler temperatures. Notably colder years included 1740, 1783, 1816–1818, 1836, 1837, 1884, and 1912. A strong warm peak occurred in 1878, and temperatures between 1930 and 1960 tended to be warmer than average.

The Palmer Drought Severity Index (PDSI) is a monthly index that indicates the severity of wet and dry conditions of a location (Palmer 1965). The values usually fall between –6 (dry) to +6 (wet), although occasional values of –7 or +7 are seen. To reconstruct PDSI, Cook *et al*. (1999) used 388 tree ring chronologies from across North America to create a gridded network of average summer (June–August) PDSI values. The dataset was expanded in 2004 to include additional chronologies, from which a 286-point 2.5 degree grid was made that covered most of the continent (Cook *et al*. 2004). In the western U.S., positive PDSI values (wetter) were linked with wildfire two years prior to the event (Baisan and Swetnam 1990), suggesting preconditioning.

This chapter will address two research questions:

1) What relationships existed between wildfire and climate from 1700 to 2006 in the western portion of Great Smoky Mountains National Park?
2) Did the relationships between climate and wildfire change over time?

### 5.2 Study Sites

Appropriate study sites were located within GSMNP with the assistance of park personnel and aerial photographs. The presence of fire-scarred yellow pines was confirmed via ground surveys. Fire scars were found on living trees, snags, stumps, logs, and remnant wood. Many of the scars showed the characteristic ridged pattern that indicated the tree had survived multiple fires. Each site was in an area classified by Pyle (1988) as having had "diffuse disturbance," meaning that there may have been small, frequent fires, livestock grazing, or small logging operations in the past, but that the sites had not experienced the large-scale damage and intense fires associated with corporate logging. Three sites were selected for this study after reviewing aerial photographs and performing ground surveys: Gold Mine Trail (35°38′N, 83°54′W), Rabbit Creek Trail (35°36′N, 83°55′W, and Pine Mountain (35°37′N, 83°55′W). The elevation range for each site was between 460 and 600 m ASL. The Gold Mine Trail site covered approximately 35 ha, while Rabbit Creek Trail and Pine Mountain were about 20 ha in area.

### 5.3 Field Methods

Across each site, samples were gathered using a targeted method because of the limited quantity and quality of fire-scarred pines (Stambaugh and Guyette 2004), a technique that has been shown to be statistically valid (Van Horne and Fulé 2006). Cross-sections were collected using a chainsaw from snags, logs, remnant wood, and a few selected living trees (Arno and Sneck 1977). Cores were collected from each live canopy tree according to standard dendrochronological procedures (Fritts 2001, Grissino-Mayer 2003). A minimum of 40 yellow pine trees were sampled per site. All of the samples were transported to the Laboratory of Tree-Ring Science at the University of Tennessee for processing and analysis.

## 5.4 Laboratory Methods

### 5.4.1 *Sample Preparation and Crossdating*

The air-dried cores were fixed to labeled, wooden core mounts with the transverse plane perpendicular to the mount and then surfaced with a belt sander and progressively finer grit sandpaper, from ANSI 120 grit (105–125 μm) to ANSI 400 grit (20.6–36.0 μm), so that the cells would be more visually apparent (Stokes and Smiley 1996, Orvis and Grissino-Mayer 2002). If necessary, the cores were further polished by hand with P1500 grit (9.8–12.3 μm) sandpaper. Cross-sections were either frozen at –40 °C for 24 hours, or treated with insecticide, and then allowed to dry. Fragile samples were mounted on particleboard and all sections were downsized into thinner sections using a band saw. The sections were surfaced similarly to the cores, except the initial grit was coarser (*e.g.* ANSI 60 grit, 250–297 μm) to remove saw marks.

Rings on cores and cross-sections were assigned calendar decades, or every tenth ring if the outer year was unknown, with the aid of a stereozoom microscope according to standard dendrochronological methods (Stokes and Smiley 1996, Speer 2010). Unusually narrow or wide rings (marker rings) were noted on all samples and were used to visually confirm their crossdating to other samples. The widths of the rings in each series for every core were measured to the nearest 0.001 mm using a Velmex measuring system coupled with Measure J2X software.

The measurement file for each cross-section was incorporated into a master raw ring-width series file for each site, which was then crossdated in COFECHA (version 6.06) using 40-year segments with a 20-year lag (Holmes 1983, Grissino-Mayer 2001a). Some samples were excluded from the master raw ring-width series file because of damage, irregular growth, or poor dating. The final measurement files used for chronology development at each site had < 10% of the segments flagged in COFECHA. Standardized chronologies were generated for each site, and also for the combined regional data, using ARSTAN (Cook 1985).

Once the fire-scarred samples were confidently dated against the tree-ring chronologies, each scar was assigned a calendar year according to its association with an annual ring. Fire-scar data with inner and outer dates for each sample were entered into FHX2 and FHAES (Grissino-Mayer 2001b, http://frames.nbii.gov/fhaes), complementary software packages used to statistically analyze and graph fire history data. Three established classes of fire data were analyzed for each site, and also for the combined (regional) data: all-scarred, 10%-scarred, and 25%-scarred (Grissino-Mayer 1996, DeWeese 2007, Fulé *et al*. 2009). The all-scarred class included all fires that occurred within the target date range. The 10% analysis was used to reduce the influence of small "spot" fires by requiring that the fires analyzed represent at least 10% of the recorder trees within the date range. The 25% class analysis was used to indicate when the most widespread fires occurred. With the FHAES software, I also generated 10-year fire frequency data (all-scarred class) for each study site (Figure 5.2).

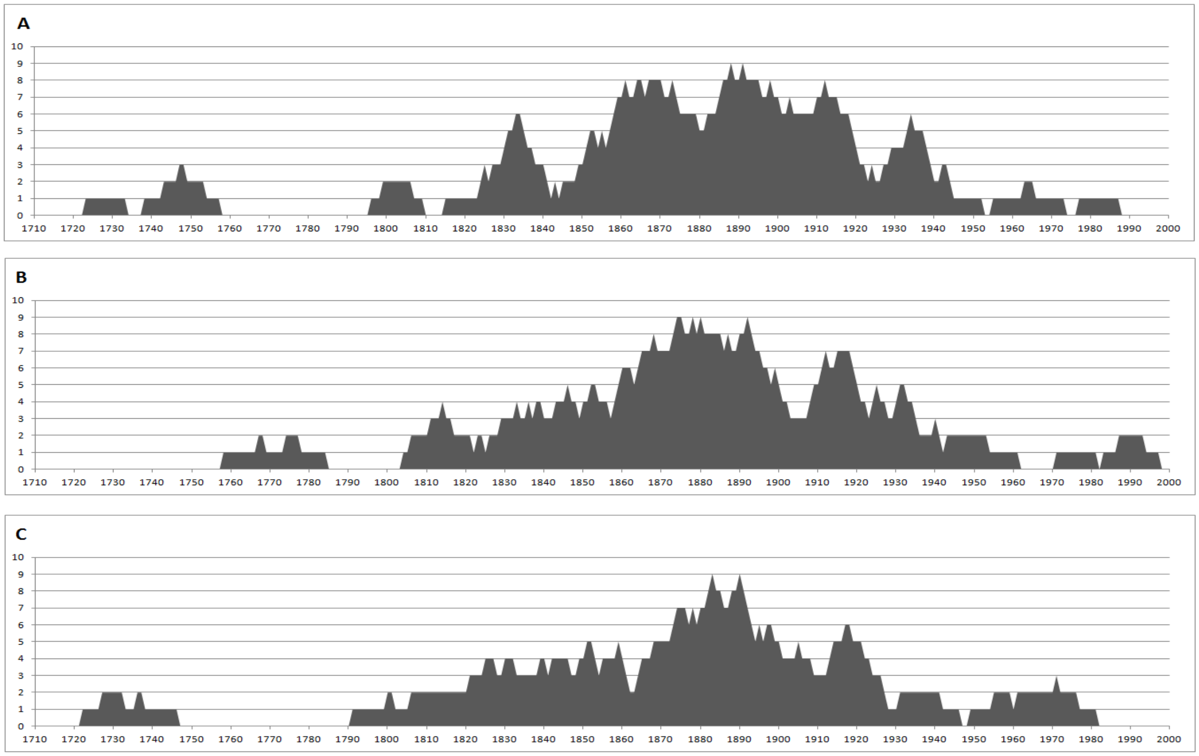

**Figure 5.2**: 10-year fire frequency by site. **A**) Gold Mine Trail, **B**) Rabbit Creek Trail, **C**) Pine Mountain. The greatest frequency occurred between 1860 and 1920 for all sites.

### 5.4.2 *Statistical Analyses*

Six reconstructed climate indices were downloaded from the World Data Center for Paleoclimatology (National Climate Data Center (NCDC) 2010): Northern Hemisphere Temperatures (NHTMP) (Briffa *et al*. 1998, NHD1 index), NIÑO-3 (Cook 2000), Pacific Decadal Oscillation (Biondi *et al*. 2001), Atlantic Multidecadal Oscillation (Gray *et al*. 2004), North Atlantic Oscillation (Cook *et al*. 2002), and four selected grid points (228, 229, 237, 238) of the Palmer Drought Severity Index (Cook *et al*. 2004). The data for the four PDSI grid points were averaged to create a drought index for the study area. Datasets for mean monthly surface air temperature and total monthly precipitation (1895–2006) were downloaded for the East Tennessee division (4001) from the NCDC.

For analyses, the timeline was divided into three periods: Pre-Settlement (approximately 1697–1834), Settlement (1835–1934), and Full (approximately 1697–2006). The Cherokee were the primary inhabitants of GSMNP and its surrounding environs until the early 1800s. European settlers had moved into Cades Cove, a large and flat valley in GSMNP, and into most of the river valleys in the area by 1834. The park was officially established in 1934 after which many residents were moved off the land and fire suppression was prevalent.

#### **5.4.2.1** ***Correlation Analyses***

Each of the six reconstructed climate variables (AMO, NAO, NIÑO-3, PDO, NHTMP and PDSI) were correlated against the instrumental mean monthly temperature (TN01TMP) and total monthly precipitation (TN01PCP) variables for East Tennessee using the correlation function in Climate Explorer (http://climexp.knmi.nl) to determine when the larger-scale climate phenomena were most strongly linked with local conditions in the study region between the years of 1895 and 2006 or the reconstruction end date if the series terminated prior to 2006. Fire frequency data for each site were analyzed using Spearman rank correlation (Wessa 2011) for each period (Native American, European Settler, and Full) against the six climate reconstructions and the tree-ring chronology associated with that site. The tree-ring data functioned as a representation of the interactions of more than one climate variable at a site.

### 5.4.2.2 *Superposed Epoch Analysis*

Each fire chronology (GMT, RCT, PMT, ALL) for each fire class (all-, 10%-, 25%-scarred) was analyzed for two periods (Pre-settlement and Settlement), using the SEA component of FHAES, against AMO, NAO, NIÑO-3, PDO, NHTMP, PDSI, and the corresponding standardized tree-ring chronology. The regional (ALL) fire chronology was also analyzed using SEA over the Full Period against the six climate variables and regional tree-ring chronology. The 10-year window for each analysis spanned from –6 to +3 years. Incomplete windows around fire events near the end of the time series were excluded (Grissino-Mayer 2006). Graphs generated from the analyses provided departures from the mean of the climate variable for each year relative to the wildfire event, and the relation to 95.0%, 99.0%, and 99.9% confidence intervals for determination of significance. The departures and confidence intervals were calculated as the difference between the actual mean index value for each window year and a simulated index based on a Monte Carlo simulation of 1000 randomly drawn windows.

## 5.5 Results

### 5.5.1 *Climate Reconstructions and East Tennessee Temperatures/Precipitation*

Between 1895 and 2006, AMO was significantly correlated only to July temperature ($r = 0.34$, $p < 0.001$) (Table 5.1). NAO was positively correlated with winter temperatures (January–March), in addition to May and October precipitation. NIÑO-3 was positively correlated with July temperatures ($r = 0.26$, $p < 0.05$) and August precipitation ($r = 0.36$, $p < 0.001$), but negatively correlated to January and February precipitation ($r = -0.23$, $p < 0.05$ and $r = -0.24$, $P < 0.05$, respectively). PDO showed a significant relationship only with March precipitation ($r = -0.29$, $p < 0.01$). NHTMP was significantly correlated with February ($r = 0.24$, $p < 0.05$) and June ($r = 0.33$, $p < 0.001$) temperatures. Between 1895 and 2007, East Tennessee mean monthly temperatures were positively associated with winter total monthly precipitation (December–February), and negatively associated with summer total monthly precipitation (May–August) (Table 5.1). PDSI was strongly and positively correlated with January and February precipitation ($r = 0.31$, $p < 0.001$ and $r = 0.40$, $p < 0.001$) and with May and June temperature ($r = 0.53$, $p < 0.001$ and $r = 0.45$, $p < 0.001$). PDSI was strongly and negatively correlated with June through August precipitation, especially in July ($r = -0.33$, $p < 0.001$) (Table 5.1).

**Table 5.1**: Correlation results for reconstructed climate variables against East Tennessee temperature and precipitation (1895–2006). **A**) East Tennessee (TN01) average monthly temperature versus AMO, NAO, NHTMP, NIÑO-3, PDO, PDSI, and TN01 Precipitation. **B**) East Tennessee (TN01) total monthly precipitation versus AMO, NAO, NHTMP, NIÑO-3, PDO, and PDSI. Significance is indicated by * (P < 0.05), ** (P < 0.01), and *** (P < 0.001).

**A) East Tennessee Temperatures**

| | | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AMO** | Correlation | 0.13 | 0.11 | –0.098 | 0.02 | 0.10 | 0.15 | 0.34 *** | 0.15 | 0.07 | 0.16 | 0.05 | 0.04 |
| | P-value | 0.219 | 0.294 | 0.354 | 0.828 | 0.350 | 0.154 | 0.001 | 0.170 | 0.543 | 0.138 | 0.633 | 0.689 |
| **NAO** | Correlation | 0.28 ** | 0.37 *** | 0.44 *** | –0.076 | –0.096 | -0.04 | 0.00 | –0.048 | –0.053 | –0.112 | –0.001 | 0.08 |
| | P-value | 0.004 | 0.000 | 0.000 | 0.439 | 0.323 | 0.684 | 0.976 | 0.627 | 0.591 | 0.251 | 0.996 | 0.408 |
| **NHTMP** | Correlation | 0.17 | 0.24 * | 0.07 | 0.00 | 0.01 | 0.33 *** | 0.18 | 0.12 | 0.15 | 0.13 | -0.03 | -0.01 |
| | P-value | 0.098 | 0.016 | 0.523 | 0.987 | 0.940 | 0.001 | 0.070 | 0.228 | 0.142 | 0.205 | 0.739 | 0.939 |
| **NIÑO3** | Correlation | –0.12 | –0.19 | –0.15 | –0.01 | –0.04 | 0.03 | 0.26 * | 0.08 | 0.12 | 0.06 | 0.13 | –0.08 |
| | P-value | 0.282 | 0.087 | 0.170 | 0.954 | 0.699 | 0.761 | 0.019 | 0.450 | 0.302 | 0.593 | 0.254 | 0.450 |
| **PDO** | Correlation | –0.12 | –0.01 | 0.06 | 0.14 | –0.11 | 0.07 | 0.01 | 0.06 | 0.04 | –0.05 | 0.18 | 0.09 |
| | P-value | 0.234 | 0.893 | 0.588 | 0.160 | 0.282 | 0.506 | 0.895 | 0.582 | 0.728 | 0.604 | 0.082 | 0.369 |
| **PDSI** | Correlation | 0.06 | 0.06 | 0.25 ** | –0.11 | –0.21 * | –0.46 *** | –0.29 ** | –0.27 ** | –0.33 *** | 0.05 | 0.13 | –0.04 |
| | P-value | 0.534 | 0.564 | 0.008 | 0.272 | 0.033 | 0.000 | 0.002 | 0.004 | 0.001 | 0.644 | 0.176 | 0.646 |
| **TN01 PCP** | Correlation | 0.31 *** | 0.40 *** | 0.10 | –0.08 | –0.23 * | –0.26 ** | –0.33 *** | –0.24 ** | –0.13 | 0.13 | 0.18 | 0.27 ** |
| | P-value | 0.001 | 0.000 | 0.273 | 0.415 | 0.014 | 0.006 | 0.000 | 0.010 | 0.180 | 0.186 | 0.055 | 0.004 |

**B) East Tennessee Precipitation**

| | | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AMO** | Correlation | –0.02 | 0.14 | 0.01 | –0.07 | –0.16 | –0.08 | 0.05 | 0.10 | –0.18 | 0.02 | –0.01 | 0.07 |
| | P-value | 0.886 | 0.173 | 0.922 | 0.516 | 0.128 | 0.440 | 0.641 | 0.370 | 0.084 | 0.841 | 0.935 | 0.495 |
| **NAO** | Correlation | 0.01 | 0.19 | –0.05 | 0.01 | * 0.25 | 0.09 | –0.11 | 0.01 | 0.05 | 0.24 * | 0.17 | 0.06 |
| | P-value | 0.883 | 0.051 | 0.617 | 0.888 | 0.011 | 0.351 | 0.280 | 0.886 | 0.629 | 0.013 | 0.072 | 0.515 |
| **NHTMP** | Correlation | –0.03 | 0.09 | –0.10 | –0.01 | –0.07 | –0.01 | 0.09 | 0.19 | –0.13 | 0.01 | –0.01 | 0.02 |
| | P-value | 0.791 | 0.355 | 0.306 | 0.934 | 0.499 | 0.926 | 0.357 | 0.058 | 0.199 | 0.950 | 0.928 | 0.842 |
| **NIÑO3** | Correlation | –0.23 * | –0.24 * | –0.05 | 0.15 | –0.05 | –0.01 | 0.02 | 0.36 *** | –0.03 | –0.11 | 0.06 | 0.14 |
| | P-value | 0.040 | 0.027 | 0.640 | 0.181 | 0.642 | 0.974 | 0.829 | 0.001 | 0.797 | 0.325 | 0.624 | 0.198 |
| **PDO** | Correlation | –0.14 | –0.13 | –0.30 ** | 0.03 | 0.13 | –0.06 | 0.19 | 0.08 | –0.01 | –0.08 | –0.10 | –0.10 |
| | P-value | 0.159 | 0.195 | 0.003 | 0.786 | 0.210 | 0.585 | 0.068 | 0.444 | 0.910 | 0.468 | 0.340 | 0.349 |
| **PDSI** | Correlation | 0.06 | 0.27 ** | 0.21 * | 0.13 | 0.53 *** | 0.45 *** | 0.14 | –0.03 | 0.09 | –0.1 | 0.13 | –0.04 |
| | P-value | 0.518 | 0.005 | 0.029 | 0.173 | 0.000 | 0.000 | 0.146 | 0.742 | 0.353 | 0.302 | 0.179 | 0.690 |

### 5.5.2 *Gold Mine Trail (GMT)*

#### 5.5.2.1 *Correlation Analyses*

In the Full Period (1687–1834) analysis, the Gold Mine Trail tree-ring chronology was positively correlated with PDSI ($r = 0.22$, $P < 0.001$), NHTMP ($r = 0.18$, $P < 0.01$), and NAO ($r = 0.18$, $P < 0.01$) (Table 5.2). The Pre-settlement Period was positively correlated with only PDSI ($r = 0.20$, $P < 0.05$). For the Settlement Period, both NAO ($r = 0.22$, $P < 0.05$) and PDSI ($r = 0.21$, $P < 0.05$) were positively correlated. The 10-year fire frequency for GMT was positively correlated with NIÑO-3 ($r = 0.10$, $P < 0.05$) and PDO ($r = 0.15$, $P < 0.01$) from 1697–2006 (Table 5.3). During the Pre-settlement Period, PDO ($r = 0.14$, $P < 0.05$) and NHTMP ($r = 0.12$, $P < 0.05$) were significantly correlated. The GMT standard chronology had a negative relationship with fire frequency during the Settlement Period ($r = -0.29$, $P < 0.01$), while AMO was positively related ($r = 0.22$, $P < 0.05$).

#### 5.5.2.2 *Superposed Epoch Analyses*

During the Pre-settlement Period, all classes of fires at GMT were most strongly associated with NIÑO-3 (Figure 5.3) and PDO (Figure 5.4). A positive relationship with NIÑO-3 was present five years prior to the fire year, and the zero year (event year) was negatively related to NIÑO-3. PDO was positively related to the fire event two and three years prior. For the zero year, strong peaks were present for NHTMP (positive) and PDSI (negative), but they were not significant. The only significant relationship during the Settlement Period was for NAO at –6 years in the 10%-scarred class (Figure 5.5). In general, discrete fire events at GMT appear unrelated to AMO, NHTMP, and PDSI.

**Table 5.2:** Correlation results for standardized site chronologies against climate reconstructions. **A**) AMO, **B**) NAO, **C**) NIÑO-3, **D**) PDO, **E**) NHTMP, **F**) PDSI. Pre-settlement Period = 1697–1834, Settlement Period = 1835–1934, Full Period = 1697–2006. Actual sample number analyzed varies by the length of overlap between the variables. Significance is indicated by * ($P < 0.05$), ** ($P < 0.01$), and *** ($P < 0.001$).

| | A) Atlantic Multidecadal Oscillation (Gray *et al*. 2004) | | | | B) North Atlantic Oscillation (Cook *et al*. 2002) | | | |
|---|---|---|---|---|---|---|---|---|
| | Correlation | P-value | Number | 95% CI | Correlation | P-value | Number | 95% CI |
| Gold Mine Trail - Pre-settlement Period | 0.02 | 0.825 | 138 | -0.11... 0.16 | 0.11 | 0.205 | 138 | -0.02... 0.25 |
| Gold Mine Trail - Settlement Period | -0.11 | 0.283 | 100 | -0.28... 0.1 | 0.22 | 0.027 * | 100 | 0.00... 0.4 |
| Gold Mine Trail - Full Period | 0.05 | 0.368 | 289 | -0.03... 0.15 | 0.18 | 0.002 ** | 305 | 0.07... 0.29 |
| Rabbit Creek Trail - Pre-settlement Period | -0.41 | 0.002 ** | 56 | -0.58... -0.2 | 0.09 | 0.498 | 56 | -0.15... 0.32 |
| Rabbit Creek Trail - Settlement Period | 0.03 | 0.794 | 100 | -0.13... 0.2 | 0.23 | 0.020 * | 100 | 0.00... 0.43 |
| Rabbit Creek Trail - Full Period | -0.11 | 0.125 | 207 | -0.22... 0.04 | 0.23 | 0.001 *** | 223 | 0.10... 0.36 |
| Pine Mountain - Pre-settlement Period | -0.14 | 0.193 | 93 | -0.34... 0.07 | -0.09 | 0.407 | 93 | -0.29... 0.12 |
| Pine Mountain - Settlement Period | 0.18 | 0.068 | 100 | -0.02... 0.4 | 0.16 | 0.112 | 100 | -0.06... 0.34 |
| Pine Mountain - Full Period | 0.06 | 0.370 | 244 | -0.05... 0.2 | 0.09 | 0.139 | 260 | -0.04... 0.21 |
| Regional (ALL) - Pre-settlement Period | -0.04 | 0.662 | 138 | -0.16... 0.09 | 0.11 | 0.209 | 138 | -0.03... 0.25 |
| Regional (ALL) - Settlement Period | -0.02 | 0.842 | 100 | -0.18... 0.19 | 0.24 | 0.015 * | 100 | 0.01... 0.43 |
| Regional (ALL) - Full Period | 0.02 | 0.800 | 289 | -0.07... 0.11 | 0.18 | 0.002 ** | 305 | 0.07... 0.28 |

| | C) El Niño/Southern Oscillation (NIÑO-3, Cook 2000) | | | | D) Pacific Decadal Oscillation (Biondi *et al*. 2001) | | | |
|---|---|---|---|---|---|---|---|---|
| | Correlation | P-value | Number | 95% CI | Correlation | P-value | Number | 95% CI |
| Gold Mine Trail - Pre-settlement Period | -0.01 | 0.952 | 138 | -0.17... 0.14 | -0.02 | 0.826 | 138 | -0.20... 0.15 |
| Gold Mine Trail - Settlement Period | 0.04 | 0.714 | 100 | -0.16... 0.22 | 0.04 | 0.667 | 100 | -0.18... 0.27 |
| Gold Mine Trail - Full Period | 0.01 | 0.905 | 282 | -0.10... 0.11 | -0.03 | 0.574 | 295 | -0.14... 0.08 |
| Rabbit Creek Trail - Pre-settlement Period | 0.05 | 0.726 | 56 | -0.19... 0.28 | -0.04 | 0.769 | 56 | -0.29... 0.17 |
| Rabbit Creek Trail - Settlement Period | 0.00 | 0.986 | 100 | -0.20... 0.16 | 0.10 | 0.312 | 100 | -0.10... 0.31 |
| Rabbit Creek Trail - Full Period | 0.02 | 0.740 | 200 | -0.10... 0.15 | -0.01 | 0.844 | 213 | -0.13... 0.12 |
| Pine Mountain - Pre-settlement Period | 0.01 | 0.925 | 93 | -0.18... 0.19 | -0.10 | 0.361 | 93 | -0.25... 0.08 |
| Pine Mountain - Settlement Period | 0.04 | 0.690 | 100 | -0.18... 0.25 | 0.16 | 0.108 | 100 | -0.02... 0.34 |
| Pine Mountain - Full Period | 0.04 | 0.578 | 237 | -0.09... 0.17 | 0.02 | 0.792 | 250 | -0.09... 0.13 |
| Regional (ALL) - Pre-settlement Period | 0.01 | 0.943 | 138 | -0.16... 0.15 | -0.04 | 0.641 | 138 | -0.22... 0.13 |
| Regional (ALL) - Settlement Period | 0.03 | 0.746 | 100 | -0.16... 0.22 | 0.05 | 0.613 | 100 | -0.17... 0.28 |
| Regional (ALL) - Full Period | 0.02 | 0.775 | 282 | -0.08... 0.12 | -0.03 | 0.597 | 295 | -0.14... 0.08 |

| | E) N. Hemisphere Temperature (NHD1, Briffa *et al*. 1998) | | | | F) Palmer Drought Severity Index (Cook *et al*. 2004) | | | |
|---|---|---|---|---|---|---|---|---|
| | Correlation | P-value | Number | 95% CI | Correlation | P-value | Number | 95% CI |
| Gold Mine Trail - Pre-settlement Period | 0.09 | 0.309 | 138 | -0.07... 0.24 | 0.20 | 0.020 * | 138 | 0.07... 0.36 |
| Gold Mine Trail - Settlement Period | 0.17 | 0.099 | 100 | 0.00... 0.32 | 0.21 | 0.038 * | 100 | 0.01... 0.36 |
| Gold Mine Trail - Full Period | 0.18 | 0.002 ** | 298 | 0.09... 0.29 | 0.22 | 0.000 *** | 307 | 0.12... 0.33 |
| Rabbit Creek Trail - Pre-settlement Period | 0.04 | 0.800 | 56 | -0.18... 0.23 | 0.01 | 0.972 | 56 | -0.21... 0.24 |
| Rabbit Creek Trail - Settlement Period | 0.10 | 0.328 | 100 | -0.06... 0.27 | 0.29 | 0.004 ** | 100 | 0.09... 0.45 |
| Rabbit Creek Trail - Full Period | 0.11 | 0.116 | 216 | 0.00... 0.22 | 0.27 | 0.000 *** | 225 | 0.14... 0.38 |
| Pine Mountain - Pre-settlement Period | -0.23 | 0.027 * | 93 | -0.40... -0.04 | 0.19 | 0.073 | 93 | -0.05... 0.38 |
| Pine Mountain - Settlement Period | 0.25 | 0.011 * | 100 | 0.08... 0.42 | 0.26 | 0.008 ** | 100 | 0.06... 0.45 |
| Pine Mountain - Full Period | 0.07 | 0.300 | 253 | -0.05... 0.19 | 0.27 | 0.000 *** | 262 | 0.14... 0.38 |
| Regional (ALL) - Pre-settlement Period | 0.05 | 0.544 | 138 | -0.11... 0.21 | 0.23 | 0.007 ** | 138 | 0.10... 0.38 |
| Regional (ALL) - Settlement Period | 0.20 | 0.045 * | 100 | 0.03... 0.36 | 0.27 | 0.007 ** | 100 | 0.08... 0.42 |
| Regional (ALL) - Full Period | 0.15 | 0.011 * | 298 | 0.04... 0.26 | 0.26 | 0.000 *** | 307 | 0.15... 0.36 |

**Table 5.3:** Correlation results for 10-year fire frequency against climate reconstructions and site tree-ring chronologies. **A**) AMO, **B**) NAO, **C**) NIÑO-3, **D**) PDO, **E**) NHTMP, **F**) PDSI, **G**) Site tree-ring chronologies. Pre-settlement Period = 1697–1834, Settlement Period = 1835–1934, Full Period = 1697–2006. Actual sample number analyzed varies by the length of overlap between the variables. Significance is indicated by * ($P < 0.05$), ** ($P < 0.01$), and *** ($P < 0.001$).

A) Atlantic Multidecadal Oscillation (Gray *et al*. 2004)

| | Correlation | P-value | Number | df |
|---|---|---|---|---|
| Gold Mine Trail - Pre-settlement Period | -0.17 | 0.303 | 120 | 118 |
| Gold Mine Trail - Settlement Period | 0.22 | 0.024 * | 100 | 98 |
| Gold Mine Trail - Full Period | 0.07 | 0.156 | 288 | 286 |
| Rabbit Creek Trail - Pre-settlement Period | -0.39 | 0.002 ** | 120 | 118 |
| Rabbit Creek Trail - Settlement Period | 0.20 | 0.031 * | 100 | 98 |
| Rabbit Creek Trail - Full Period | 0.01 | 0.631 | 289 | 287 |
| Pine Mountain - Pre-settlement Period | -0.43 | 0.000 *** | 120 | 118 |
| Pine Mountain - Settlement Period | 0.05 | 0.529 | 100 | 98 |
| Pine Mountain - Full Period | -0.11 | 0.107 | 288 | 286 |

B) North Atlantic Oscillation (Cook *et al*. 2002)

| | Correlation | P-value | Number | df |
|---|---|---|---|---|
| Gold Mine Trail - Pre-settlement Period | 0.03 | 0.322 | 120 | 118 |
| Gold Mine Trail - Settlement Period | -0.07 | 0.555 | 100 | 98 |
| Gold Mine Trail - Full Period | -0.04 | 0.726 | 288 | 286 |
| Rabbit Creek Trail - Pre-settlement Period | -0.07 | 0.912 | 120 | 118 |
| Rabbit Creek Trail - Settlement Period | -0.11 | 0.337 | 100 | 98 |
| Rabbit Creek Trail - Full Period | -0.01 | 0.857 | 289 | 287 |
| Pine Mountain - Pre-settlement Period | 0.05 | 0.298 | 120 | 118 |
| Pine Mountain - Settlement Period | 0.04 | 0.542 | 100 | 98 |
| Pine Mountain - Full Period | 0.01 | 0.631 | 288 | 286 |

C) El Niño/Southern Oscillation (NIÑO-3, Cook 2000)

| | Correlation | P-value | Number | df |
|---|---|---|---|---|
| Gold Mine Trail - Pre-settlement Period | 0.09 | 0.105 | 120 | 118 |
| Gold Mine Trail - Settlement Period | 0.02 | 0.764 | 100 | 98 |
| Gold Mine Trail - Full Period | 0.10 | 0.041 * | 288 | 286 |
| Rabbit Creek Trail - Pre-settlement Period | 0.01 | 0.337 | 120 | 118 |
| Rabbit Creek Trail - Settlement Period | -0.01 | 0.984 | 100 | 98 |
| Rabbit Creek Trail - Full Period | 0.05 | 0.294 | 289 | 287 |
| Pine Mountain - Pre-settlement Period | 0.08 | 0.165 | 120 | 118 |
| Pine Mountain - Settlement Period | 0.06 | 0.459 | 100 | 98 |
| Pine Mountain - Full Period | 0.09 | 0.073 | 288 | 286 |

D) Pacific Decadal Oscillation (Biondi *et al*. 2001)

| | Correlation | P-value | Number | df |
|---|---|---|---|---|
| Gold Mine Trail - Pre-settlement Period | 0.14 | 0.038 * | 120 | 118 |
| Gold Mine Trail - Settlement Period | 0.17 | 0.078 | 100 | 98 |
| Gold Mine Trail - Full Period | 0.15 | 0.005 ** | 288 | 286 |
| Rabbit Creek Trail - Pre-settlement Period | 0.02 | 0.298 | 120 | 118 |
| Rabbit Creek Trail - Settlement Period | 0.11 | 0.226 | 100 | 98 |
| Rabbit Creek Trail - Full Period | 0.08 | 0.095 | 289 | 287 |
| Pine Mountain - Pre-settlement Period | 0.02 | 0.447 | 120 | 118 |
| Pine Mountain - Settlement Period | 0.03 | 0.631 | 100 | 98 |
| Pine Mountain - Full Period | 0.01 | 0.704 | 288 | 286 |

E) N. Hemisphere Temperatures (NHD1, Briffa *et al*. 1998)

| | Correlation | P-value | Number | df |
|---|---|---|---|---|
| Gold Mine Trail - Pre-settlement Period | 0.12 | 0.050 * | 120 | 118 |
| Gold Mine Trail - Settlement Period | -0.10 | 0.407 | 100 | 98 |
| Gold Mine Trail - Full Period | 0.05 | 0.234 | 288 | 286 |
| Rabbit Creek Trail - Pre-settlement Period | -0.21 | 0.194 | 120 | 118 |
| Rabbit Creek Trail - Settlement Period | -0.08 | 0.529 | 100 | 98 |
| Rabbit Creek Trail - Full Period | -0.04 | 0.631 | 289 | 287 |
| Pine Mountain - Pre-settlement Period | -0.01 | 0.660 | 120 | 118 |
| Pine Mountain - Settlement Period | -0.12 | 0.312 | 100 | 98 |
| Pine Mountain - Full Period | -0.05 | 0.624 | 288 | 286 |

F) Palmer Drought Severity Index (Cook *et al*. 2004)

| | Correlation | P-value | Number | df |
|---|---|---|---|---|
| Gold Mine Trail - Pre-settlement Period | -0.02 | 0.653 | 120 | 118 |
| Gold Mine Trail - Settlement Period | -0.08 | 0.490 | 100 | 98 |
| Gold Mine Trail - Full Period | -0.06 | 0.472 | 288 | 286 |
| Rabbit Creek Trail - Pre-settlement Period | 0.07 | 0.134 | 120 | 118 |
| Rabbit Creek Trail - Settlement Period | -0.16 | 0.156 | 100 | 98 |
| Rabbit Creek Trail - Full Period | -0.02 | 0.960 | 289 | 287 |
| Pine Mountain - Pre-settlement Period | 0.05 | 0.303 | 120 | 118 |
| Pine Mountain - Settlement Period | -0.09 | 0.496 | 100 | 98 |
| Pine Mountain - Full Period | -0.04 | 0.749 | 288 | 286 |

G) Site Tree-ring Chronology (GMT, RCT, PMT)

| | Correlation | P-value | Number | df |
|---|---|---|---|---|
| Gold Mine Trail - Pre-settlement Period | 0.02 | 0.363 | 120 | 118 |
| Gold Mine Trail - Settlement Period | -0.29 | 0.007 ** | 100 | 98 |
| Gold Mine Trail - Full Period | 0.06 | 0.197 | 288 | 286 |
| Rabbit Creek Trail - Pre-settlement Period | 0.31 | 0.012 * | 120 | 118 |
| Rabbit Creek Trail - Settlement Period | 0.00 | 0.897 | 100 | 98 |
| Rabbit Creek Trail - Full Period | -0.07 | 0.358 | 225 | 223 |
| Pine Mountain - Pre-settlement Period | -0.06 | 0.936 | 120 | 118 |
| Pine Mountain - Settlement Period | -0.04 | 0.865 | 100 | 98 |
| Pine Mountain - Full Period | -0.09 | 0.238 | 261 | 259 |

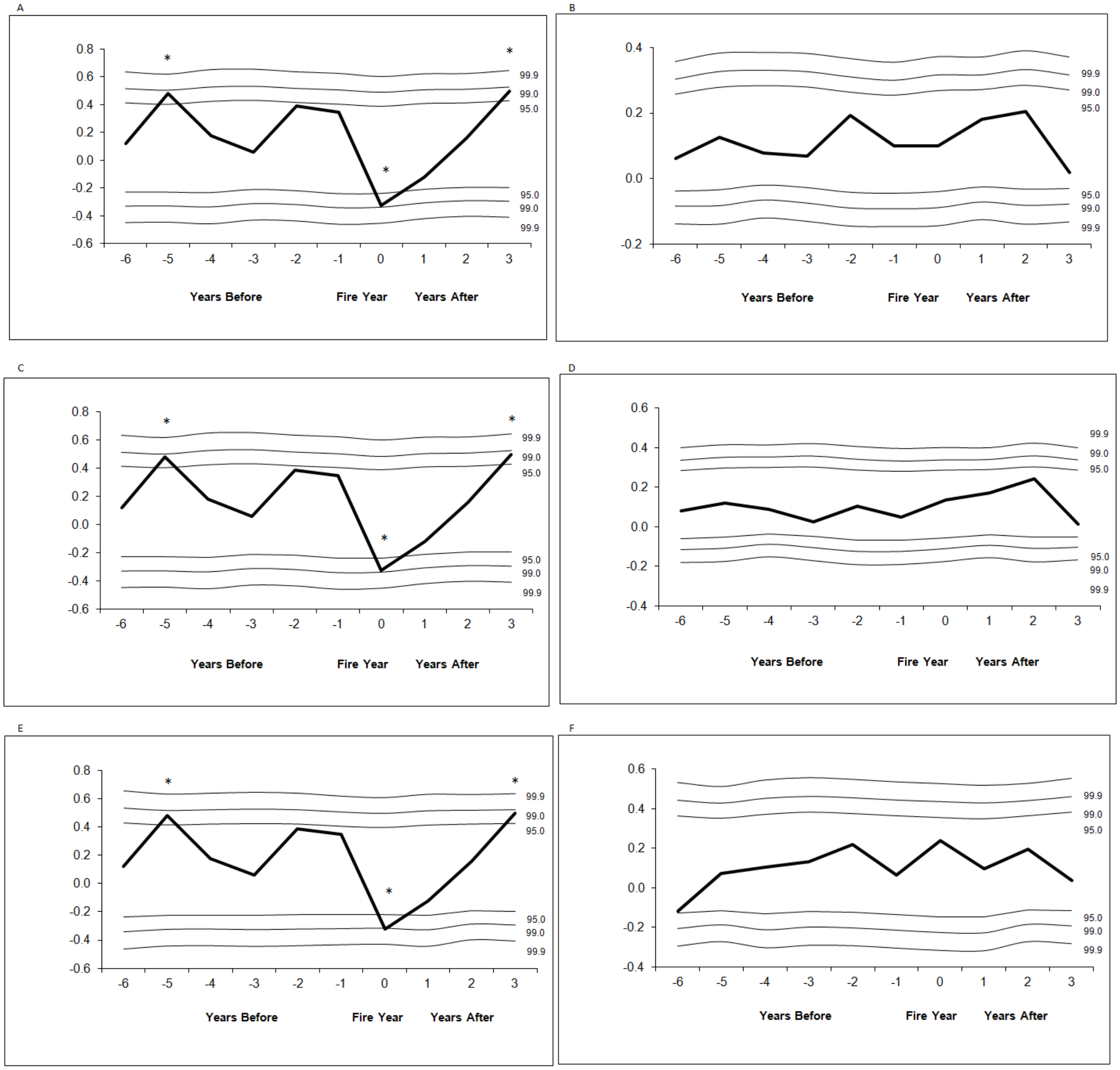

**Figure 5.3**: Superposed Epoch Analysis of Gold Mine Trail fires and El Niño-Southern Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NIÑO-3 reconstruction by Cook 2000. Significant relationship indicated by *.

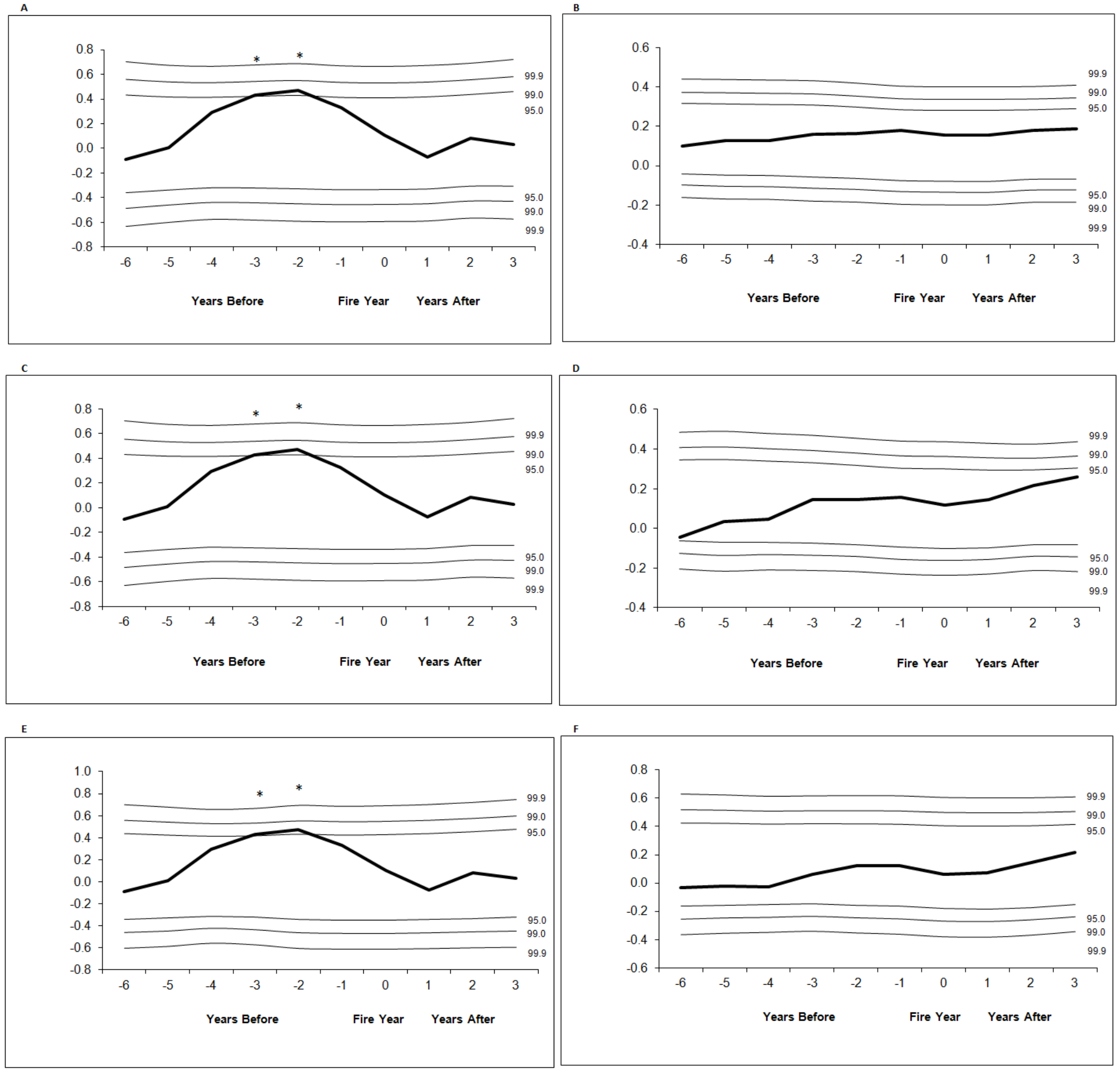

**Figure 5.4**: Superposed Epoch Analysis of Gold Mine Trail fires and Pacific Decadal Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. PDO reconstruction by Biondi *et al*. 2001. Significant relationship indicated by *.

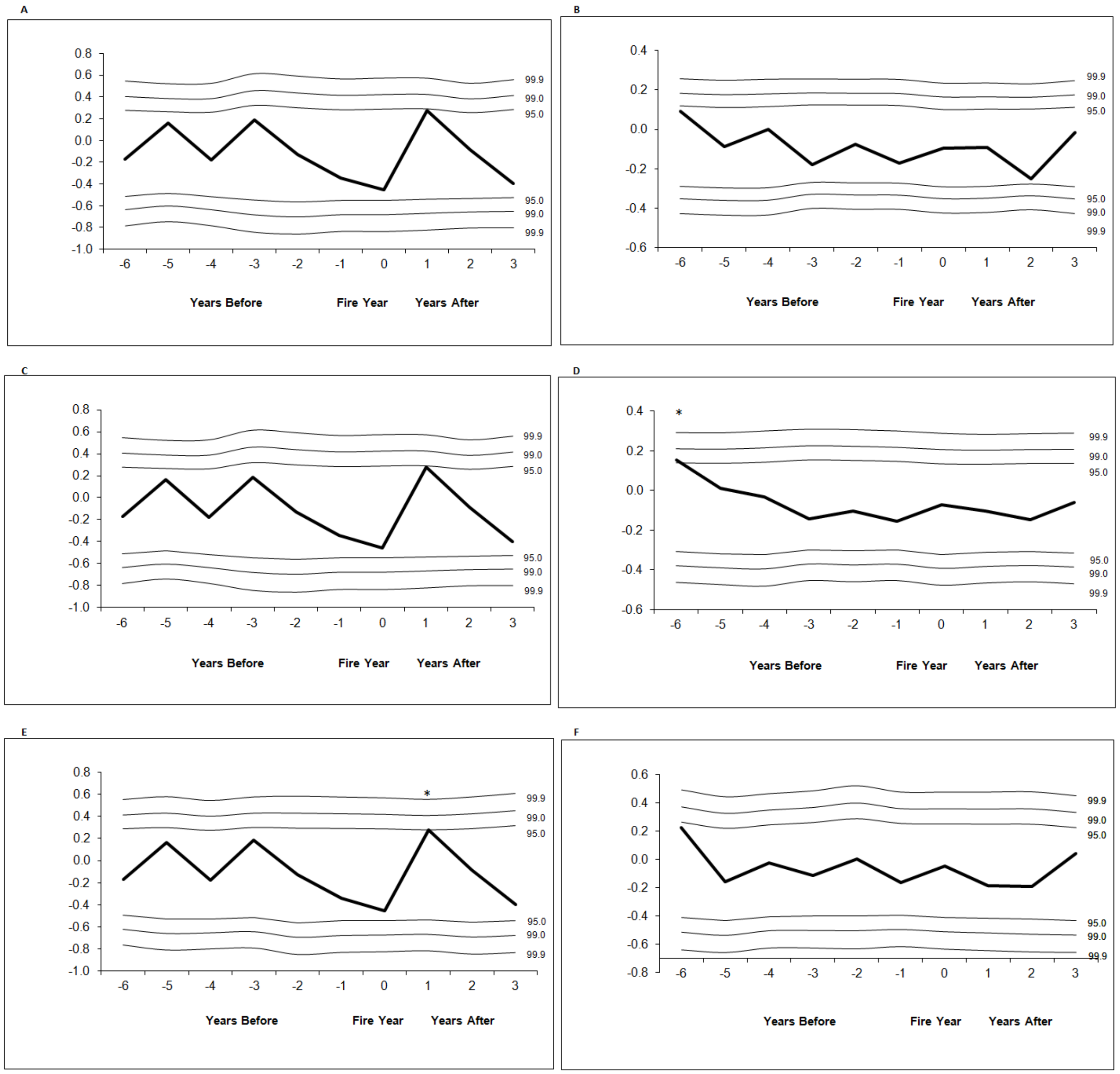

**Figure 5.5**: Superposed Epoch Analysis of Gold Mine Trail fires and North Atlantic Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NAO reconstruction by Cook *et al*. 2002. Significant relationship indicated by *.

### 5.5.3 *Rabbit Creek Trail (RCT)*

#### 5.5.3.1 *Correlation Analyses*

The Rabbit Creek Trail standardized chronology for the Full Period was significantly correlated with both NAO ($r = 0.23$, $P < 0.001$) and PDSI ($r = 0.27$, $P < 0.001$) (Table 5.2). A negative relationship was found with AMO ($r = –0.41$, $P < 0.01$) in the Pre-settlement Period. During the Settlement Period, NAO ($r = 0.23$, $P < 0.05$) and PDSI ($r = 0.29$, $P < 0.05$) were positively correlated. No significant relationships were found over the Full Period at RCT for fire frequency (Table 5.3). When the timeline was subdivided, AMO was negatively related to fire frequency during the Pre-settlement Period ($r = –0.39$, $P < 0.01$), while the RCT standard chronology was positively related ($r = 0.31$, $p < 0.05$) to AMO. During the Settlement Period, AMO ($r = 0.20$, $P < 0.05$) was positively associated with fire frequency.

#### 5.5.3.2 *Superposed Epoch Analyses*

Wildfire events at RCT were associated primarily with NAO (Figure 5.6), NHTMP (Figure 5.7), and PDSI (Figure 5.8) in the Pre-settlement Period. Negative relationships were present for NAO at –5 years, and for NHTMP during the actual fire year, while PDSI was positively related four years prior. In the Settlement Period, NAO shifted to –4 years for all fire classes, but was only significant in the 10%-scarred class. Fires at RCT showed little to no relationship with PDO, AMO, or NIÑO-3 in either period.

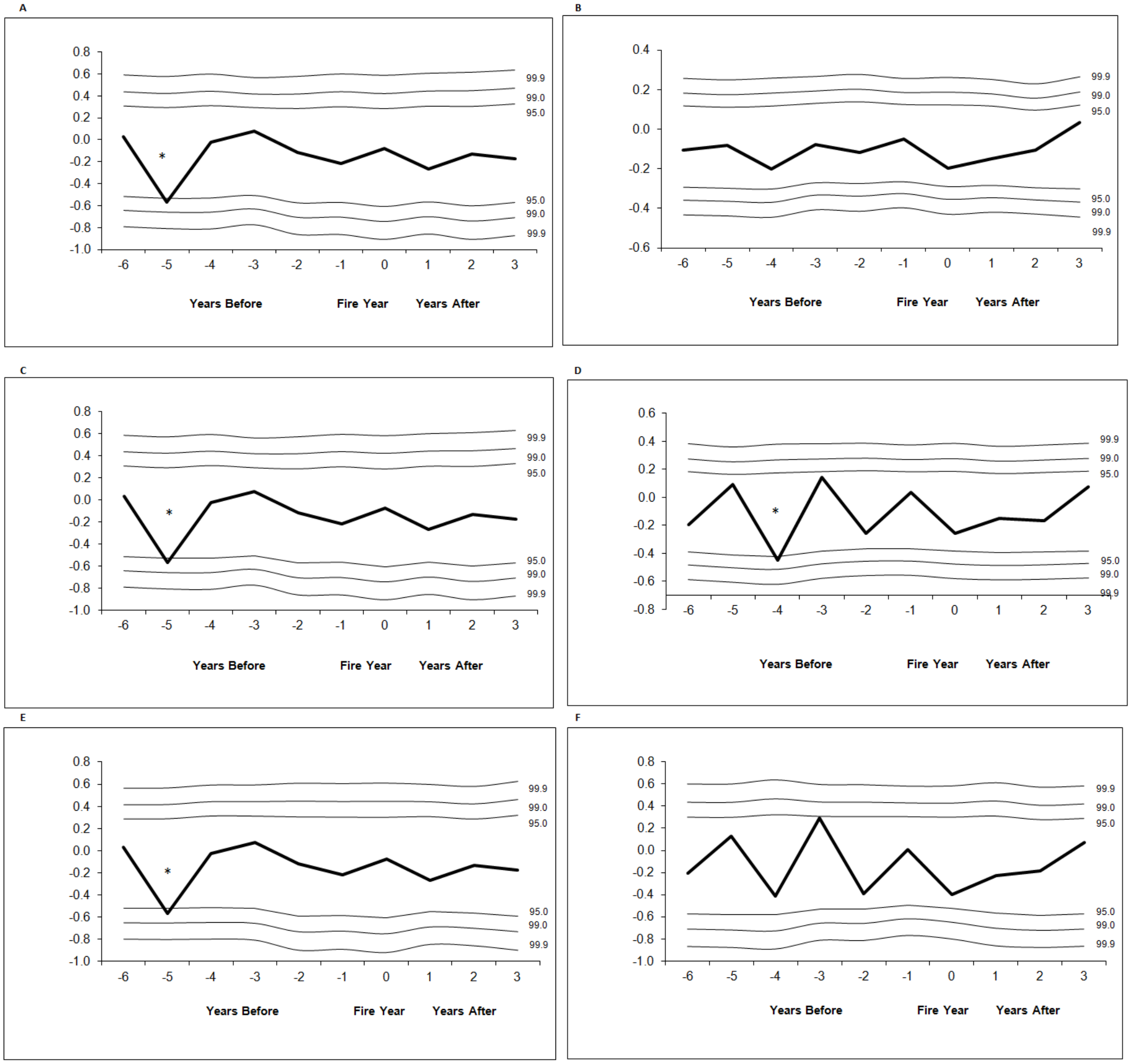

**Figure 5.6**: Superposed Epoch Analysis of Rabbit Creek Trail fires and North Atlantic Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NAO reconstruction by Cook *et al*. 2002. Significant relationship indicated by *.

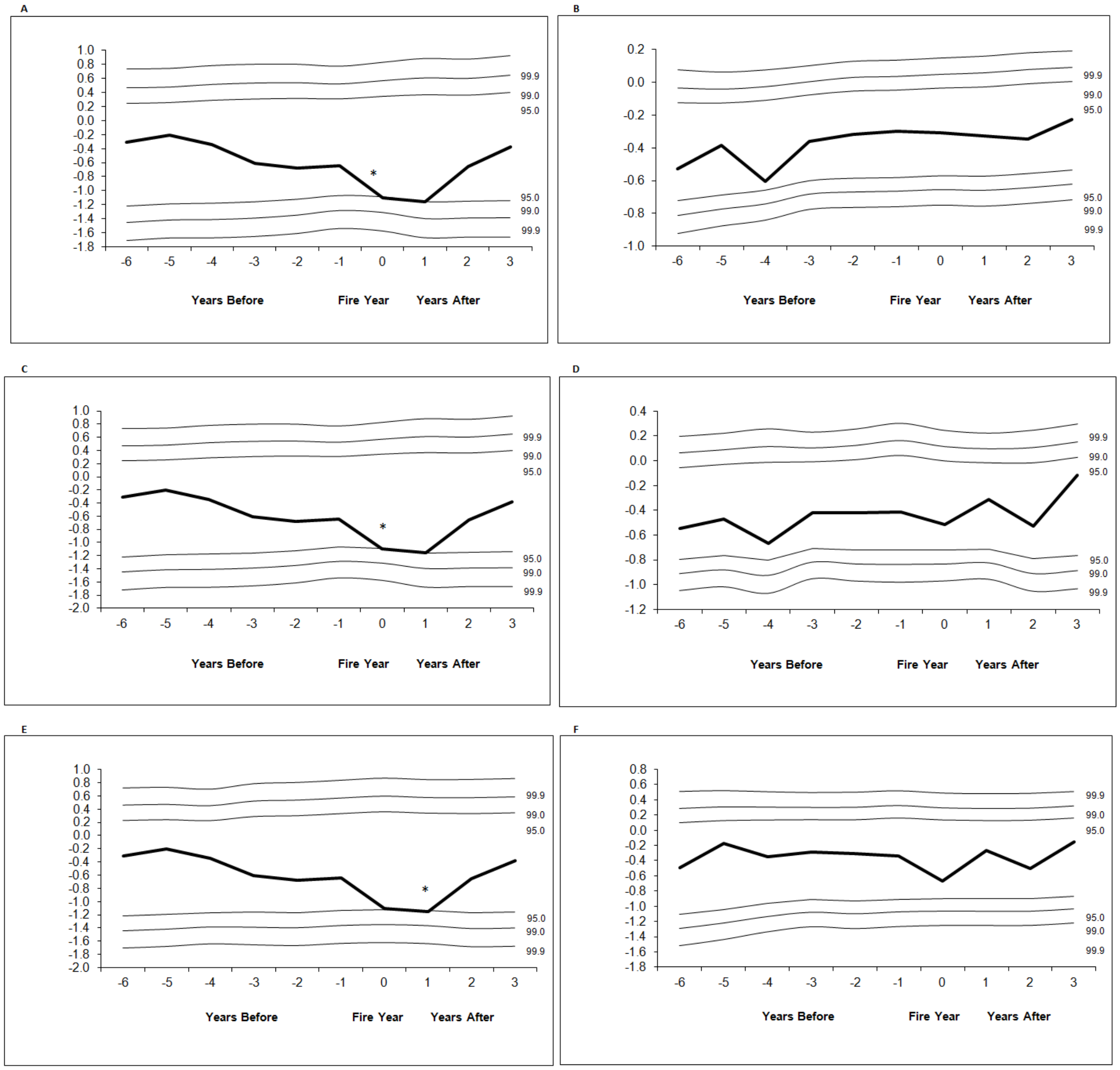

**Figure 5.7**: Superposed Epoch Analysis of Rabbit Creek Trail fires and Northern Hemisphere Temperatures. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NHD1 reconstruction by Briffa *et al*. 1998. Significant relationship indicated by *.

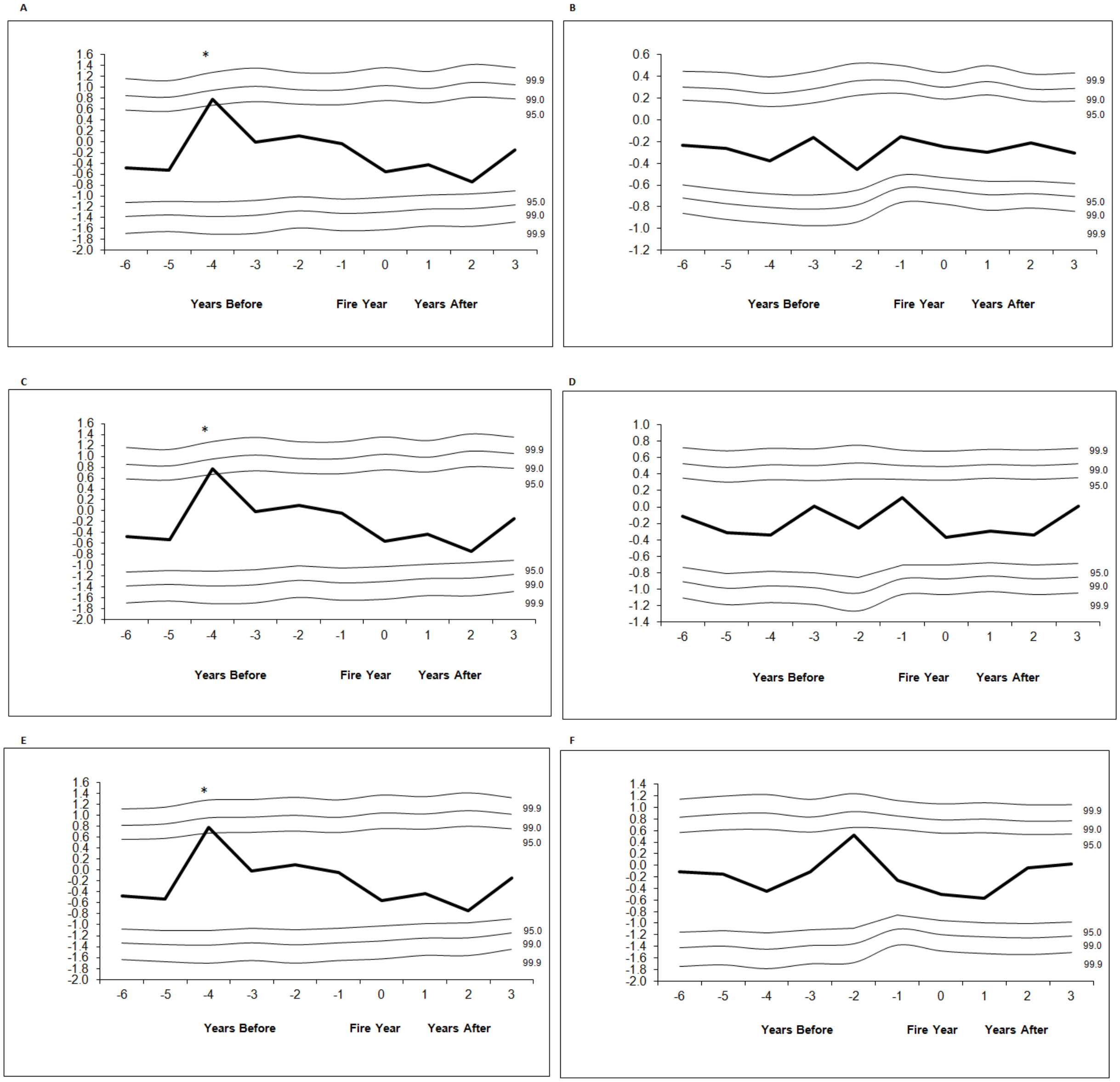

**Figure 5.8**: Superposed Epoch Analysis of Rabbit Creek Trail fires and Palmer Drought Severity Index. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. PDSI reconstruction by Cook et *al*. 2004. Significant relationship indicated by *.

### 5.5.4 *Pine Mountain (PMT)*

#### 5.5.4.1 *Correlation Analyses*

The chronology for the Full Period at Pine Mountain was significantly correlated only with PDSI ($r = 0.27$, $P < 0.001$) (Table 5.2). NHTMP was significantly correlated with both the Pre-settlement Period ($r= -0.23$, $P < 0.05$) and Settlement Period ($r = 0.25$, $P < 0.05$); however, the relationship reversed signs between the periods, first negative, then positive. PDSI was positively correlated with the Settlement Period ($r = 0.26$, $P < 0.01$). For PMT fire frequency during the Full Period, no climate variables were significantly related (Table 5.3). In the Pre-settlement Period, AMO showed a strong negative association with fire frequency ($r = -0.43$, $P < 0.001$). There were no significant relationships in the Settlement Period for fire frequency.

#### 5.5.4.2 *Superposed Epoch Analyses*

Wildfires at PMT showed an interesting sloped and negative relationship with AMO (–6 years through 0) (Figure 5.9), while PDSI was significant one year after the fire during the Pre-settlement Period (Figure 5.10). NIÑO-3 had a strong positive peak at –1 years, but it was not statistically significant. In the Settlement Period, the fire year was negatively related to NAO, significantly so in the 10%-scarred class (Figure 5.11). NHTMP showed somewhat confusing negative and positive associations 3 and 4 years prior to the fire event in the 10%- and 25%-scarred classes (Figure 5.12). Fire events at PMT appeared unrelated to the PDO.

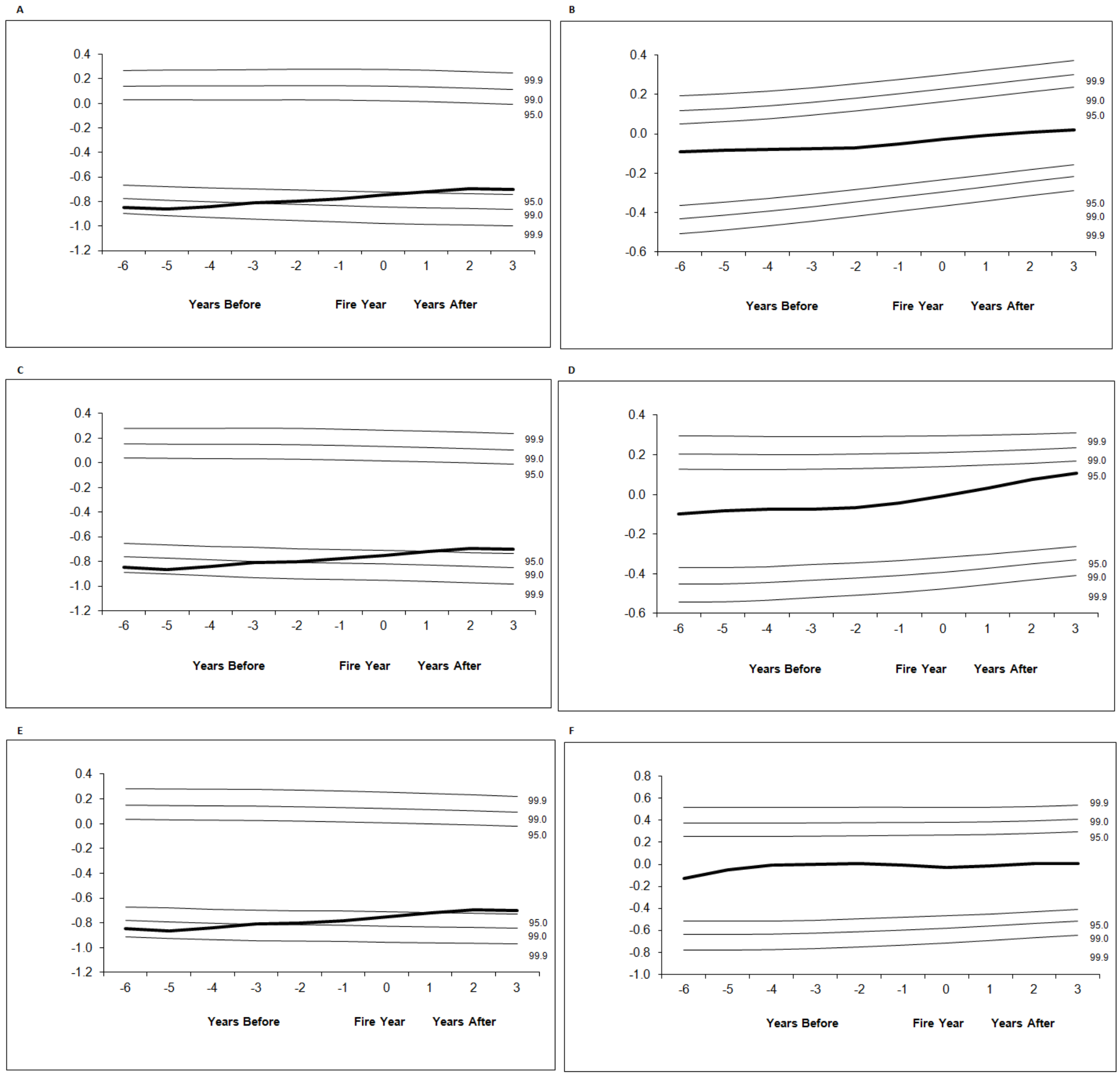

**Figure 5.9**: Superposed Epoch Analysis of Pine Mountain fires and Atlantic Multidecadal Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. AMO reconstruction by Gray *et al*. 2004. During the Pre-Settlement Period, 6 years prior through the event year were significantly (negatively) related to wildfire occurrence for all classes.

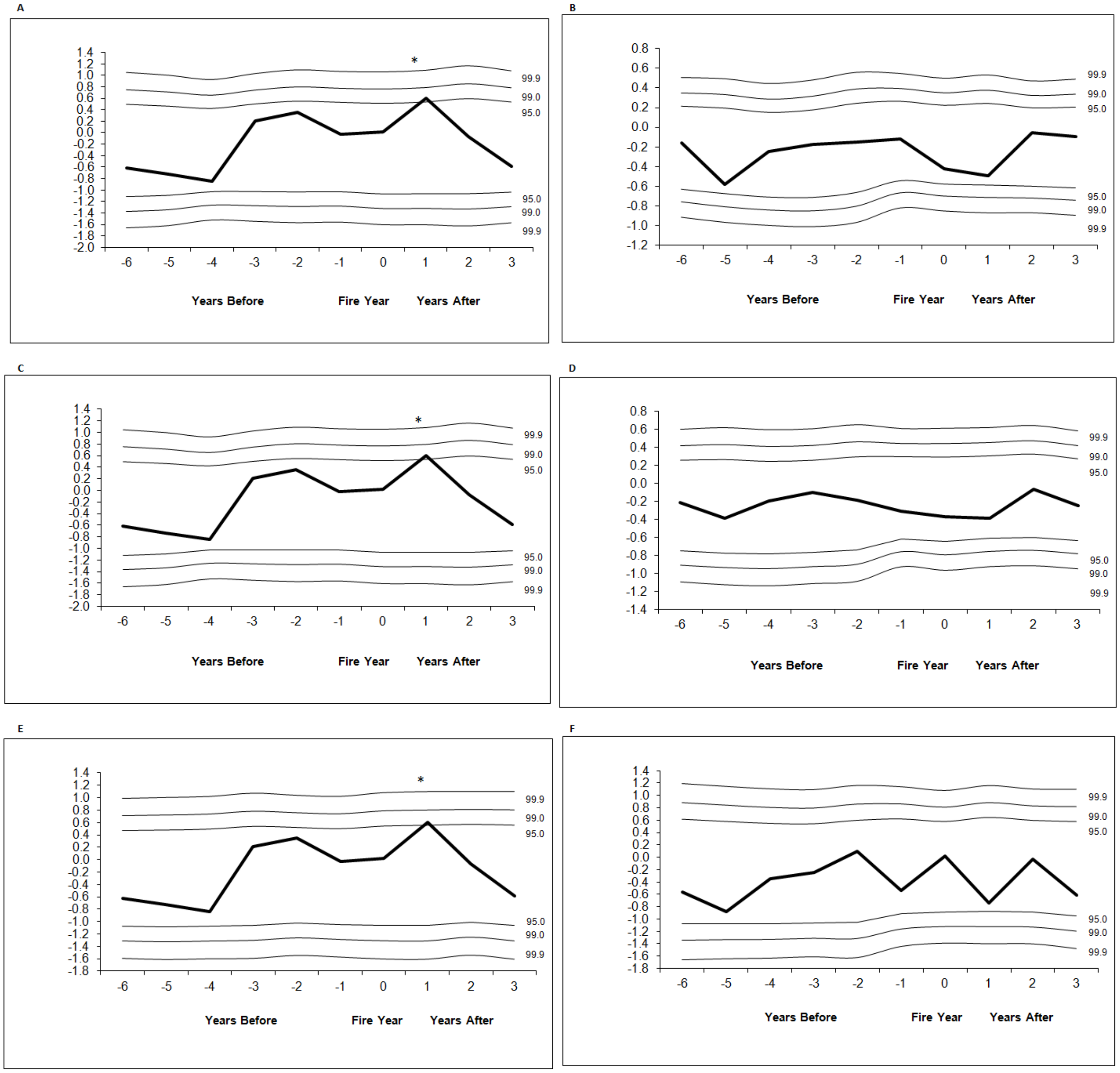

**Figure 5.10**: Superposed Epoch Analysis of Pine Mountain fires and Palmer Drought Severity Index. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period, Dark line is mean value of the climate variable at each year prior, during, and after the fire. PDSI reconstruction by Cook et *al*. 2004. Significant relationship indicated by *.

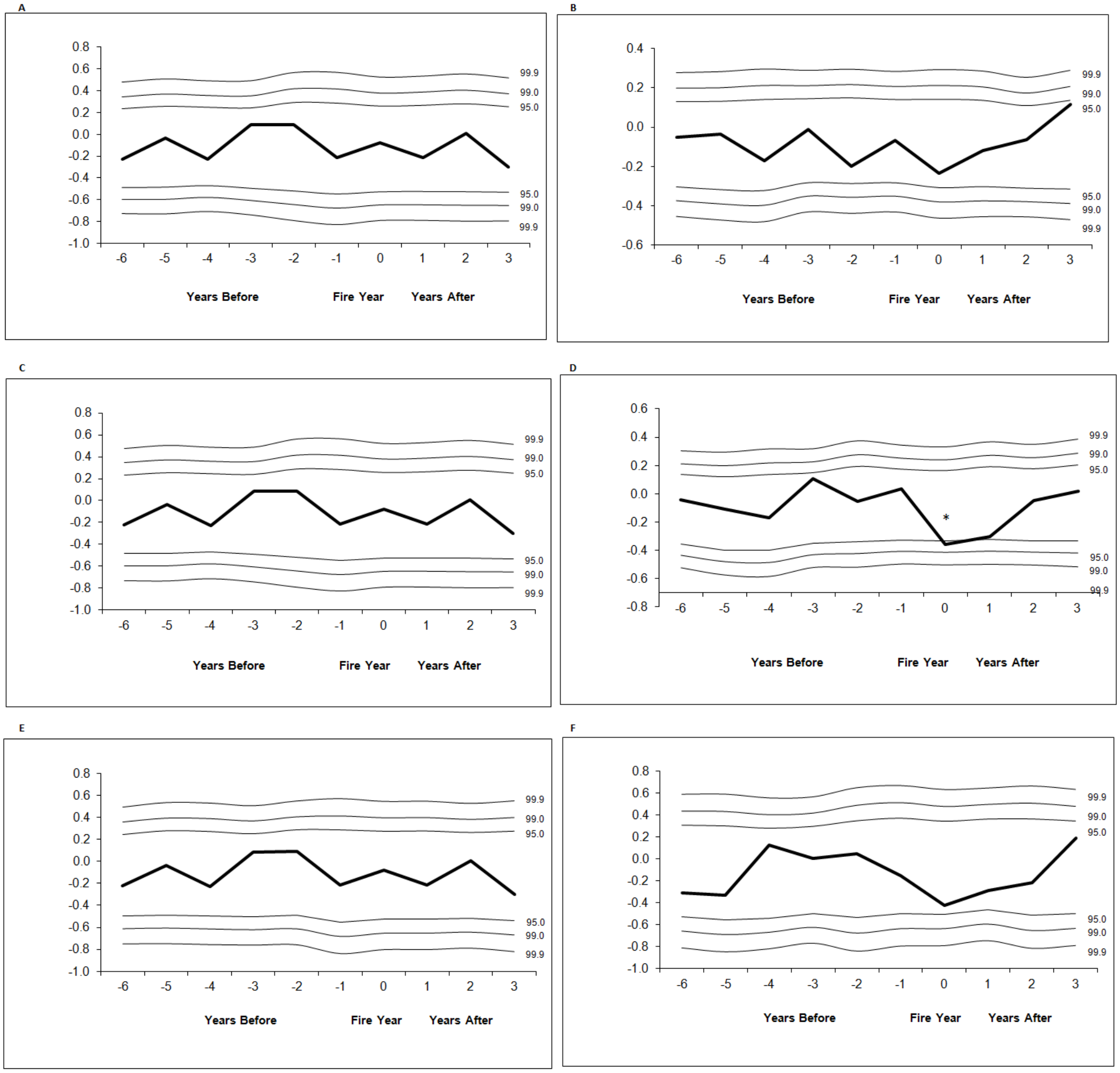

**Figure 5.11**: Superposed Epoch Analysis of Pine Mountain fires and North Atlantic Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NAO reconstruction by Cook *et al*. 2002. Significant relationship indicated by *.

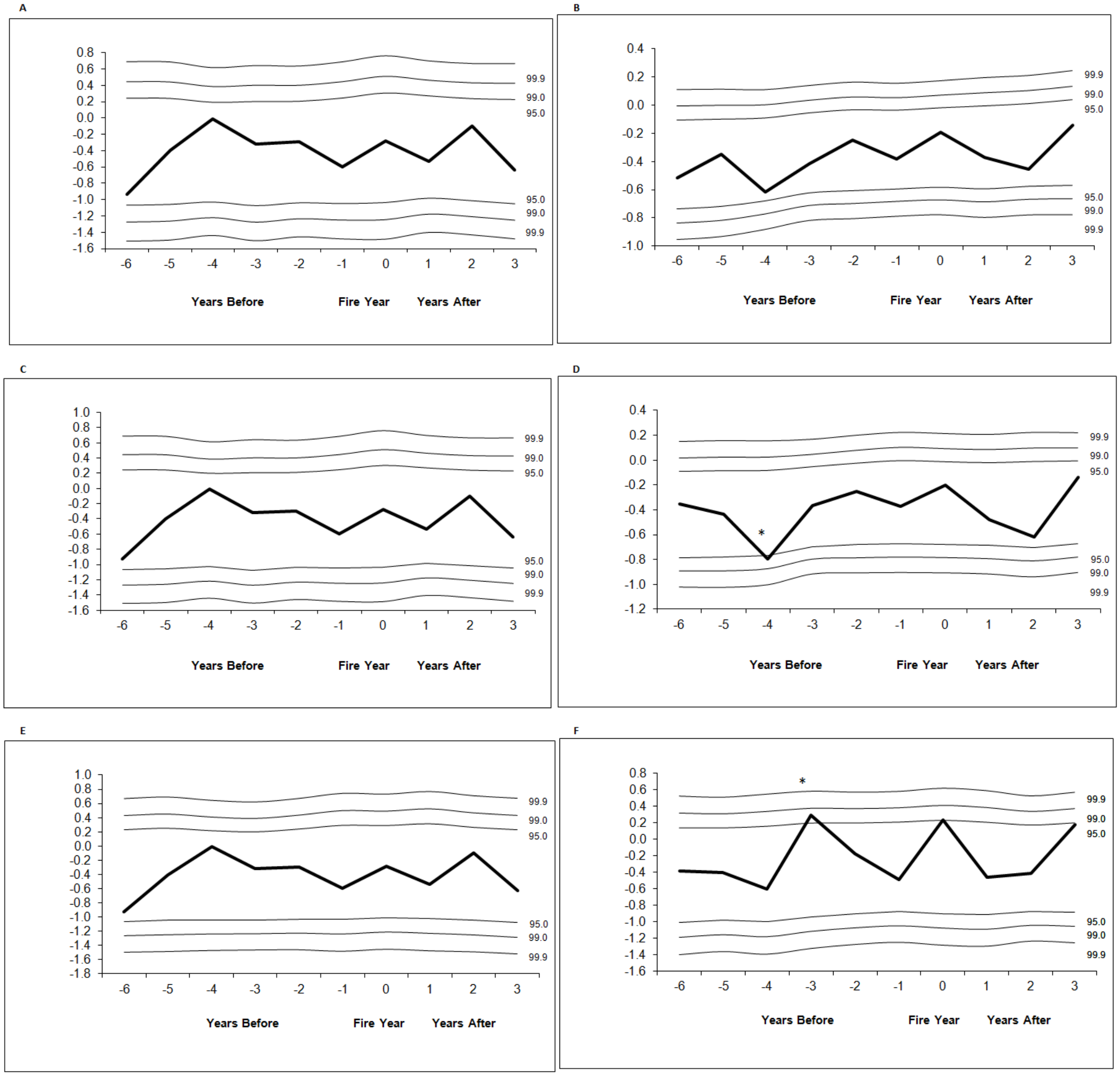

**Figure 5.12**: Superposed Epoch Analysis of Pine Mountain fires and Northern Hemisphere Temperatures. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NHD1 reconstruction by Briffa *et al*. 1998. Significant relationship indicated by *.

### 5.5.5 *Regional (ALL)*

#### 5.5.5.1 ***Correlation Analyses***

The Full Period chronology for the regional data set was positively correlated with NHTMP ($r = 0.15$, $P < 0.05$), NAO ($r = 0.18$, $P < 0.01$), and PDSI ($r = 0.26$, $P < 0.001$) (Table 5.2). Only PDSI was significant for the Pre-settlement Period ($r = 0.23$, $P < 0.01$). During the Settlement Period, NHTMP ($r = 0.20$, $P < 0.05$), NAO ($r = 0.24$, $P < 0.05$) and PDSI ($r = 0.27$, $P < 0.01$) were significantly correlated.

#### 5.5.5.2 ***Superposed Epoch Analyses***

During the Pre-settlement Period, regional fires were significantly related to NAO and NIÑO-3. NAO had a positive association 3 years prior to fire events (Figure 5.13). NIÑO-3 was positively associated for both 1 year and 5 years prior, and negatively so 1 year after the event (Figure 5.14). Positive relationships for AMO (–1 year) (Figure 5.15) and PDSI (–2 years) (Figure 5.16) were present in the Settlement Period for the 25%-scarred class. Fire events in the regional data set appeared unrelated to either NHTMP or PDO.

## 5.6 Discussion

Both temporal and site-specific response differences were found in the relationships between pine growth, wildfire frequency and occurrence, and the selected climate variables. Climate during the Pre-settlement Period (1700–1834) appeared to have a greater influence on both wildfire frequency and wildfire occurrence. Growth was more strongly tied with climate during the Settlement Period (1835–1934). The temperature and precipitation

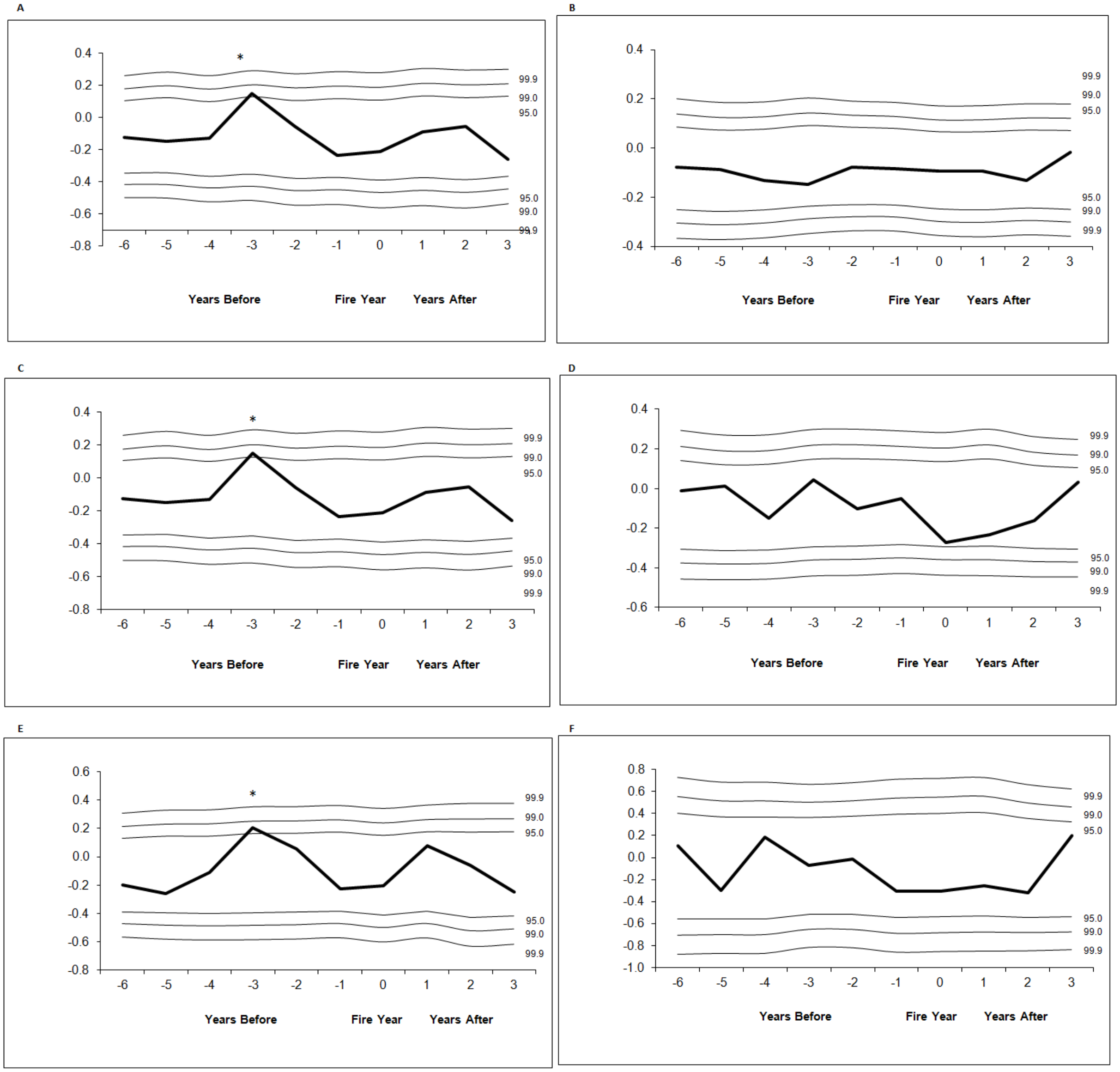

**Figure 5.13**: Superposed Epoch Analysis of Regional fires and North Atlantic Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NAO reconstruction by Cook *et al*. 2002. Significant relationship indicated by *.

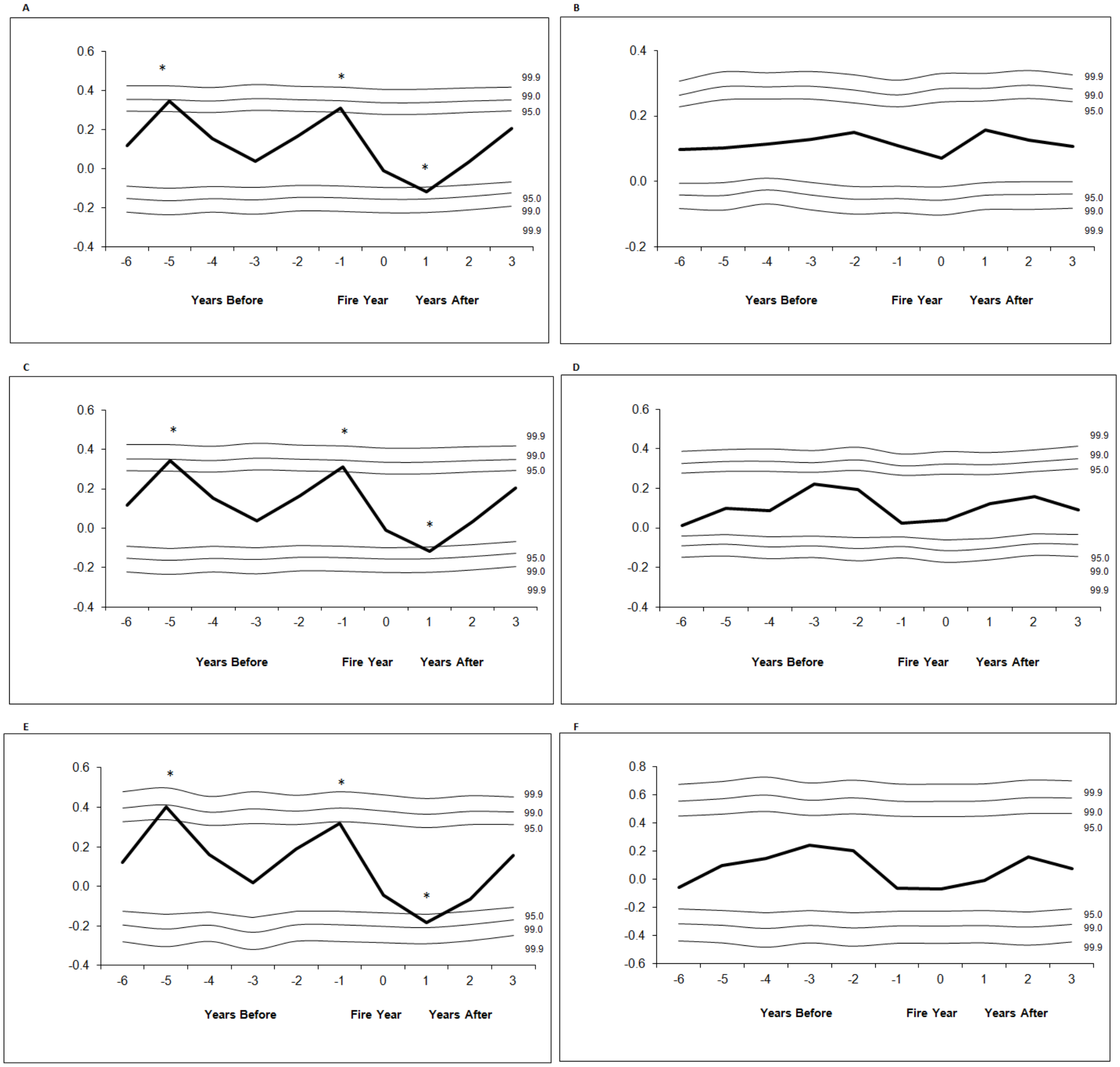

**Figure 5.14**: Superposed Epoch Analysis of Regional fires and El Niño-Southern Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NIÑO-3 reconstruction by Cook 2000. Significant relationship indicated by *.

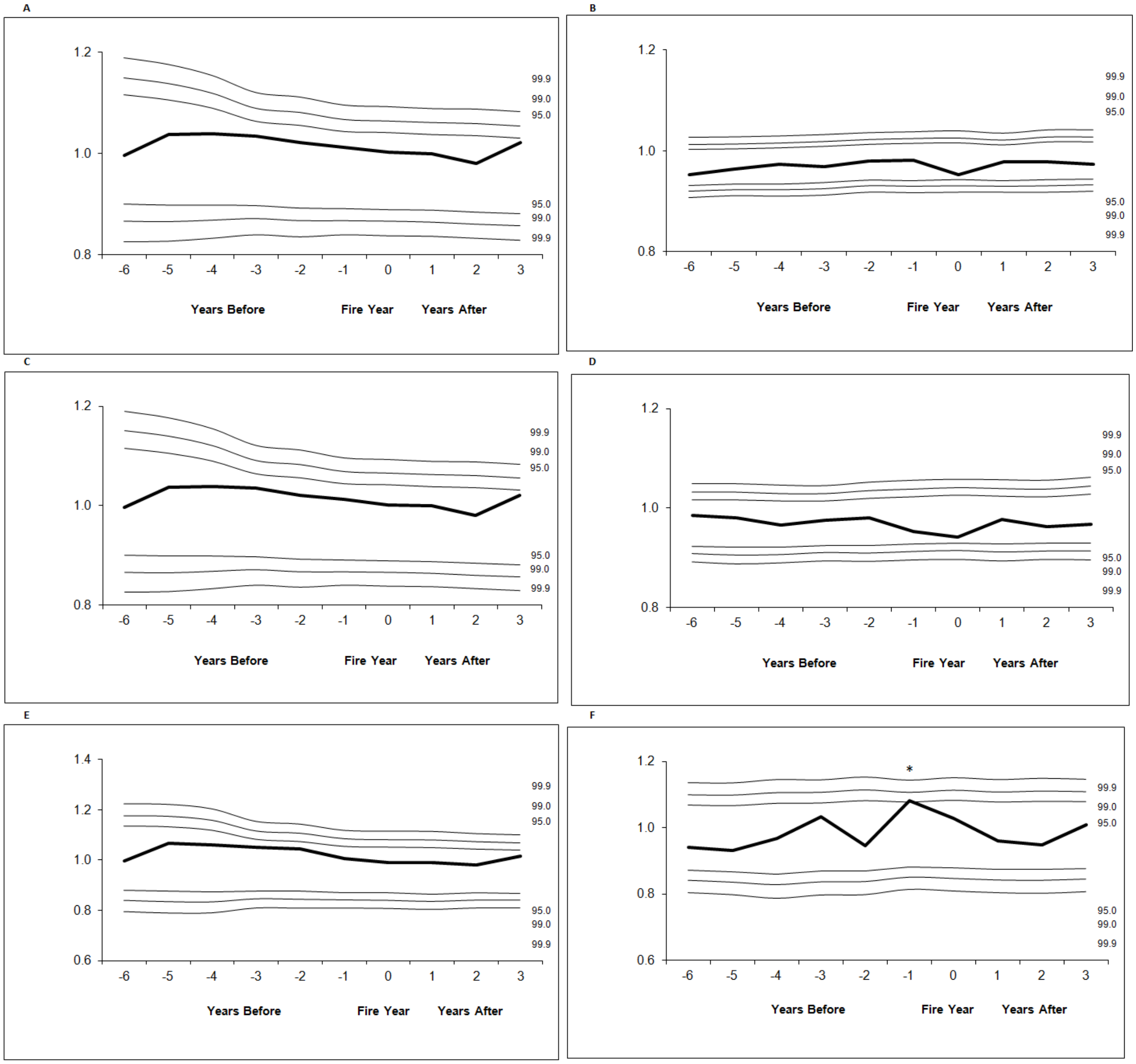

**Figure 5.15**: Superposed Epoch Analysis of Regional fires and Atlantic Multidecadal Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. AMO reconstruction by Gray *et al*. 2004. Significant relationship indicated by *.

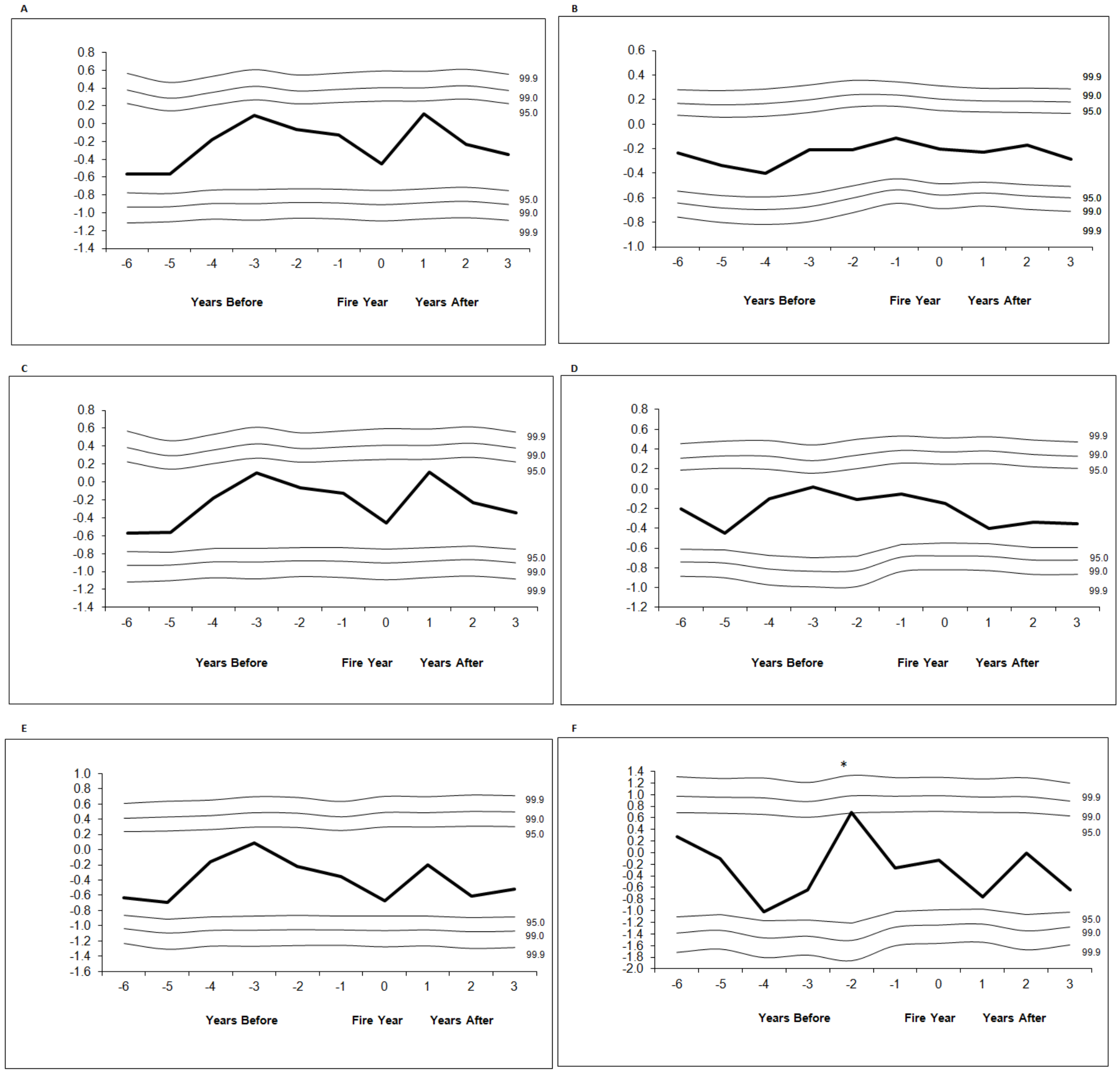

**Figure 5.16**: Superposed Epoch Analysis of Regional fires and Palmer Drought Severity Index. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. PDSI reconstruction by Cook et *al*. 2004. Significant relationship indicated by *.

records for East Tennessee only go back to 1895, so relationships of temperature and precipitation with wildfire were determined through the intermediary of reconstructed climate variables.

The Atlantic Multidecadal Oscillation (AMO) was significantly correlated only with July temperatures, and had no significant relationship with precipitation in any month. Cool phase AMO has been associated with an increase in precipitation over the southern Appalachian Mountains (Enfield *et al*. 2001, Tootle *et al*. 2005), but it did not correlate significantly with total monthly precipitation for East Tennessee in this study. My analysis indicated that the cool phase is associated with cooler summer temperatures. Radial growth of trees at Rabbit Creek Trail was negatively correlated with AMO during the Pre-settlement Period, as was the 10-year fire frequency. This suggests that both tree growth and fire frequency increased prior to 1834 during the cool (negative) phase of AMO. However, it seems counterintuitive that fire frequency would increase with cooler temperatures and more precipitation, unless humans were taking advantage of desirable environmental conditions to ignite fires that would be less likely to burn uncontrolled. It could also be that higher precipitation levels were associated with increased storm activity. Fire frequency at Pine Mountain was also strongly and negatively correlated during the Pre-settlement Period. There was a negative association at GMT, but it was not statistically significant. The relationship between AMO and fire frequency reversed at GMT and RCT during the Settlement Period (1835–1934), suggesting that at that time, warm phase AMO (drier, warmer) was connected to increased fire frequency.

The AMO experienced a phase shift from a negative (cool) trend to a positive (warm) trend around 1834 which could account for the change in the relationship between periods. Also, the southern Appalachian Mountains are very close to a boundary over which the AMO has been shown to have opposite effects (Enfield et al. 2001). The boundary may shift over time, which could lead to different results. In the Settlement Period, AMO was positively correlated with widespread (25%-scarred) fires for the study region (ALL) one year prior to the fire event. During the Pre-settlement Period, the AMO index values for the year prior to each 25%-scarred class fire were all negative, whereas most of the index values in the Settlement Period were positive. This indicates that more widespread fires during the Pre-settlement Period were preconditioned by cooler, moister conditions the year before the fire event, but this reversed during the Settlement Period. Further analysis is required to determine if cool- and warm-phase AMO were consistently associated with the same temperature and precipitation trends over time.

The North Atlantic Oscillation (NAO) was primarily associated with warmer winter temperatures and more weakly so with May and October precipitation. The NAO was positively related to growth during the Settlement Period and Full Period at GMT, RCT, and for the regional study area (ALL). NAO was not correlated with fire frequency at any site. It was, however, related to fire event years. All fire classes during the Pre-settlement Period at Rabbit Creek Trail were negatively correlated with NAO five years prior to the fire year. This suggests that cold and dry winters were associated with fire several years later. When the sites were combined into the regional dataset, I observed a positive correlation three years prior during the Pre-settlement Period. This suggests that prior to 1834, warmer, wetter winters preconditioned both small and more-widespread wildfires within a few years before the fire event.

The El Niño-Southern Oscillation was most strongly linked with August precipitation. It was also positively correlated with July temperatures, which is in line with other research findings (Allan and D'Arrigo 1999). It was negatively correlated, however, with winter (January–February) precipitation, unlike other areas of the southern U.S., indicating that Gulf moisture carried by storms did not reach the study area (CPC 2010). In summary, during El Niño years in East Tennessee, summer temperatures and precipitation increase, while winter temperatures and precipitation decrease. ENSO was not associated with radial growth at any site. Fire frequency at GMT was positively correlated, although weakly, with ENSO over the Full Period. During the Pre-settlement Period, ENSO was positively correlated with fires one year and five years prior to the event for the regional dataset (ALL). The individual sites displayed the same pattern, but the results were not significant. Gold Mine Trail was negatively correlated to ENSO during the fire event year. This would correspond to the warmer and drier conditions that are typically associated with La Niña (negative phase) conditions, but not with the results from the correlation analysis in this study. Again, the study area is close to a boundary line across which ENSO may have a different influence on local conditions. I found no significant relationships between fire events and ENSO during the European Settler Period and Full Period in the superposed epoch analyses for any site.

The Pacific Decadal Oscillation (PDO) was significantly and negatively correlated only with March precipitation. This negative relationship is contrary to the general increase in precipitation for warm phase PDO (positive) in the southeastern U.S. during winter months. This may, again, derive from a boundary effect as is suspected with ENSO. We found no association between PDO and radial growth at any site. For fire frequency, only the GMT Full Period was positively correlated to PDO. This suggests that more fires occurred at Gold Mine Trail between 1697 and 2006 when PDO effects increased and March precipitation decreased. This makes sense as many of the fires were early season at the study site (Chapter 4). Dry fuels that remained from the previous fall would feed spring season fires. In the superposed epoch analysis, only Gold Mine Trail had a significant relationship (positive) between fire events and PDO (–2 and –3 years) in the Pre-settlement Period. This suggests that drier springs in the years prior to the wildfire promote the event. The Gold Mine Trail site has several small streams running through it and appears to be more mesic than the other two sites. Perhaps drier spring seasons would have more of an influence on conditions there as the moisture-dependent vegetation dried up and provided fine fuel for fires.

Northern hemisphere temperatures were strongly correlated with June temperature in East Tennessee and slightly less so with February temperature. We found no correlation, however, between NHTMP and precipitation. During the Pre-settlement Period, pine growth at Pine Mountain was negatively correlated with NHTMP. In the Settlement Period, PMT and regional growth (ALL) both showed a positive relationship with NHTMP. The regional dataset was also positively correlated with NHTMP over the Full Period, as was Gold Mine Trail. These patterns imply that cooler temperatures enhanced growth during the Pre-settlement Period, while warmer temperatures enhanced growth during the Settlement Period and the Full Period, in general. These seemingly contradictory results could be from the relationship of NHTMP with both winter (February) and summer (June) temperatures. Perhaps summer temperatures were cooler in the Pre-settlement Period and winter temperatures were warmer in the Settlement Period, conditions that would enhance yellow pine growth (Chapter 3).

Fire frequency at Gold Mine Trail was positively correlated with NHTMP during the Pre-settlement Period. Warmer temperatures were linked with increased fire activity at the site, or conversely, cooler temperatures were linked with fewer fires. In the superposed epoch analysis, Gold Mine Trail had a strong (but not significant) positive peak at the event year that linked higher temperatures with wildfire years. RCT was negatively correlated with NHTMP during wildfire years. Perhaps this is an anthropogenic artifact as RCT was the closest site to a river valley where human habitation and activity was likely. At Pine Mountain, years prior to burn were negatively associated with NHTMP for the 10%-scarred class and positively associated with NHTMP in the 25%-scarred class, both during the Settlement Period. Now-abandoned home sites were known to be in relatively close proximity to PMT, so the human activity also may have affected these results.

Drought (PDSI) was positively correlated with March temperatures, and negatively correlated with May through September temperatures. For precipitation, PDSI was positively correlated in February, March, May, and June. Growth of pines was strongly tied to drought across the study area, especially in the Full Period analysis for each site. This suggests that warmer, wetter late-winter months (February–March) and cooler, wetter summers promote increased yellow pine growth. Drought was not correlated with fire frequency at any site; however, while neither PDSI nor NAO were significantly related to fire frequency independently, perhaps interactions between the two influenced the fire regime during the Settlement Period. The Gold Mine Trail standard chronology, which was primarily associated with NAO and PDSI during that period, was negatively correlated with GMT fire frequency (warmer summers, more fires). In the superposed epoch analysis, a strong negative (but not significant) association with PDSI was evident for wildfire years at GMT. This supports the connection between dry or droughty conditions at the site with fires. Wildfires of all classes at RCT were positively associated with PDSI four years prior to the event during the Pre-settlement Period. During the Settlement Period, only the regional (ALL) 25%-scarred class was significant (–2 years, positive). These results suggest preconditioning as positive PDSI values denote wetter conditions.

### 5.7 Conclusions

Broad-scale climate phenomena influence both East Tennessee climate conditions and wildfires in Great Smoky Mountains National Park. The Atlantic oscillations (AMO and NAO) were more influential on temperature in East Tennessee than the other tested variables, while ENSO influenced precipitation. Further analysis should be conducted to see if this holds true when the data are divided between the Pre-settlement Period (1697–1834) and the Settlement Period (1835–1934). This could be done with simple correlations for a broad idea of the relationships, or with moving correlation analysis to obtain a clearer view of the changing relationships over time. The AMO is also the oscillation most related to fire frequency in GSMNP, especially during the Pre-settlement Period. The El Niño-Southern Oscillation displayed the most consistent superposed epoch results for all the study sites, indicating that fire events are more likely to occur when preceded by wetter conditions in the years prior to a wildfire followed by drier conditions in the event year. The response of fire to the various climate factors was much more evident in the Pre-settlement Period than in the Settlement Period. Anthropogenic influences could have overridden the signal in the latter. Nonetheless, climate (primarily precipitation) is still strongly related to fire occurrence as evidenced by the seasonal patterns, and drought influences fire probability and severity. Interactions between climate oscillations can also modify the environmental conditions of an area. For example, when PDO and AMO indices are both negative, East Tennessee experiences the highest drought frequency (for the oscillation combination), and the region experiences the fewest droughts when both indices are positive (McCabe *et al*. 2008). Additional interaction analyses should be explored. Global climate models predict that the number of droughts in eastern North American will double by the end of the century, and that their intensity will increase (Sheffield and Wood 2008). In light of irrefutable climate change, research should be continued to enhance our understanding of relationships between droughts, wildfires, and other associated climate factors.

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# CHAPTER 6

# CONCLUSIONS

The purpose of this study was to reconstruct and evaluate the wildfire-related disturbance history of lower-elevation xeric pine and pine-oak stands in Great Smoky Mountains National Park, Tennessee. Specifically, this study developed multi-century yellow pine tree-ring chronologies, reconstructed the historic fire regime, surveyed stand composition and age structure, and elucidated climate influences on yellow pine radial growth and wildfire occurrence. This chapter summarizes the major conclusions and findings of this research.

## 6.1 Yellow Pine Radial Growth

***1. The strong climate response in yellow pines indicates they can provide multi-century records of past climate.***

The Gold Mine Trail chronology spanned 310 years (1697–2006) and is one of the longest yellow pine chronologies generated so far for GSMNP. Somewhat shorter chronologies were created for Rabbit Creek Trail (229 years) and Pine Mountain (265 years), but these lengths are very good for the southeastern U.S. where most forestland was cut over during the past century. The interseries correlations of the site chronologies ranged from 0.51 to 0.54, exceeding the minimum target of 0.40, which indicates accurate crossdating and a response by the trees to a common climate signal (Grissino Mayer 2001). A value of 0.50 is considered high for southeastern U.S. yellow pine species. The average mean sensitivity ranged from 0.27 to 0.28

indicating an intermediate level of year-to-year variability within the tree-ring series. Series having values above 0.30 are considered sensitive to climate (Grissino-Mayer 2001). Other yellow pine chronologies constructed in the region displayed comparable interseries correlation and average mean sensitivity values (Biermann 2009, Li 2011). Common wide and narrow marker rings were found for the same years across all sites demonstrating the common climate signal response, but I observed some variability between sites.

Prior to standardization, first-order autocorrelation values for the site chronologies ranged from 0.68 to 0.74. These values are typical for pine trees growing on moderate sites, and indicate a strong relationship between the current-year radial growth and the prior-year environmental conditions. After filtering, the autocorrelation of the site chronologies averaged near zero. Of the four yellow pine species used in our chronologies, shortleaf pine provided the most clearly-defined rings, the best crossdating, and the longest series; however, availability of living shortleaf pines to sample in the study area was somewhat limited, especially at Rabbit Creek Trail where Virginia pines were dominant.

### *2. Winter temperatures strongly influence yellow pine growth.*

Yellow pine growth at all sites and for the regional chronology was significantly and positively correlated to January temperatures (instrumental data, 1940–2007). Gold Mine Trail was the most responsive ($r = 0.47$, $P < 0.001$), and was also the only individual site that showed a significant correlation to February temperatures ($r = 0.40$, $P < 0.001$). When temperatures for both January and February were merged into one variable (Jan-Feb), correlations with growth at all sites were significant, and the strength of the response was greater for the combined variable than for any individual month. Warmer winters prior to the growing season may have allowed pines to initiate cambial growth earlier in the year and to grow for a longer period. Conversely, cold winters could have delayed growth while the tree continued to use up nutrients for basic maintenance and metabolic processes. Also, cold soil temperatures in winter may have inhibited pine photosynthesis and growth through limiting water uptake by roots (Rundel and Yoder 1998, Jurik *et al*. 1988). A similar winter-month correlation pattern was found in other studies of yellow pine growth within the park (Grissino-Mayer *et al*. 2007, Biermann 2009).

Li (2011) found that during the middle of the 20th century, yellow pine growth response in Tennessee and North Carolina tended to shift away from a precipitation signal toward a temperature signal. My chronologies were analyzed against more recent instrumental data (1940–2007) because data collected prior to 1940 tends to be less accurate. Even though there may be a risk of diminished data quality, it would be useful to follow up this research with monthly and seasonal temperature and precipitation analyses with yellow pine growth for 1895–1939 to determine if a change in climate signal strength occurred at my study sites.

### ***3. Winter North Atlantic Oscillation conditions strongly influence winter temperatures in East Tennessee and affect yellow pine growth.***

Instrumental NAO values (1950–2006) were significantly and positively correlated with January yellow pine growth at all study sites. February growth was also positively correlated, but only significantly at Gold Mine Trail and for the regional chronology. The combined Jan-Feb variable had the strongest relationship and was significant for all four chronologies (ALL, $r = 0.43$, $P < 0.01$). Reconstructed NAO data (Cook *et al*. 2002) strongly correlated with East Tennessee winter temperature data from 1895 to 2006 (January $r = 0.28$, $P < 0.05$, February $r = 0.37$, $P < 0.001$, and March $r = 0.44$, $P < 0.001$). When the chronologies were divided into three periods for analysis (Pre-Settlement Period = 1697–1834, Settlement Period = 1835–1934, Full Period = 1697–2006), relationships between yellow pine growth and reconstructed NAO varied between the periods and between the sites. Gold Mine Trail, Rabbit Creek Trail, and the regional chronology were all significantly related to NAO in the Settlement Period and in the Full Period. The NAO has been unusually strong during the 20th century (Cook *et al.* 2002), which may explain the significance of the relationship during the Settlement and Full Periods.

## 6.2 Wildfire History

### *1. Wildfire was historically a frequent event on the landscape*

Wildfires frequently occurred in the western portion of GSMNP throughout the 1700s and into the early 1900s. Most of the fires recorded at the sites were localized and likely low-severity; however, a few were widespread and of moderate severity. Frequent fire occurrence would have kept small woody fuels, such as dried leaves and branches, from accumulating on the forest floor, minimizing the occurrence of higher-severity fires. While there were no common widespread fire event years between the three sites, they exhibited similar overall patterns of fire frequency. Wildfire occurrence averaged one to three years, primarily during the dormant or early-growing season, and most likely originated from Native Americans

(Cherokee) and European settlers starting fires to clear underbrush and to promote grasses in early spring (Pierce 2000). In contrast, many of the widespread fires burned during the middle of the growing season and probably originated from lightning strikes during summer storms (Harmon 1981). Widespread fires occurred about every five to seven years. Fire occurrence sharply declined after park establishment in 1934 and during enforcement of suppression policies.

### *2. Changes in temporal patterns were present in the wildfire record*

The fire record was divided into three periods: Pre-settlement (~1700–1834), European Settlement (1835–1934), and Post-suppression (1935–2007). At all sites, fire frequency was relatively low during the Pre-settlement Period, peaked during the European Settlement Period, and then decreased during the Suppression Period. Pre-settlement Period fires burned on average every six to twelve years, and were primarily in the dormant or early-growing season. Wildfires burned once every two years during the European Settlement Period, but most still occurred in the dormant or early-growing season. More widespread fires, however, tended to burn in the middle of the growing season, indicating that they may have originated from lightning strikes during summer storms. After the Suppression Period began, the average return interval was six to eight years; however, a higher proportion of fires occurred late in the growing season. Late-season wildfires were likely ignited by humans because anthropogenic fires peak in the fall (Harmon 1981). Active suppression of fires would have kept them localized. These findings imply that the current fire regime is similar to that during Cherokee occupation, but with a seasonal shift, suggesting an anthropogenic influence.

### 6.3 Age Structure and Stand Composition

#### *1.* The age structure of stands corresponds to widespread fire events

Through the 1800s, establishment of oaks and yellow pines was relatively low but consistent across the decades at each site. Establishment of shortleaf pine and oak cohorts was most likely related to moderate-severity fire events occurring within the study area. A pulse of establishment in the 1860s was evident at Gold Mine Trail; almost half (40%) of the yellow pines at the site established during that decade. Few of the yellow pines were recording fires during that time, but three of seven recorder trees showed a fire in 1860. At GMT, the last widespread wildfire (and the largest at the site) occurred in 1929. Many oaks and mixed-hardwoods established immediately following the event; however, because of the temporal proximity of the fire to suppression, it is difficult to fully connect the establishment with the 1929 fire event.

Establishment pulses that followed fire suppression at both Rabbit Creek Trail and Pine Mountain included more fire-intolerant species, such as eastern white pine and eastern hemlock, whereas at GMT, those species established at least a decade later. The most widespread fire at RCT (n = 5) occurred in 1894. A large cluster of oaks in the macroplots established around the same time, as did six of the yellow pines used in the fire history, likely in response to the fire. At Pine Mountain, the majority of recorder trees (n = 20) showed a widespread fire in 1910. Other notable fires at PMT occurred in 1892, 1900, and 1922. Oak establishment drastically increased around 1920, possibly in relation to the 1910 and 1922 wildfires. Other fires that were recorded in five or more trees at PMT occurred in 1916 and 1936, which could explain the continuance of higher levels of oak establishment until about 1940. A large cluster of yellow pine establishment also occurred between 1930 and 1945 at the site.

The majority of canopy tree establishment occurred after 1930 at all three sites, placing most of the trees in the stands at less than 80 years old. The park was established in 1934 and fire suppression policy was being enforced by that time. It was not until the 1970s that park personnel allowed a lightning fire to burn, while being managed, to encourage a change in policy. They were successful in the 1990s with the enactment of the Wildland Fire Use plan. The WFU plan allows wildfires that are away from the park boundary, and within certain parameters, to continue burning until naturally extinguished (National Park Service 2010). Between 1930 and 2007, very few fires were recorded at the sites (GMT=6, RCT=8, and PMT=7). Approximately 70% of the canopy-class trees established during that period. The surveyed stands were crowded with saplings and smaller canopy-class trees.

### *2. The current stand composition corresponds to fire suppression effects*

A lack of fire on the landscape allowed for the growth of fire-intolerant tree species. Shade-tolerant species also flourished as stands become more crowded and closed. The most dominant canopy-class species across the study area was eastern white pine. Other species with high importance values for the combined study area included blackgum, chestnut oak, red maple, and eastern hemlock. Sourwood was important at Gold Mine Trail, as was white oak.

Red maples, eastern white pine, eastern hemlock, blackgum, and sourwood are all shade-tolerant, fire-intolerant species (Vose 2003). Seedling and sapling counts of red maple were high at each site. Eastern white pine seedling and sapling counts were also high at Rabbit Creek Trail, but were moderate at Gold Mine Trail and Pine Mountain. Pioneer species, such as these, are known to have high rates of seed production and germination, and many do not reach maturity. Even so, eastern white pine and red maple will likely maintain a strong presence in the stands for many years, if not decades. Gold Mine Trail showed moderate sapling counts for five other hardwood species; however, seedling regeneration was primarily limited to scarlet oak at GMT and also at RCT. Scarlet oak has the shortest average lifespan of the oaks (80 years; Virginia Big Tree Program 2008). Pine Mountain had low to moderate levels of oak regeneration for four species.

### 3. *Yellow pine regeneration is not favored under current conditions.*

Four species of yellow pine were found in the study area: shortleaf pine, pitch pine, Virginia pine, and Table Mountain pine (uncommon). The oldest living shortleaf pine on record (GMX307, 324 years) was found on the Gold Mine Trail site. The peak of shortleaf pine establishment occurred in the 1860s. Many Virginia pines established during the 1900s, especially in the 1930s, and primarily at Rabbit Creek Trail. Regeneration since 1970 was virtually nonexistent. Only a few Virginia pine saplings were documented at each site. Gold Mine Trail and Pine Mountain had a few pitch pine or shortleaf pine saplings, but not enough to maintain a foothold for the species in the competitive, shady environment. Numerous mature yellow pines on the sites were killed in the last decade by bark beetles. Wind and storms brought down large numbers of trees during the course of this study. A tornado that crossed the western portion of GSMNP in April 2011 likely felled many more, especially near the PMT site which was close to the path. Resprouting and germinating hardwoods will probably out-compete any sprouting yellow pines in the disturbed zone. Any remaining standing yellow pines are at risk, and their loss would further reduce a major seed source for any potential yellow pine regeneration. Duff depths at the sites averaged 5 cm, which is too thick to allow for adequate germination and successful regeneration of yellow pine (Jenkins *et al.* 2011).

### 6.4 Climate Influence on Wildfire

#### *1. Both Atlantic and Pacific oscillations regulate wildfire frequency.*

The Atlantic Multidecadal Oscillation showed the strongest association with fire frequency, especially prior to 1834. During that period, cool-phase AMO was related to an increase in fire frequency. The relationship reversed between 1835 and 1934, which may have been associated with a phase shift of the AMO. Fire frequency at Rabbit Creek Trail and Pine Mountain was significantly correlated with AMO during the Pre-settlement Period (1697–1834). Fire frequency at Rabbit Creek Trail was also significantly correlated with AMO during the Settlement Period (1835–1934). Gold Mine Trail fire frequency was significantly correlated with both the El Niño-Southern Oscillation and the Pacific Decadal Oscillation during the Full Period (1697–2006), but to only PDO during the Pre-settlement Period.

AMO and ENSO were positively correlated with July temperatures, and ENSO was positively correlated with August precipitation. Cool phase (negative) AMO has been associated with an increase in precipitation over the southern Appalachian Mountains (Enfield *et al*. 2001, Tootle *et al*. 2005), but it did not correlate significantly with total monthly precipitation for East Tennessee in this study. An extended cool phase was observed in the reconstructed AMO data from 1789 to 1849, following a neutral period that began about 1700. Short oscillations occurred between 1850 and 1925 that led into an extended warm phase that lasted until about 1970 (Gray *et al*. 2004). My analysis indicated that the cool phase was associated with cooler summer temperatures. However, it seems counterintuitive that fire frequency would increase with cooler temperatures and more precipitation, unless humans were taking advantage of desirable environmental conditions to ignite fires that would be less likely to burn uncontrolled. It could also be that higher precipitation levels in the summer were associated with increased storm activity, and therefore, an increased number of lightning-ignited fires. It would be useful to reconstruct summer temperature and precipitation for East Tennessee beyond the 1895 limit of the instrumental record to determine if significant relationships exist between those variables and fire frequency during the 18th and 19th centuries.

### *2. **Both Atlantic and Pacific oscillations precondition and influence wildfire events***

The El Niño-Southern Oscillation, the Pacific Decadal Oscillation, and the North Atlantic Oscillation were all significantly related to wildfire in the years preceding the event, implying preconditioning, *i.e.* a flush of vegetation growth in more optimal conditions that later became fuel during drier conditions. For all fire classes in the regional dataset during the Pre-settlement Period, I found a positive correlation with NAO three years prior to the wildfire. This suggests that prior to 1834, warmer, wetter winters preconditioned forests for both small and widespread fires. During that time, ENSO was also positively correlated with fires one year and five years prior to the wildfire event for the regional dataset, also suggesting that previous wetter years may have preconditioned forests for fire.

While regional wildfires were not significantly correlated with ENSO during event years, fires at Gold Mine Trail were negatively correlated. This negative relationship corresponds to the warmer and drier conditions that are typically associated with La Niña (ENSO negative phase) conditions, but not to the results from the correlation analysis of ENSO and East Tennessee temperature in this study, *i.e.* negative ENSO index was correlated with cooler July temperature. Fire events at Gold Mine Trail were also significantly correlated (positive) with PDO (–2 and –3 years) in the Pre-settlement Period, a relationship that was not found with the regional data. This suggests that drier springs in the years prior to the wildfire enhanced conditions for the event at GMT.

Relationships at all sites between fires and climate were more evident prior to 1834, suggesting that the increase in human activity may have masked the climate signal after European settlement. Additionally, Great Smoky Mountains National Park is located on an ambiguous boundary over which climate oscillations have different effects on local weather variables. It would be valuable to clarify relationships between ENSO, temperature, and precipitation around the boundary area for both the instrumental record period, and for reconstructed variables.

### 6.5 Future Research

Long-term instrumental records of climate and wildfire are relatively rare in the southeastern United States. Tree-ring records provide an annual proxy of environmental conditions. Unfortunately, old, living trees are not abundant in eastern forests because much of the landscape was heavily logged by the early 1900s. Many of the surviving old trees are succumbing to stress from pollution and competition pressures, or are being decimated by insect outbreaks. The loss of these trees does not only change the stands in which they reside, but also deprives us of valuable environmental records. My study documented and analyzed the tree-ring series from yellow pine trees in the western portion of Great Smoky Mountains National Park, one of the few areas in the region with protected old-growth stands. My analyses indicated that these trees hold quality records of environmental conditions for the past three centuries or more.

Further collection of samples from other old, living trees in the area should be conducted, as well as additional sample collection from old trees that have been more recently brought down by beetles and storm events before they are lost to rot, animal or insect damage, and fire. Resinous and flammable yellow pine remnants that would likely hold the oldest records are at high risk. Few yellow pine chronologies have been made public for the southern

Appalachian Mountains (International Tree-Ring Data Bank 2012). A network of tree-ring chronologies is needed to understand regional climate signals.

Tree-ring chronologies have been used to accurately reconstruct climate variables beyond the instrumental record. Yellow pine records from GSMNP should be used to reconstruct winter temperatures and (possibly) summer precipitation for East Tennessee beyond the 1895 limit of the instrumental records. The association of radial growth with temperatures and precipitation is stronger in winter than other seasons for my yellow pines, primarily related to the NAO. The NAO reconstruction has already been "well-verified" (Cook *et al*. 2002); however, it would be useful to clarify the specifics of yellow pine growth relationship with NAO in the southern Appalachian Mountains.

Summer precipitation was indirectly related through ENSO to fire frequency in my study area during the 18th and 19th centuries. Reconstructing summer precipitation and testing it directly against the fire frequency data would help clarify the relationship. My analysis indicated that the relationships of climate oscillations to temperature and precipitation in East Tennessee may not be consistent over time. Further research should be conducted on these relationships, perhaps using moving correlation analysis. A limiting factor would be the availability of weather data prior to 1895, but reconstructing those variables would provide a means to perform the analysis.

Another subject of interest is divergence in the relationship between temperature and radial growth of various tree species since the 1960s (Johnson *et al.* 1988, Briffa *et al.* 1998, D'Arrigo *et al.* 2008, Biermann 2009). It would be useful to determine if this phenomenon is occurring at my sites, as controversy still exists as to the cause or existence of the divergence (Esper and Frank 2009, Loehle 2009). Multivariate analyses should be conducted to further explore the interrelationships between the climate variables and the yellow pine chronologies. This would improve understanding of how the climate variables interact and also how the radial growth of yellow pines fluctuates in response to those interactions.

This study provided four yellow pine tree-ring chronologies that provided a quality record of climate into the 1700s that can be further used in our own research, and also shared with the dendrochronological community. The fire history analysis produced records detailing specific fire event years and fire frequency over time. Clear changes have occurred in the western portion of GSMNP with regard to shifts in the fire regime that likely have been largely influenced by anthropogenic activity, but also influenced by climate. My data can be used in conjunction with other fire history studies to better understand patterns in the region. In the face of certain climate change, we as a society need to better understand how those changes will affect other aspects of the environment around us.

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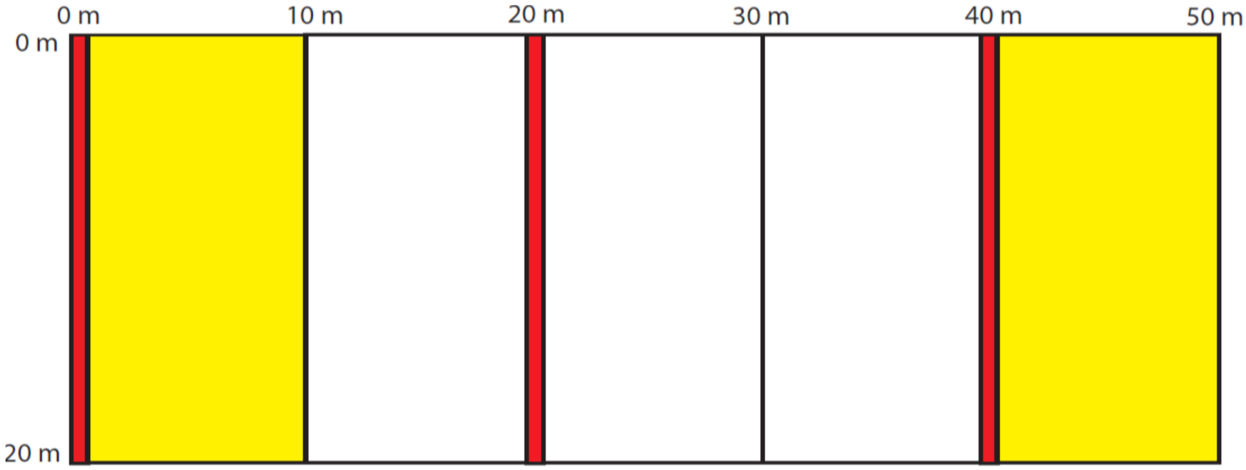
# APPENDICES

**Appendix A-1:** Diagram of a 20 x 50 m (0.1 ha) macroplot. Canopy-class trees were inventoried and cored across the entire macroplot. Saplings were inventoried in the first and last subplots (yellow, 400 m$^2$ total). Three 1 x 20 m transects (red) were used to inventory seedlings (60 m$^2$ total). Each site had three macroplots for a total of nine in the study. Duff thickness was measured on the long boundary line of each subplot for a total of six measurements per macroplot.



**Appendix A-2:** Statistical descriptions of the series in the Gold Mine Trail total ring-width chronology. Standard deviation and autocorrelation are filtered.

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 1 | GMC001A | 1847 | 2006 | 160 | 0.520 | 0.256 | 0.371 | -0.011 |
| 2 | GMC008AL | 1866 | 1961 | 96 | 0.413 | 0.308 | 0.406 | -0.047 |
| 3 | GMC008BL | 1890 | 2003 | 114 | 0.363 | 0.350 | 0.564 | -0.075 |
| 4 | GMC010AL | 1869 | 2004 | 136 | 0.593 | 0.233 | 0.441 | 0.021 |
| 5 | GMC010B | 1873 | 2006 | 134 | 0.628 | 0.259 | 0.527 | -0.004 |
| 6 | GMC016A | 1863 | 2004 | 142 | 0.391 | 0.370 | 0.406 | -0.003 |
| 7 | GMC022A | 1880 | 2006 | 127 | 0.315 | 0.283 | 0.430 | 0.012 |
| 8 | GMC022B | 1880 | 2006 | 127 | 0.550 | 0.309 | 0.492 | -0.005 |
| 9 | GMC033A | 1880 | 2006 | 127 | 0.567 | 0.277 | 0.421 | -0.009 |
| 10 | GMC033B | 1868 | 2006 | 139 | 0.608 | 0.243 | 0.372 | -0.027 |
| 11 | GMC035A | 1860 | 2006 | 147 | 0.600 | 0.258 | 0.564 | -0.060 |
| 12 | GMC035B | 1862 | 2006 | 145 | 0.537 | 0.260 | 0.443 | -0.013 |
| 13 | GMC047A | 1890 | 2006 | 117 | 0.554 | 0.291 | 0.599 | 0.038 |
| 14 | GMC047B | 1920 | 2006 | 87 | 0.554 | 0.241 | 0.482 | 0.038 |
| 15 | GMC048A | 1870 | 2006 | 137 | 0.479 | 0.281 | 0.252 | -0.073 |
| 16 | GMC048B | 1873 | 2006 | 134 | 0.562 | 0.272 | 0.433 | -0.033 |
| 17 | GMC074AL | 1800 | 2006 | 207 | 0.568 | 0.274 | 0.390 | -0.006 |
| 18 | GMC074BL | 1731 | 1800 | 70 | 0.607 | 0.233 | 0.460 | 0.024 |
| 19 | GMT001A | 1790 | 2004 | 215 | 0.591 | 0.305 | 0.374 | -0.014 |
| 20 | GMT001B | 1804 | 2004 | 201 | 0.542 | 0.249 | 0.276 | -0.013 |
| 21 | GMT002AR | 1729 | 2004 | 276 | 0.534 | 0.248 | 0.387 | -0.004 |
| 22 | GMT002B | 1753 | 2004 | 252 | 0.530 | 0.213 | 0.405 | 0.029 |
| 23 | GMT002C | 1800 | 2004 | 205 | 0.448 | 0.300 | 0.353 | -0.015 |
| 24 | GMT003A | 1838 | 2004 | 167 | 0.543 | 0.246 | 0.377 | -0.006 |
| 25 | GMT003B | 1852 | 2004 | 153 | 0.612 | 0.214 | 0.408 | -0.023 |
| 26 | GMT003C | 1815 | 1997 | 183 | 0.505 | 0.249 | 0.423 | -0.024 |
| 27 | GMT004A | 1780 | 1982 | 203 | 0.662 | 0.270 | 0.398 | 0.030 |
| 28 | GMT004B | 1780 | 1983 | 204 | 0.563 | 0.275 | 0.464 | 0.014 |
| 29 | GMT005A | 1905 | 2004 | 100 | 0.531 | 0.261 | 0.523 | -0.014 |
| 30 | GMT005B | 1910 | 2004 | 95 | 0.594 | 0.300 | 0.472 | -0.060 |
| 31 | GMT006A | 1895 | 2004 | 110 | 0.563 | 0.341 | 0.542 | 0.054 |
| 32 | GMT007AR | 1882 | 2005 | 124 | 0.540 | 0.273 | 0.351 | 0.016 |
| 33 | GMT007B | 1890 | 2004 | 115 | 0.445 | 0.289 | 0.290 | -0.046 |
| 34 | GMT008AR | 1883 | 2005 | 123 | 0.538 | 0.283 | 0.414 | -0.010 |
| 35 | GMT008BR | 1880 | 2005 | 126 | 0.494 | 0.337 | 0.462 | -0.013 |

**Appendix A-2:** *continued*

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 36 | GMT009A | 1815 | 1943 | 129 | 0.519 | 0.197 | 0.493 | 0.049 |
| 37 | GMT009B | 1826 | 1987 | 162 | 0.545 | 0.230 | 0.503 | -0.007 |
| 38 | GMT010A | 1812 | 1962 | 151 | 0.533 | 0.212 | 0.493 | -0.008 |
| 39 | GMT010C | 1770 | 1906 | 137 | 0.610 | 0.209 | 0.523 | -0.012 |
| 40 | GMT011A | 1810 | 1926 | 117 | 0.697 | 0.233 | 0.488 | 0.058 |
| 41 | GMT011B | 1810 | 1980 | 171 | 0.632 | 0.233 | 0.440 | 0.047 |
| 42 | GMT015A | 1888 | 2000 | 113 | 0.533 | 0.226 | 0.499 | -0.048 |
| 43 | GMT016A | 1884 | 1925 | 42 | 0.486 | 0.204 | 0.443 | 0.207 |
| 44 | GMT017A | 1907 | 1963 | 57 | 0.650 | 0.241 | 0.436 | 0.059 |
| 45 | GMT017B | 1920 | 2001 | 82 | 0.660 | 0.242 | 0.404 | 0.048 |
| 46 | GMT018A | 1753 | 2004 | 252 | 0.669 | 0.252 | 0.384 | -0.016 |
| 47 | GMT018BR | 1741 | 2005 | 265 | 0.659 | 0.239 | 0.358 | 0.007 |
| 48 | GMT019A | 1761 | 1850 | 90 | 0.538 | 0.257 | 0.498 | -0.008 |
| 49 | GMT019BR | 1754 | 2005 | 252 | 0.541 | 0.269 | 0.425 | 0.005 |
| 50 | GMT021AR | 1890 | 2005 | 116 | 0.574 | 0.263 | 0.360 | -0.060 |
| 51 | GMT021B | 1917 | 2004 | 88 | 0.670 | 0.239 | 0.435 | -0.036 |
| 52 | GMT022AR | 1912 | 2005 | 94 | 0.552 | 0.252 | 0.350 | -0.035 |
| 53 | GMT022B | 1882 | 1999 | 118 | 0.619 | 0.216 | 0.454 | -0.012 |
| 54 | GMT023AR | 1934 | 2005 | 72 | 0.561 | 0.330 | 0.574 | 0.013 |
| 55 | GMT023BR | 1936 | 2005 | 70 | 0.495 | 0.334 | 0.459 | 0.003 |
| 56 | GMT024AR | 1887 | 2005 | 119 | 0.449 | 0.241 | 0.377 | -0.028 |
| 57 | GMT024BR | 1884 | 2005 | 122 | 0.586 | 0.314 | 0.487 | 0.001 |
| 58 | GMT026A | 1857 | 2004 | 148 | 0.620 | 0.358 | 0.424 | -0.040 |
| 59 | GMT026B | 1857 | 2004 | 148 | 0.628 | 0.359 | 0.450 | -0.004 |
| 60 | GMT027A | 1914 | 2004 | 91 | 0.616 | 0.269 | 0.604 | -0.069 |
| 61 | GMT027BR | 1911 | 2004 | 94 | 0.686 | 0.245 | 0.507 | 0.006 |
| 62 | GMT028AR | 1908 | 2005 | 98 | 0.506 | 0.313 | 0.530 | 0.001 |
| 63 | GMT028BR | 1904 | 1989 | 86 | 0.483 | 0.320 | 0.353 | -0.044 |
| 64 | GMT029AR | 1892 | 2005 | 114 | 0.470 | 0.291 | 0.439 | 0.023 |
| 65 | GMT029BR | 1878 | 1989 | 112 | 0.398 | 0.335 | 0.592 | -0.021 |
| 66 | GMT030AR | 1928 | 2005 | 78 | 0.456 | 0.323 | 0.462 | -0.067 |
| 67 | GMT030BR | 1928 | 2004 | 77 | 0.457 | 0.298 | 0.506 | -0.122 |
| 68 | GMT031A | 1900 | 2004 | 105 | 0.486 | 0.267 | 0.524 | -0.046 |
| 69 | GMT032AR | 1891 | 2005 | 115 | 0.448 | 0.205 | 0.459 | -0.027 |
| 70 | GMT032BR | 1885 | 2005 | 121 | 0.565 | 0.237 | 0.543 | -0.036 |
| 71 | GMT033A | 1937 | 2004 | 68 | 0.595 | 0.285 | 0.382 | 0.011 |
| 72 | GMT034AR | 1940 | 1990 | 51 | 0.387 | 0.206 | 0.505 | 0.027 |

**Appendix A-2:** *continued*

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 73 | GMT035A | 1902 | 2004 | 103 | 0.626 | 0.277 | 0.433 | -0.103 |
| 74 | GMT035BR | 1895 | 2005 | 111 | 0.630 | 0.234 | 0.515 | 0.021 |
| 75 | GMT036AR | 1760 | 2005 | 246 | 0.511 | 0.221 | 0.417 | -0.002 |
| 76 | GMT036BR | 1818 | 2005 | 188 | 0.555 | 0.275 | 0.385 | 0.001 |
| 77 | GMT037A | 1856 | 1971 | 116 | 0.613 | 0.295 | 0.470 | -0.018 |
| 78 | GMT037B | 1860 | 1980 | 121 | 0.612 | 0.271 | 0.402 | 0.017 |
| 79 | GMT038A | 1883 | 2005 | 123 | 0.546 | 0.261 | 0.363 | -0.070 |
| 80 | GMT038B | 1883 | 2005 | 123 | 0.399 | 0.316 | 0.415 | 0.007 |
| 81 | GMT041A | 1970 | 2005 | 36 | 0.490 | 0.249 | 0.668 | -0.139 |
| 82 | GMT042B | 1968 | 2005 | 38 | 0.568 | 0.153 | 0.614 | -0.009 |
| 83 | GMT043A | 1877 | 1953 | 77 | 0.585 | 0.340 | 0.524 | -0.027 |
| 84 | GMT044A | 1863 | 1963 | 101 | 0.688 | 0.299 | 0.394 | -0.027 |
| 85 | GMT045A | 1861 | 2005 | 145 | 0.593 | 0.261 | 0.363 | -0.012 |
| 86 | GMT045B | 1861 | 2005 | 145 | 0.529 | 0.259 | 0.557 | 0.006 |
| 87 | GMT047A | 1902 | 2005 | 104 | 0.488 | 0.246 | 0.466 | -0.051 |
| 88 | GMT047B | 1902 | 1950 | 49 | 0.510 | 0.285 | 0.459 | -0.021 |
| 89 | GMT048A | 1909 | 2005 | 97 | 0.413 | 0.282 | 0.410 | -0.013 |
| 90 | GMT048B | 1909 | 2005 | 97 | 0.546 | 0.286 | 0.499 | 0.013 |
| 91 | GMT050A | 1943 | 2005 | 63 | 0.536 | 0.239 | 0.423 | -0.043 |
| 92 | GMT050B | 1943 | 2005 | 63 | 0.507 | 0.251 | 0.627 | 0.037 |
| 93 | GMT051A | 1897 | 2005 | 109 | 0.559 | 0.240 | 0.602 | -0.006 |
| 94 | GMT051B | 1885 | 2005 | 121 | 0.623 | 0.217 | 0.439 | -0.037 |
| 95 | GMT053A | 1850 | 2005 | 156 | 0.600 | 0.247 | 0.479 | -0.022 |
| 96 | GMT053B | 1865 | 2005 | 141 | 0.656 | 0.245 | 0.406 | -0.002 |
| 97 | GMT054A | 1856 | 2005 | 150 | 0.558 | 0.253 | 0.358 | 0.019 |
| 98 | GMT054B | 1872 | 2005 | 134 | 0.655 | 0.257 | 0.478 | -0.071 |
| 99 | GMT055A | 1860 | 1940 | 81 | 0.612 | 0.261 | 0.428 | -0.072 |
| 100 | GMT055B | 1862 | 2005 | 144 | 0.572 | 0.295 | 0.336 | -0.022 |
| 101 | GMT056A | 1880 | 2005 | 126 | 0.485 | 0.240 | 0.542 | -0.063 |
| 102 | GMT056B | 1890 | 2005 | 116 | 0.468 | 0.277 | 0.399 | -0.067 |
| 103 | GMT057A | 1862 | 2005 | 144 | 0.548 | 0.246 | 0.621 | -0.051 |
| 104 | GMT057B | 1862 | 2005 | 144 | 0.657 | 0.256 | 0.474 | -0.003 |
| 105 | GMT058A | 1874 | 2005 | 132 | 0.568 | 0.331 | 0.488 | -0.015 |
| 106 | GMT058B | 1885 | 2005 | 121 | 0.599 | 0.286 | 0.384 | -0.061 |
| 107 | GMT059A | 1862 | 2005 | 144 | 0.599 | 0.326 | 0.540 | -0.006 |
| 108 | GMT059B | 1862 | 2005 | 144 | 0.515 | 0.346 | 0.421 | -0.042 |
| 109 | GMT060A | 1868 | 1998 | 131 | 0.644 | 0.344 | 0.544 | -0.010 |

**Appendix A-2:** *continued*

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 110 | GMT060B | 1868 | 1940 | 73 | 0.584 | 0.313 | 0.504 | 0.118 |
| 111 | GMT061A | 1928 | 2005 | 78 | 0.412 | 0.265 | 0.486 | -0.038 |
| 112 | GMT063A | 1948 | 2005 | 58 | 0.358 | 0.195 | 0.526 | -0.091 |
| 113 | GMT063B | 1948 | 2005 | 58 | 0.365 | 0.199 | 0.631 | 0.027 |
| 114 | GMT064A | 1904 | 2005 | 102 | 0.482 | 0.266 | 0.583 | -0.045 |
| 115 | GMT064B | 1904 | 2005 | 102 | 0.493 | 0.359 | 0.391 | -0.066 |
| 116 | GMT065A | 1941 | 2005 | 65 | 0.328 | 0.289 | 0.568 | 0.063 |
| 117 | GMT066A | 1930 | 2005 | 76 | 0.549 | 0.378 | 0.347 | -0.080 |
| 118 | GMT066B | 1940 | 2005 | 66 | 0.343 | 0.344 | 0.538 | -0.049 |
| 119 | GMX005A | 1854 | 2006 | 153 | 0.592 | 0.211 | 0.506 | -0.019 |
| 120 | GMX005B | 1853 | 2006 | 154 | 0.685 | 0.205 | 0.458 | 0.000 |
| 121 | GMX006B | 1910 | 2006 | 97 | 0.578 | 0.286 | 0.423 | 0.009 |
| 122 | GMX007A | 1890 | 2006 | 117 | 0.497 | 0.209 | 0.471 | -0.066 |
| 123 | GMX007B | 1890 | 2006 | 117 | 0.502 | 0.181 | 0.370 | -0.016 |
| 124 | GMX008A | 1863 | 2006 | 144 | 0.474 | 0.295 | 0.505 | -0.009 |
| 125 | GMX009A | 1847 | 2006 | 160 | 0.471 | 0.236 | 0.428 | 0.014 |
| 126 | GMX009B | 1860 | 2006 | 147 | 0.574 | 0.277 | 0.432 | -0.062 |
| 127 | GMT101A | 1846 | 1950 | 105 | 0.455 | 0.268 | 0.384 | -0.005 |
| 128 | GMT101A2 | 1849 | 1915 | 67 | 0.491 | 0.254 | 0.505 | -0.091 |
| 129 | GMT102 | 1850 | 1918 | 69 | 0.525 | 0.261 | 0.460 | 0.109 |
| 130 | GMT103 | 1869 | 1967 | 99 | 0.582 | 0.290 | 0.530 | 0.018 |
| 131 | GMT104U | 1862 | 1997 | 136 | 0.451 | 0.363 | 0.477 | -0.050 |
| 132 | GMT105 | 1885 | 2005 | 121 | 0.487 | 0.257 | 0.360 | -0.028 |
| 133 | GMT106 | 1841 | 1927 | 87 | 0.473 | 0.308 | 0.416 | -0.042 |
| 134 | GMT107 | 1820 | 1928 | 109 | 0.443 | 0.231 | 0.453 | 0.049 |
| 135 | GMT108 | 1883 | 2000 | 118 | 0.494 | 0.343 | 0.493 | -0.010 |
| 136 | GMT110 | 1877 | 1949 | 73 | 0.483 | 0.249 | 0.354 | -0.028 |
| 137 | GMT111 | 1864 | 1979 | 116 | 0.430 | 0.290 | 0.505 | -0.012 |
| 138 | GMT111B | 1864 | 2001 | 138 | 0.569 | 0.297 | 0.452 | -0.030 |
| 139 | GMT114 | 1920 | 2001 | 82 | 0.540 | 0.307 | 0.477 | -0.045 |
| 140 | GMT119A | 1851 | 2001 | 151 | 0.699 | 0.209 | 0.382 | -0.010 |
| 141 | GMT119B | 1851 | 2001 | 151 | 0.536 | 0.221 | 0.332 | -0.021 |
| 142 | GMT121 | 1856 | 1979 | 124 | 0.379 | 0.261 | 0.384 | 0.032 |
| 143 | GMT122 | 1866 | 2000 | 135 | 0.544 | 0.302 | 0.468 | -0.034 |
| 144 | GMT123A | 1778 | 1968 | 191 | 0.374 | 0.310 | 0.328 | -0.038 |
| 145 | GMT123BU | 1840 | 1981 | 142 | 0.432 | 0.283 | 0.450 | -0.019 |
| 146 | GMT124 | 1790 | 1928 | 139 | 0.510 | 0.257 | 0.483 | 0.022 |

**Appendix A-2:** *continued*

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 147 | GMT125R | 1729 | 1929 | 201 | 0.531 | 0.283 | 0.341 | 0.030 |
| 148 | GMT126A | 1739 | 1928 | 190 | 0.476 | 0.234 | 0.400 | 0.030 |
| 149 | GMT126B | 1737 | 1927 | 191 | 0.494 | 0.211 | 0.437 | -0.005 |
| 150 | GMT127A | 1870 | 1958 | 89 | 0.422 | 0.327 | 0.479 | -0.017 |
| 151 | GMT127A2 | 1825 | 1925 | 101 | 0.478 | 0.283 | 0.521 | -0.072 |
| 152 | GMT128 | 1785 | 1919 | 135 | 0.491 | 0.226 | 0.398 | -0.030 |
| 153 | GMT130C | 1860 | 1925 | 66 | 0.459 | 0.266 | 0.441 | 0.058 |
| 154 | GMT131 | 1854 | 1939 | 86 | 0.621 | 0.162 | 0.652 | 0.052 |
| 155 | GMT132 | 1896 | 1998 | 103 | 0.671 | 0.284 | 0.553 | -0.049 |
| 156 | GMT133 | 1823 | 1999 | 177 | 0.640 | 0.256 | 0.367 | -0.025 |
| 157 | GMT134 | 1807 | 1939 | 133 | 0.472 | 0.286 | 0.537 | 0.066 |
| 158 | GMT135R | 1836 | 1939 | 104 | 0.434 | 0.296 | 0.470 | -0.003 |
| 159 | GMT136 | 1873 | 1979 | 107 | 0.370 | 0.267 | 0.557 | 0.031 |
| 160 | GMT137A | 1810 | 1908 | 99 | 0.568 | 0.279 | 0.443 | -0.058 |
| 161 | GMT137B | 1850 | 1927 | 78 | 0.628 | 0.287 | 0.510 | 0.041 |
| 162 | GMT139 | 1855 | 1949 | 95 | 0.426 | 0.287 | 0.524 | 0.052 |
| 163 | GMT140 | 1864 | 1930 | 67 | 0.470 | 0.340 | 0.469 | -0.014 |
| 164 | GMT141 | 1850 | 1949 | 100 | 0.422 | 0.230 | 0.461 | 0.015 |
| 165 | GMT142B | 1848 | 2001 | 154 | 0.533 | 0.233 | 0.502 | 0.019 |
| 166 | GMT143BL | 1860 | 2001 | 142 | 0.610 | 0.295 | 0.402 | -0.044 |
| 167 | GMT143C | 1870 | 2001 | 132 | 0.459 | 0.265 | 0.550 | -0.071 |
| 168 | GMT144AL | 1861 | 1999 | 139 | 0.534 | 0.284 | 0.425 | -0.003 |
| 169 | GMT144BL | 1861 | 2001 | 141 | 0.503 | 0.258 | 0.488 | -0.065 |
| 170 | GMT145A | 1890 | 1999 | 110 | 0.456 | 0.336 | 0.445 | -0.037 |
| 171 | GMT146A | 1941 | 2001 | 61 | 0.521 | 0.270 | 0.587 | -0.046 |
| 172 | GMT146B | 1941 | 2001 | 61 | 0.542 | 0.227 | 0.527 | -0.120 |
| 173 | GMT147A | 1916 | 1997 | 82 | 0.533 | 0.225 | 0.479 | -0.039 |
| 174 | GMT147L | 1916 | 1975 | 60 | 0.576 | 0.217 | 0.549 | -0.104 |
| 175 | GMT149A | 1848 | 2000 | 153 | 0.607 | 0.281 | 0.539 | -0.071 |
| 176 | GMT149B | 1848 | 2000 | 153 | 0.604 | 0.296 | 0.426 | -0.007 |
| 177 | GMT151BR | 1840 | 1929 | 90 | 0.376 | 0.342 | 0.574 | 0.025 |
| 178 | GMT153AL | 1939 | 2001 | 63 | 0.452 | 0.195 | 0.466 | -0.020 |
| 179 | GMT153BL | 1939 | 2001 | 63 | 0.479 | 0.244 | 0.458 | -0.018 |
| 180 | GMX301AR | 1697 | 1930 | 234 | 0.615 | 0.241 | 0.392 | -0.014 |
| 181 | GMX301BR | 1697 | 1890 | 194 | 0.629 | 0.277 | 0.337 | 0.007 |
| 182 | GMX3021R | 1810 | 1916 | 107 | 0.455 | 0.270 | 0.394 | 0.013 |
| 183 | GMX3022R | 1830 | 1929 | 100 | 0.413 | 0.277 | 0.483 | -0.047 |

**Appendix A-2:** *continued*

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 184 | GMX305A | 1731 | 1897 | 167 | 0.413 | 0.338 | 0.514 | -0.014 |
| 185 | GMX307R | 1720 | 2006 | 287 | 0.459 | 0.275 | 0.422 | 0.004 |
| 186 | GMX309AR | 1731 | 1897 | 167 | 0.541 | 0.272 | 0.375 | 0.014 |
| 187 | GMX401A | 1859 | 1930 | 72 | 0.524 | 0.235 | 0.536 | 0.039 |
| 188 | GMX402A | 1852 | 1911 | 60 | 0.538 | 0.253 | 0.633 | -0.006 |
| 189 | GMX402B | 1851 | 1910 | 60 | 0.514 | 0.293 | 0.613 | -0.009 |
| 190 | GMX403 | 1837 | 1970 | 134 | 0.630 | 0.241 | 0.421 | -0.008 |
| 191 | GMX404 | 1838 | 1991 | 154 | 0.629 | 0.305 | 0.487 | -0.025 |
| 192 | GMX405 | 1783 | 1902 | 120 | 0.462 | 0.267 | 0.554 | -0.005 |
| 193 | GMX406 | 1814 | 1998 | 185 | 0.570 | 0.239 | 0.448 | 0.014 |
| 194 | GMX503 | 1864 | 2001 | 138 | 0.507 | 0.246 | 0.499 | 0.016 |
| 195 | GMX504 | 1870 | 1949 | 80 | 0.454 | 0.308 | 0.576 | 0.107 |
| 196 | GMT505 | 1880 | 2001 | 122 | 0.510 | 0.277 | 0.396 | 0.083 |
| 197 | GMX506 | 1853 | 1972 | 120 | 0.493 | 0.303 | 0.424 | -0.048 |
| 198 | GMX509 | 1890 | 1998 | 109 | 0.674 | 0.314 | 0.549 | -0.029 |
|  | **Total or Mean** |  |  | **24363** | **0.538** | **0.269** | **0.449** | **-0.011** |

**Appendix A-3:** Statistical descriptions of the series in the Rabbit Creek Trail total ring-width chronology. Standard deviation and autocorrelation are filtered.

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 1 | RCA020A | 1903 | 2005 | 103 | 0.534 | 0.277 | 0.522 | 0.055 |
| 2 | RCA020B | 1903 | 2005 | 103 | 0.532 | 0.263 | 0.537 | -0.069 |
| 3 | RCA033A2 | 1900 | 2005 | 106 | 0.508 | 0.379 | 0.542 | 0.045 |
| 4 | RCA067B | 1904 | 2005 | 102 | 0.594 | 0.277 | 0.471 | 0.031 |
| 5 | RCB001AR | 1892 | 2007 | 116 | 0.637 | 0.288 | 0.433 | -0.046 |
| 6 | RCB001A2 | 1892 | 2003 | 112 | 0.559 | 0.283 | 0.479 | -0.009 |
| 7 | RCB001BR | 1902 | 2007 | 106 | 0.677 | 0.230 | 0.408 | -0.005 |
| 8 | RCB001B2 | 1902 | 1963 | 62 | 0.413 | 0.270 | 0.593 | 0.018 |
| 9 | RCB007AR | 1939 | 2007 | 69 | 0.588 | 0.193 | 0.670 | -0.033 |
| 10 | RCB007BR | 1939 | 2007 | 69 | 0.541 | 0.240 | 0.490 | 0.022 |
| 11 | RCB014AR | 1934 | 2007 | 74 | 0.474 | 0.257 | 0.456 | -0.070 |
| 12 | RCB015AL | 1850 | 1997 | 148 | 0.507 | 0.356 | 0.453 | -0.017 |
| 13 | RCB015BL | 1857 | 1930 | 74 | 0.551 | 0.297 | 0.464 | -0.033 |
| 14 | RCB030A | 1935 | 2007 | 73 | 0.611 | 0.236 | 0.464 | -0.001 |
| 15 | RCB030B | 1932 | 2007 | 76 | 0.467 | 0.220 | 0.406 | -0.049 |
| 16 | RCB037A | 1938 | 2004 | 67 | 0.607 | 0.273 | 0.545 | -0.109 |
| 17 | RCB045A | 1936 | 2007 | 72 | 0.528 | 0.201 | 0.586 | -0.094 |
| 18 | RCB045B | 1936 | 2007 | 72 | 0.635 | 0.238 | 0.557 | 0.039 |
| 19 | RCB055B | 1948 | 2007 | 60 | 0.429 | 0.256 | 0.608 | 0.055 |
| 20 | RCB083AR | 1940 | 2007 | 68 | 0.516 | 0.189 | 0.515 | -0.022 |
| 21 | RCB083B | 1940 | 2007 | 68 | 0.536 | 0.225 | 0.563 | -0.080 |
| 22 | RCC002BS | 1863 | 1985 | 123 | 0.561 | 0.311 | 0.442 | -0.001 |
| 23 | RCC003AR | 1932 | 2007 | 76 | 0.558 | 0.232 | 0.499 | -0.041 |
| 24 | RCC003BR | 1932 | 2002 | 71 | 0.607 | 0.220 | 0.558 | -0.067 |
| 25 | RCC004A | 1946 | 2007 | 62 | 0.482 | 0.284 | 0.587 | -0.069 |
| 26 | RCC017AR | 1907 | 2007 | 101 | 0.504 | 0.252 | 0.391 | -0.017 |
| 27 | RCC017BR | 1907 | 2007 | 101 | 0.494 | 0.258 | 0.397 | -0.022 |
| 28 | RCC020AL | 1934 | 1998 | 65 | 0.513 | 0.338 | 0.439 | -0.004 |
| 29 | RCC029A | 1949 | 2007 | 59 | 0.653 | 0.260 | 0.615 | -0.026 |
| 30 | RCC029B | 1949 | 2007 | 59 | 0.541 | 0.282 | 0.550 | 0.018 |
| 31 | RCC048BS | 1817 | 1879 | 63 | 0.487 | 0.369 | 0.607 | 0.049 |
| 32 | RCC051A | 1947 | 2007 | 61 | 0.317 | 0.227 | 0.504 | -0.025 |
| 33 | RCT001AL | 1944 | 2006 | 63 | 0.685 | 0.239 | 0.407 | -0.028 |
| 34 | RCT001B | 1928 | 2005 | 78 | 0.653 | 0.228 | 0.381 | 0.049 |
| 35 | RCT002B | 1903 | 2007 | 105 | 0.523 | 0.236 | 0.401 | 0.055 |

**Appendix A-3:** *continued*

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 36 | RCT003A | 1935 | 2005 | 71 | 0.564 | 0.277 | 0.511 | 0.006 |
| 37 | RCT003B | 1943 | 2005 | 63 | 0.396 | 0.288 | 0.457 | -0.060 |
| 38 | RCT005A | 1950 | 2003 | 54 | 0.591 | 0.367 | 0.425 | 0.014 |
| 39 | RCT005B | 1936 | 2005 | 70 | 0.703 | 0.273 | 0.384 | 0.104 |
| 40 | RCT006B | 1925 | 2005 | 81 | 0.636 | 0.198 | 0.365 | -0.003 |
| 41 | RCT008B | 1957 | 2005 | 49 | 0.614 | 0.403 | 0.423 | -0.104 |
| 42 | RCT009AX | 1819 | 1893 | 75 | 0.512 | 0.374 | 0.378 | 0.005 |
| 43 | RCT010AX | 1911 | 1994 | 84 | 0.616 | 0.272 | 0.484 | -0.002 |
| 44 | RCT010B | 1913 | 2006 | 94 | 0.646 | 0.276 | 0.450 | -0.037 |
| 45 | RCT011A | 1935 | 2005 | 71 | 0.482 | 0.225 | 0.591 | -0.029 |
| 46 | RCT012AL | 1953 | 2000 | 48 | 0.698 | 0.214 | 0.598 | -0.021 |
| 47 | RCT012BL | 1953 | 2006 | 54 | 0.487 | 0.198 | 0.437 | -0.101 |
| 48 | RCT013A | 1934 | 2005 | 72 | 0.521 | 0.246 | 0.485 | -0.001 |
| 49 | RCT013B | 1906 | 2006 | 101 | 0.598 | 0.202 | 0.541 | -0.054 |
| 50 | RCT014BL | 1885 | 1961 | 77 | 0.548 | 0.258 | 0.605 | -0.074 |
| 51 | RCT015B | 1934 | 2005 | 72 | 0.437 | 0.195 | 0.430 | -0.050 |
| 52 | RCT016A | 1899 | 1961 | 63 | 0.462 | 0.250 | 0.556 | -0.063 |
| 53 | RCT016B | 1899 | 1988 | 90 | 0.387 | 0.325 | 0.365 | -0.011 |
| 54 | RCT018A | 1925 | 2005 | 81 | 0.654 | 0.261 | 0.496 | 0.035 |
| 55 | RCT018B | 1925 | 2005 | 81 | 0.601 | 0.311 | 0.469 | 0.058 |
| 56 | RCT019BL | 1896 | 2006 | 111 | 0.523 | 0.262 | 0.536 | 0.002 |
| 57 | RCT020A | 1900 | 2003 | 104 | 0.460 | 0.318 | 0.490 | -0.008 |
| 58 | RCT020B | 1905 | 2001 | 97 | 0.532 | 0.332 | 0.605 | 0.030 |
| 59 | RCT101R | 1824 | 1919 | 96 | 0.430 | 0.260 | 0.424 | -0.073 |
| 60 | RCT103L | 1920 | 2006 | 87 | 0.524 | 0.278 | 0.370 | -0.022 |
| 61 | RCT104BR | 1827 | 1891 | 65 | 0.511 | 0.221 | 0.431 | -0.036 |
| 62 | RCT105R | 1886 | 1935 | 50 | 0.688 | 0.220 | 0.520 | 0.014 |
| 63 | RCT106Q | 1888 | 1934 | 47 | 0.615 | 0.227 | 0.500 | -0.003 |
| 64 | RCT107L | 1887 | 1956 | 70 | 0.657 | 0.309 | 0.442 | 0.065 |
| 65 | RCT109 | 1940 | 1993 | 54 | 0.547 | 0.333 | 0.470 | -0.023 |
| 66 | RCT111A | 1825 | 1915 | 91 | 0.460 | 0.239 | 0.503 | 0.016 |
| 67 | RCT114R | 1840 | 1894 | 55 | 0.445 | 0.344 | 0.618 | -0.051 |
| 68 | RCT115M | 1875 | 1923 | 49 | 0.483 | 0.288 | 0.440 | -0.056 |
| 69 | RCT120L | 1920 | 1966 | 47 | 0.512 | 0.206 | 0.516 | -0.082 |
| 70 | RCT121L | 1910 | 1997 | 88 | 0.480 | 0.226 | 0.455 | 0.035 |
| 71 | RCT122 | 1870 | 2002 | 133 | 0.514 | 0.345 | 0.361 | -0.010 |
| 72 | RCT123A | 1820 | 1896 | 77 | 0.573 | 0.281 | 0.455 | 0.018 |

**Appendix A-3:** *continued*

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 73 | RCT129 | 1880 | 2003 | 124 | 0.396 | 0.246 | 0.410 | -0.010 |
| 74 | RCT131A | 1840 | 1902 | 63 | 0.452 | 0.403 | 0.626 | -0.025 |
| 75 | RCT131BL | 1820 | 1886 | 67 | 0.556 | 0.355 | 0.507 | -0.051 |
| 76 | RCT131C | 1818 | 1872 | 55 | 0.599 | 0.370 | 0.530 | 0.055 |
| 77 | RCT133A | 1780 | 1939 | 160 | 0.596 | 0.365 | 0.553 | 0.032 |
| 78 | RCT133AX | 1780 | 1950 | 171 | 0.612 | 0.384 | 0.415 | 0.011 |
| 79 | RCT133B | 1779 | 1928 | 150 | 0.662 | 0.351 | 0.475 | 0.031 |
| 80 | RCT133BX | 1780 | 1929 | 150 | 0.526 | 0.349 | 0.469 | -0.009 |
| 81 | RCT134 | 1863 | 2006 | 144 | 0.502 | 0.268 | 0.335 | -0.013 |
| 82 | RCT135L | 1871 | 1919 | 49 | 0.496 | 0.378 | 0.473 | 0.074 |
| 83 | RCT136 | 1845 | 1943 | 99 | 0.382 | 0.287 | 0.570 | -0.001 |
| 84 | RCT138L | 1903 | 1972 | 70 | 0.478 | 0.192 | 0.475 | 0.018 |
| 85 | RCT139B | 1845 | 1939 | 95 | 0.380 | 0.385 | 0.642 | 0.032 |
| 86 | RCT142 | 1860 | 1986 | 127 | 0.384 | 0.292 | 0.492 | 0.019 |
| 87 | RCT143 | 1790 | 1883 | 94 | 0.384 | 0.273 | 0.475 | 0.032 |
|  | **Total or Mean** |  |  | **7277** | **0.534** | **0.283** | **0.482** | **-0.007** |

**Appendix A-4:** Statistical descriptions of the series in the Pine Mountain total ring-width chronology. Standard deviation and autocorrelation are filtered.

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 1 | PMA001A | 1815 | 1988 | 174 | 0.520 | 0.323 | 0.414 | 0.034 |
| 2 | PMA001B | 1826 | 1988 | 163 | 0.517 | 0.292 | 0.466 | 0.057 |
| 3 | PMA003A | 1936 | 1999 | 64 | 0.488 | 0.279 | 0.479 | -0.094 |
| 4 | PMA012A | 1943 | 2006 | 64 | 0.644 | 0.206 | 0.475 | -0.009 |
| 5 | PMA012B | 1945 | 2005 | 61 | 0.516 | 0.208 | 0.499 | -0.099 |
| 6 | PMA016A | 1966 | 2006 | 41 | 0.682 | 0.136 | 0.567 | -0.074 |
| 7 | PMA016B | 1966 | 2006 | 41 | 0.561 | 0.156 | 0.501 | -0.060 |
| 8 | PMA025A | 1937 | 2006 | 70 | 0.434 | 0.196 | 0.580 | -0.057 |
| 9 | PMA026A | 1838 | 2006 | 169 | 0.563 | 0.302 | 0.388 | 0.076 |
| 10 | PMA043A | 1938 | 1995 | 58 | 0.617 | 0.264 | 0.435 | -0.026 |
| 11 | PMA043B | 1938 | 1995 | 58 | 0.668 | 0.236 | 0.488 | -0.115 |
| 12 | PMA046A | 1935 | 2000 | 66 | 0.476 | 0.229 | 0.494 | 0.051 |
| 13 | PMA046B | 1935 | 1993 | 59 | 0.505 | 0.229 | 0.577 | 0.035 |
| 14 | PMA052A | 1927 | 1976 | 50 | 0.496 | 0.255 | 0.494 | -0.063 |
| 15 | PMA052B | 1927 | 1987 | 61 | 0.504 | 0.297 | 0.612 | -0.025 |
| 16 | PMA065B | 1807 | 2006 | 200 | 0.594 | 0.232 | 0.331 | -0.027 |
| 17 | PMA072A | 1936 | 2003 | 68 | 0.572 | 0.220 | 0.612 | -0.022 |
| 18 | PMA101B | 1914 | 2005 | 92 | 0.525 | 0.301 | 0.556 | -0.054 |
| 19 | PMA104A | 1900 | 2006 | 107 | 0.562 | 0.262 | 0.374 | -0.005 |
| 20 | PMA104B | 1903 | 2006 | 104 | 0.581 | 0.221 | 0.368 | 0.010 |
| 21 | PMA112B | 1948 | 2006 | 59 | 0.524 | 0.210 | 0.448 | -0.027 |
| 22 | PMB017A | 1935 | 2006 | 72 | 0.459 | 0.239 | 0.624 | 0.007 |
| 23 | PMB017B | 1942 | 2006 | 65 | 0.405 | 0.231 | 0.639 | -0.064 |
| 24 | PMB021A | 1900 | 2006 | 107 | 0.610 | 0.247 | 0.531 | 0.076 |
| 25 | PMB021B | 1900 | 2005 | 106 | 0.574 | 0.257 | 0.458 | -0.043 |
| 26 | PMB032B | 1952 | 2006 | 55 | 0.398 | 0.233 | 0.417 | 0.049 |
| 27 | PMB043A | 1935 | 2006 | 72 | 0.503 | 0.212 | 0.393 | -0.011 |
| 28 | PMB043B | 1941 | 2004 | 64 | 0.509 | 0.221 | 0.487 | 0.051 |
| 29 | PMB046B | 1940 | 2006 | 67 | 0.457 | 0.254 | 0.512 | 0.082 |
| 30 | PMB050A | 1940 | 2006 | 67 | 0.538 | 0.189 | 0.495 | 0.024 |
| 31 | PMB050B | 1940 | 1999 | 60 | 0.396 | 0.155 | 0.500 | 0.004 |
| 32 | PMC012A | 1937 | 2003 | 67 | 0.602 | 0.315 | 0.642 | -0.052 |
| 33 | PMC012B | 1934 | 2000 | 67 | 0.535 | 0.344 | 0.527 | 0.136 |
| 34 | PMC081A | 1955 | 2006 | 52 | 0.466 | 0.399 | 0.548 | -0.023 |
| 35 | PMC091A | 1940 | 2006 | 67 | 0.504 | 0.296 | 0.473 | -0.047 |

**Appendix A-4:** *continued*

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 36 | PMC091B | 1940 | 2006 | 67 | 0.559 | 0.322 | 0.429 | -0.064 |
| 37 | PMT001A | 1906 | 2005 | 100 | 0.442 | 0.368 | 0.461 | 0.035 |
| 38 | PMT001B | 1905 | 2006 | 102 | 0.518 | 0.326 | 0.454 | -0.017 |
| 39 | PMT002A | 1828 | 1989 | 162 | 0.495 | 0.381 | 0.359 | 0.056 |
| 40 | PMT003A | 1928 | 2006 | 79 | 0.607 | 0.236 | 0.438 | 0.032 |
| 41 | PMT003B | 1945 | 2006 | 62 | 0.429 | 0.266 | 0.564 | 0.090 |
| 42 | PMT004A | 1934 | 2006 | 73 | 0.619 | 0.299 | 0.389 | -0.074 |
| 43 | PMT004B | 1944 | 2006 | 63 | 0.560 | 0.231 | 0.589 | -0.077 |
| 44 | PMT005A | 1924 | 2006 | 83 | 0.511 | 0.367 | 0.490 | 0.032 |
| 45 | PMT005B | 1930 | 2006 | 77 | 0.675 | 0.279 | 0.576 | 0.007 |
| 46 | PMT006A | 1841 | 2006 | 166 | 0.539 | 0.297 | 0.366 | -0.038 |
| 47 | PMT006B | 1848 | 2006 | 159 | 0.598 | 0.308 | 0.473 | 0.001 |
| 48 | PMT007A | 1777 | 1939 | 163 | 0.603 | 0.223 | 0.404 | 0.111 |
| 49 | PMT007B | 1783 | 1999 | 217 | 0.581 | 0.223 | 0.369 | 0.012 |
| 50 | PMT008A | 1812 | 2004 | 193 | 0.568 | 0.238 | 0.427 | 0.005 |
| 51 | PMT008B | 1812 | 1999 | 188 | 0.651 | 0.254 | 0.471 | 0.022 |
| 52 | PMT009A | 1746 | 2006 | 261 | 0.509 | 0.281 | 0.377 | -0.014 |
| 53 | PMT010A | 1743 | 2006 | 264 | 0.543 | 0.261 | 0.421 | -0.012 |
| 54 | PMT010B | 1745 | 2006 | 262 | 0.543 | 0.260 | 0.397 | 0.002 |
| 55 | PMT011A | 1742 | 2006 | 265 | 0.526 | 0.241 | 0.395 | 0.003 |
| 56 | PMT011B | 1795 | 2006 | 212 | 0.505 | 0.214 | 0.342 | 0.014 |
| 57 | PMT102R | 1794 | 2005 | 212 | 0.557 | 0.272 | 0.387 | -0.009 |
| 58 | PMT103L | 1905 | 2006 | 102 | 0.544 | 0.290 | 0.458 | -0.004 |
| 59 | PMT104 | 1849 | 1909 | 61 | 0.483 | 0.266 | 0.568 | -0.116 |
| 60 | PMT105U | 1840 | 1926 | 87 | 0.532 | 0.275 | 0.578 | 0.041 |
| 61 | PMT106L | 1942 | 2002 | 61 | 0.507 | 0.305 | 0.601 | -0.017 |
| 62 | PMT108 | 1818 | 1979 | 162 | 0.449 | 0.326 | 0.496 | 0.011 |
| 63 | PMT110L1 | 1897 | 1961 | 65 | 0.628 | 0.267 | 0.535 | 0.048 |
| 64 | PMT110L2 | 1749 | 1838 | 90 | 0.430 | 0.302 | 0.518 | -0.030 |
| 65 | PMT111A | 1790 | 1905 | 116 | 0.394 | 0.223 | 0.412 | 0.007 |
| 66 | PMT112B | 1788 | 1909 | 122 | 0.514 | 0.269 | 0.460 | -0.031 |
| 67 | PMT113A | 1843 | 2006 | 164 | 0.521 | 0.261 | 0.438 | -0.058 |
| 68 | PMT1152 | 1778 | 1861 | 84 | 0.428 | 0.253 | 0.455 | -0.008 |
| 69 | PMT116M | 1750 | 1809 | 60 | 0.510 | 0.205 | 0.508 | 0.012 |
| 70 | PMT119R | 1872 | 1969 | 98 | 0.548 | 0.311 | 0.610 | -0.007 |
| 71 | PMT119L | 1885 | 1945 | 61 | 0.699 | 0.319 | 0.415 | -0.068 |
| 72 | PMT120 | 1923 | 2000 | 78 | 0.522 | 0.314 | 0.464 | -0.031 |

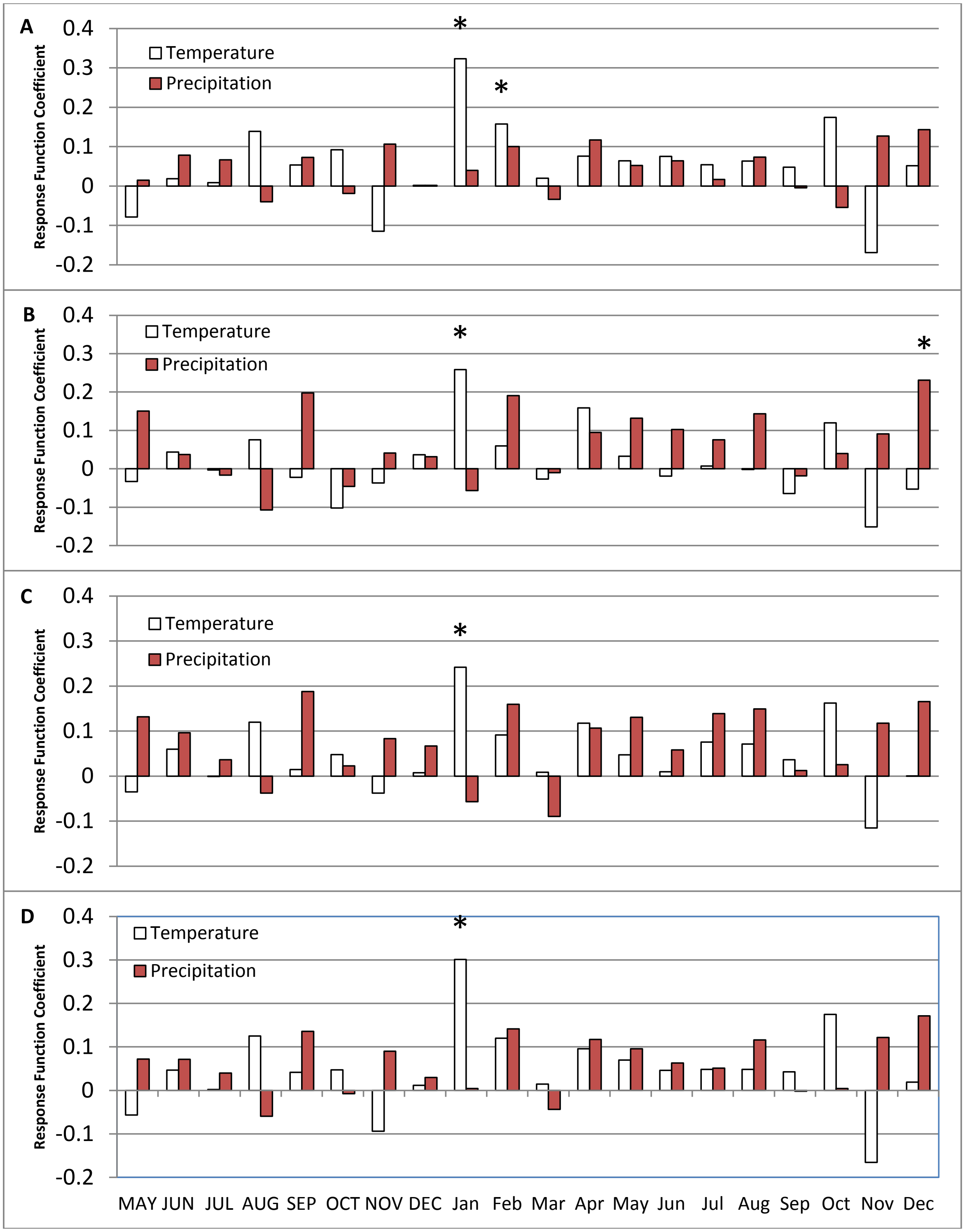
**Appendix A-4:** *continued*

| Seq. | Series | First Year | Last Year | Number of Years | Corr. with Master | Mean Sensitivity | Standard Deviation | Auto Corr. |
|---|---|---|---|---|---|---|---|---|
| 73 | PMT120S1 | 1833 | 1900 | 68 | 0.594 | 0.270 | 0.533 | -0.007 |
| 74 | PMT120S2 | 1903 | 2001 | 99 | 0.659 | 0.296 | 0.668 | 0.112 |
| 75 | PMT120M | 1833 | 2001 | 169 | 0.627 | 0.287 | 0.325 | -0.024 |
| 76 | PMT121A | 1840 | 1926 | 87 | 0.532 | 0.275 | 0.578 | 0.041 |
| 77 | PMT121A3 | 1827 | 1918 | 92 | 0.622 | 0.256 | 0.501 | -0.011 |
| 78 | PMT122A | 1860 | 1975 | 116 | 0.544 | 0.323 | 0.476 | 0.045 |
| 79 | PMT122BR | 1830 | 1976 | 147 | 0.522 | 0.284 | 0.397 | 0.037 |
| 80 | PMT123A | 1806 | 1932 | 127 | 0.429 | 0.266 | 0.510 | 0.005 |
| 81 | PMT123B | 1782 | 1942 | 161 | 0.439 | 0.245 | 0.398 | -0.018 |
| 82 | PMT126 | 1850 | 1989 | 140 | 0.405 | 0.183 | 0.468 | -0.034 |
| 83 | PMT126L | 1908 | 2003 | 96 | 0.500 | 0.262 | 0.398 | -0.067 |
| 84 | PMX102A | 1830 | 1923 | 94 | 0.465 | 0.276 | 0.606 | -0.056 |
| 85 | PMX102B | 1833 | 1942 | 110 | 0.464 | 0.267 | 0.494 | 0.040 |
| 86 | PMX105AR | 1838 | 1980 | 143 | 0.608 | 0.365 | 0.454 | -0.016 |
| 87 | PMX106R | 1830 | 1937 | 108 | 0.451 | 0.363 | 0.415 | 0.001 |
| 88 | PMX107 | 1848 | 1953 | 106 | 0.537 | 0.277 | 0.428 | -0.078 |
| 89 | PMX108 | 1872 | 1979 | 108 | 0.562 | 0.291 | 0.429 | -0.033 |
| 90 | PMX109A | 1850 | 1959 | 110 | 0.528 | 0.276 | 0.595 | -0.008 |
| 91 | PMX109B | 1850 | 1949 | 100 | 0.420 | 0.243 | 0.567 | -0.035 |
| 92 | PMX113 | 1874 | 1969 | 96 | 0.540 | 0.286 | 0.482 | 0.010 |
| 93 | PMX113L | 1880 | 2000 | 121 | 0.533 | 0.318 | 0.442 | 0.003 |
| 94 | PMX114A | 1889 | 1979 | 91 | 0.571 | 0.390 | 0.612 | 0.045 |
| 95 | PMX114BL | 1882 | 1969 | 88 | 0.438 | 0.338 | 0.526 | -0.020 |
| 96 | PMX115 | 1885 | 2000 | 116 | 0.479 | 0.341 | 0.284 | -0.064 |
| 97 | PMX116 | 1790 | 1969 | 180 | 0.384 | 0.247 | 0.413 | -0.051 |
| 98 | PMX117 | 1815 | 1945 | 131 | 0.480 | 0.214 | 0.395 | -0.007 |
| 99 | PMX1192B | 1835 | 1909 | 75 | 0.308 | 0.280 | 0.590 | -0.039 |
| | | | | | | | | |
| | **Total or Mean** | | | **10737** | **0.527** | **0.272** | **0.457** | **-0.003** |

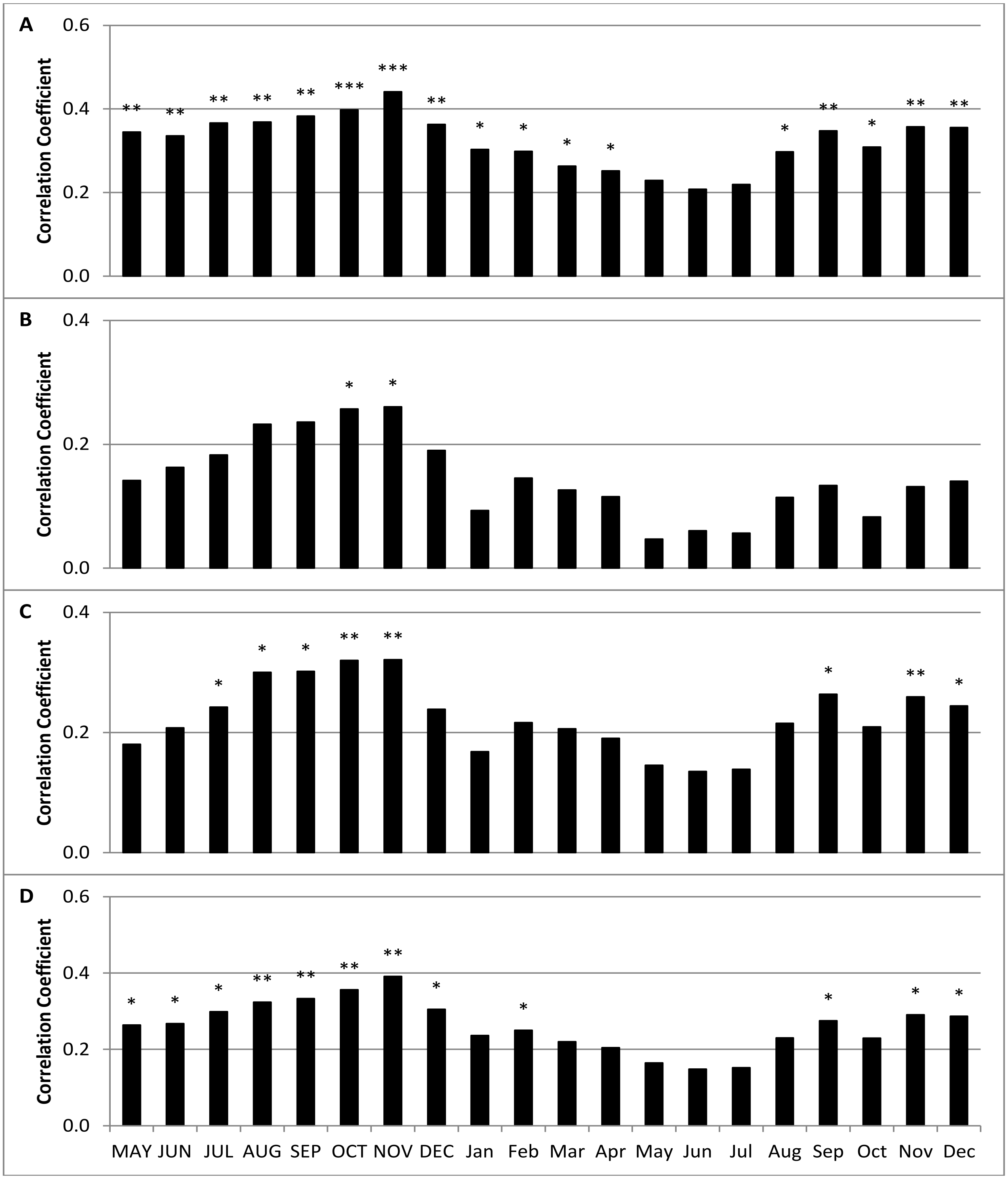
**Appendix A-5:** Standard index chronology for the combined study region . Total ring width measurements were combined from Gold Mine Trail, Rabbit Creek Trail, and Pine Mountain. The indices are displayed without decimal points, but the actual value can be obtained by dividing the numbers by 100. The left column represents the decades, and the top row represents the year within that decade.

| | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
|---|---|---|---|---|---|---|---|---|---|---|
| **1697** | | | | | | | | 1360 | 515 | 838 |
| **1700** | 223 | 396 | 572 | 890 | 1064 | 1002 | 1063 | 732 | 841 | 893 |
| **1710** | 1163 | 1185 | 764 | 1103 | 358 | 763 | 954 | 726 | 845 | 1127 |
| **1720** | 1157 | 1279 | 1682 | 2098 | 1574 | 1477 | 1178 | 1066 | 1163 | 1050 |
| **1730** | 1404 | 1479 | 1371 | 1394 | 1361 | 1194 | 915 | 829 | 934 | 1180 |
| **1740** | 965 | 1211 | 1164 | 1116 | 1246 | 1176 | 967 | 821 | 758 | 889 |
| **1750** | 780 | 754 | 788 | 1029 | 812 | 656 | 844 | 1041 | 961 | 1080 |
| **1760** | 1143 | 1198 | 1196 | 1006 | 797 | 808 | 958 | 1124 | 1008 | 951 |
| **1770** | 972 | 1120 | 719 | 667 | 768 | 935 | 1231 | 1106 | 1061 | 1165 |
| **1780** | 980 | 1074 | 1097 | 1038 | 901 | 986 | 1002 | 1073 | 1071 | 1012 |
| **1790** | 1119 | 1043 | 867 | 1107 | 1082 | 978 | 862 | 675 | 687 | 690 |
| **1800** | 794 | 897 | 925 | 895 | 1100 | 1106 | 1161 | 987 | 1131 | 1032 |
| **1810** | 868 | 945 | 1106 | 995 | 1247 | 1262 | 1090 | 1115 | 1052 | 1171 |
| **1820** | 1006 | 1078 | 1204 | 937 | 802 | 1038 | 759 | 1052 | 1036 | 1054 |
| **1830** | 968 | 1199 | 1001 | 901 | 1029 | 949 | 945 | 860 | 773 | 911 |
| **1840** | 1095 | 1033 | 1021 | 766 | 927 | 1147 | 1063 | 1014 | 895 | 971 |
| **1850** | 922 | 1081 | 1143 | 1107 | 928 | 1123 | 745 | 897 | 940 | 1266 |
| **1860** | 1019 | 1286 | 867 | 850 | 1019 | 879 | 892 | 1110 | 1021 | 940 |
| **1870** | 1037 | 1178 | 854 | 839 | 935 | 1273 | 1091 | 1024 | 1218 | 1010 |
| **1880** | 1128 | 969 | 1400 | 928 | 1035 | 819 | 1023 | 941 | 1114 | 1185 |
| **1890** | 962 | 699 | 782 | 806 | 713 | 608 | 832 | 972 | 840 | 652 |
| **1900** | 762 | 1033 | 903 | 1123 | 948 | 981 | 1148 | 1065 | 961 | 1175 |
| **1910** | 955 | 867 | 920 | 859 | 852 | 1014 | 1268 | 1103 | 1187 | 1058 |
| **1920** | 1092 | 962 | 1090 | 1177 | 886 | 810 | 1053 | 939 | 1193 | 1125 |
| **1930** | 876 | 1082 | 986 | 1237 | 852 | 1174 | 854 | 1114 | 1452 | 1174 |
| **1940** | 1002 | 889 | 1084 | 1086 | 955 | 1253 | 1055 | 1180 | 1409 | 1189 |
| **1950** | 1200 | 982 | 1024 | 944 | 895 | 997 | 1127 | 1189 | 1112 | 1078 |
| **1960** | 906 | 951 | 724 | 624 | 757 | 844 | 832 | 764 | 832 | 1007 |
| **1970** | 1025 | 928 | 950 | 1166 | 1329 | 919 | 783 | 789 | 616 | 675 |
| **1980** | 811 | 1009 | 949 | 1036 | 1062 | 660 | 631 | 567 | 687 | 1069 |
| **1990** | 1431 | 1348 | 926 | 869 | 782 | 1024 | 1293 | 1139 | 1163 | 952 |
| **2000** | 1168 | 1067 | 952 | 1130 | 1177 | 1095 | 1059 | 854 | | |

**Appendix B-1:** Results of Response Function Analysis for temperature and precipitation against yellow pine growth. A) GMT, B) RCT, C) PMT, D) Combined (ALL). Significance indicated by * (P < 0.05). Months in previous year are capitalized.



**Appendix B-2:** Correlation results for AMO and yellow pine growth. **A)** GMT, **B)** RCT, **C)** PMT, **D)** Combined (ALL). Months in previous year are capitalized. Significance is indicated by * ($P < 0.05$), ** ($P < 0.01$), and *** ($P < 0.001$).



**Appendix B-3:** Correlation results for monthly and seasonal climate variables at Gold Mine Trail. Positive values are highlighted in yellow and negative values are brown.

| Temperature | | Precipitation | | PDSI | | PHDI | | NAO | | AMO | | EA | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation |
| Jan-Feb | 0.54 *** | Dec | 0.28 * | Feb | 0.34 ** | None | None | Jan-Feb | 0.45 *** | NOV | 0.44 *** | JUL | 0.33 * |
| Jan | 0.47 *** | Feb | 0.25 * | Feb-Mar | 0.30 * | | | Jan | 0.37 ** | OCT-NOV | 0.43 *** | | |
| Feb | 0.40 *** | | | Feb-Apr | 0.29 * | | | Feb | 0.37 ** | SEP-NOV | 0.42 *** | | |
| Oct | 0.25 * | | | Feb-May | 0.29 * | | | NOV | -0.28 * | AUG-NOV | 0.41 *** | | |
| | | | | Jan-May | 0.29 * | | | Jun | -0.29 * | SEP-DEC | 0.41 *** | | |
| | | | | Jan-Mar | 0.29 * | | | | | OCT-DEC | 0.41 *** | | |
| | | | | Dec | 0.28 * | | | | | JUL-NOV | 0.41 *** | | |
| | | | | Jan-Apr | 0.28 * | | | | | AUG-DEC | 0.41 *** | | |
| | | | | Feb-Jun | 0.28 * | | | | | JUL-DEC | 0.41 *** | | |
| | | | | Jan-Jun | 0.28 * | | | | | OCT | 0.40 *** | | |
| | | | | Mar-May | 0.26 * | | | | | SEP | 0.38 ** | | |
| | | | | Mar-Jun | 0.26 * | | | | | AUG | 0.37 ** | | |
| | | | | Apr-May | 0.26 * | | | | | JUL | 0.37 ** | | |
| | | | | Mar-Apr | 0.26 * | | | | | DEC | 0.36 ** | | |
| | | | | May | 0.25 * | | | | | Nov | 0.36 ** | | |
| | | | | Mar | 0.25 * | | | | | Dec | 0.36 ** | | |
| | | | | Apr | 0.24 * | | | | | Sep | 0.35 ** | | |
| | | | | | | | | | | MAY | 0.35 ** | | |
| | | | | | | | | | | JUN | 0.34 ** | | |
| | | | | | | | | | | Oct | 0.31 * | | |
| | | | | | | | | | | Jan | 0.30 * | | |
| | | | | | | | | | | Feb | 0.30 * | | |
| | | | | | | | | | | Aug | 0.30 * | | |
| | | | | | | | | | | Mar | 0.26 * | | |
| | | | | | | | | | | Apr | 0.25 * | | |

| | |
|---|---|
| * | p < 0.05 |
| ** | p < 0.01 |
| *** | P < 0.001 |

**Appendix B-4:** Correlation results for monthly and seasonal climate variables at Rabbit Creek Trail. Positive values are highlighted in yellow and negative values are brown.

| Temperature | | Precipitation | | PDSI | | PHDI | | NAO | | AMO | | EA | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation |
| Jan-Feb | 0.33 ** | Dec | 0.35 ** | Feb-Dec | 0.52 *** | Dec | 0.46 *** | Jan-Feb | 0.37 ** | OCT-NOV | 0.26 * | None | None |
| Jan | 0.30 * | May | 0.33 ** | Mar-Dec | 0.52 *** | Jun-Dec | 0.46 *** | Feb | 0.34 ** | NOV | 0.26 * | | |
| | | Feb | 0.31 * | Apr-Dec | 0.52 *** | May-Dec | 0.46 *** | Jan | 0.27 * | SEP-NOV | 0.26 * | | |
| | | SEP | 0.29 * | Dec | 0.52 *** | Jul-Dec | 0.46 *** | OCT | -0.33 * | OCT | 0.26 * | | |
| | | | | May-Dec | 0.52 *** | Apr-Dec | 0.45 *** | | | AUG-NOV | 0.26 * | | |
| | | | | Feb-Nov | 0.51 *** | Aug-Dec | 0.45 *** | | | | | | |
| | | | | Jun-Dec | 0.51 *** | Mar-Dec | 0.45 *** | | | | | | |
| | | | | Mar-Nov | 0.50 *** | Feb-Dec | 0.44 *** | | | | | | |
| | | | | Apr-Nov | 0.50 *** | Nov-Dec | 0.44 *** | | | | | | |
| | | | | May-Aug | 0.50 *** | Jun-Nov | 0.44 *** | | | | | | |
| | | | | May-Sep | 0.50 *** | May-Nov | 0.44 *** | | | | | | |
| | | | | Apr-Sep | 0.50 *** | Sep-Dec | 0.44 *** | | | | | | |
| | | | | May-Jun | 0.50 *** | Jul-Nov | 0.44 *** | | | | | | |
| | | | | Feb-Oct | 0.50 *** | Apr-Nov | 0.44 *** | | | | | | |
| | | | | Feb-Sep | 0.50 *** | Oct-Dec | 0.43 *** | | | | | | |
| | | | | May-Jul | 0.50 *** | Jun-Oct | 0.43 *** | | | | | | |
| | | | | Apr-Aug | 0.50 *** | Jul-Oct | 0.43 *** | | | | | | |
| | | | | May-Nov | 0.50 *** | Aug-Nov | 0.43 *** | | | | | | |
| | | | | Apr-Oct | 0.50 *** | May-Oct | 0.43 *** | | | | | | |
| | | | | Mar-Sep | 0.50 *** | Mar-Nov | 0.43 *** | | | | | | |
| | | | | Mar-Oct | 0.50 *** | Feb-Nov | 0.43 *** | | | | | | |
| | | | | Feb-Aug | 0.50 *** | Jun-Sep | 0.43 *** | | | | | | |
| | | | | May-Oct | 0.50 *** | Aug-Oct | 0.42 *** | | | | | | |
| | | | | May | 0.50 *** | Apr-Oct | 0.42 *** | | | | | | |
| | | | | Jul-Dec | 0.50 *** | Aug-Sep | 0.42 *** | | | | | | |
| | | | | Mar-Aug | 0.49 *** | Jul-Sep | 0.42 *** | | | | | | |
| | | | | Jun-Aug | 0.49 *** | Sep-Nov | 0.42 *** | | | | | | |
| | | | | Jun | 0.49 *** | May-Sep | 0.42 *** | | | | | | |
| | | | | Aug | 0.47 *** | Sep | 0.42 *** | | | | | | |
| | | | | Jul | 0.47 *** | Mar-Oct | 0.42 *** | | | | | | |
| | | | | Feb | 0.43 *** | Feb-Oct | 0.41 *** | | | | | | |
| | | | | Sep | 0.42 *** | Jul-Aug | 0.41 *** | | | | | | |
| | | | | Nov | 0.42 *** | Sep-Oct | 0.41 *** | | | | | | |
| | | | | Oct | 0.40 *** | Nov | 0.41 *** | | | | | | |
| | | | | Apr | 0.39 ** | Aug | 0.41 *** | | | | | | |
| | | | | Mar | 0.38 ** | Oct-Nov | 0.41 *** | | | | | | |
| | | | | DEC | 0.31 * | Jul | 0.40 *** | | | | | | |
| | | | | SEP | 0.30 * | Oct | 0.40 *** | | | | | | |
| | | | | Jan | 0.29 * | Jun | 0.37 ** | | | | | | |
| | | | | NOV | 0.29 * | May | 0.34 ** | | | | | | |
| | | | | OCT | 0.28 * | Feb | 0.33 ** | | | | | | |
| | | | | | | Mar | 0.29 * | | | | | | |
| | | | | | | Apr | 0.28 * | | | | | | |

| | |
|---|---|
| * | p < 0.05 |
| ** | p < 0.01 |
| *** | P < 0.001 |

**Appendix B-5:** Correlation results for monthly and seasonal climate variables at Pine Mountain Trail. Positive values are highlighted in yellow and negative values are brown.

| Temperature | | Precipitation | | PDSI | | PHDI | | NAO | | AMO | | EA | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation |
| Jan-Feb | 0.33 ** | Dec | 0.31 * | Dec | 0.43 *** | Dec | 0.35 ** | Jan-Feb | 0.37 ** | OCT-NOV | 0.33 ** | None | None |
| Jan | 0.29 * | Feb | 0.30 * | Feb-Dec | 0.41 *** | Jul-Dec | 0.35 ** | Jan | 0.30 * | SEP-NOV | 0.32 ** | | |
| | | May | 0.27 * | Mar-Dec | 0.40 *** | May-Dec | 0.35 ** | Feb | 0.30 * | AUG-NOV | 0.32 ** | | |
| | | | | Apr-Dec | 0.40 *** | Jun-Dec | 0.35 ** | OCT | -0.31 * | NOV | 0.32 ** | | |
| | | | | Feb-Aug | 0.40 *** | Apr-Dec | 0.35 ** | | | OCT | 0.32 ** | | |
| | | | | May | 0.40 *** | Feb-Dec | 0.34 ** | | | SEP-OCT | 0.32 ** | | |
| | | | | Nov-Dec | 0.40 *** | Aug-Dec | 0.34 ** | | | AUG-OCT | 0.31 * | | |
| | | | | Feb | 0.39 *** | Mar-Dec | 0.34 ** | | | JUL-NOV | 0.31 * | | |
| | | | | Feb-Sep | 0.39 ** | Jul-Nov | 0.34 ** | | | AUG-DEC | 0.31 * | | |
| | | | | May-Dec | 0.39 ** | Nov-Dec | 0.34 ** | | | SEP-DEC | 0.31 * | | |
| | | | | Feb-Nov | 0.39 ** | May-Nov | 0.33 ** | | | AUG-SEP | 0.30 * | | |
| | | | | May-Aug | 0.39 ** | Jul-Sep | 0.33 ** | | | JUL-DEC | 0.30 * | | |
| | | | | Apr-Aug | 0.39 ** | Jun-Nov | 0.33 ** | | | JUL-OCT | 0.30 * | | |
| | | | | Jan-Aug | 0.39 ** | Apr-Nov | 0.33 ** | | | SEP | 0.30 * | | |
| | | | | Feb-Jul | 0.39 ** | Jul-Oct | 0.33 ** | | | OCT-DEC | 0.30 * | | |
| | | | | Jan-Sep | 0.39 ** | Sep-Dec | 0.33 ** | | | AUG | 0.30 * | | |
| | | | | Mar-Aug | 0.39 ** | Feb-Nov | 0.33 ** | | | Sep | 0.26 * | | |
| | | | | Feb-Oct | 0.39 ** | Aug-Sep | 0.33 ** | | | Nov | 0.26 * | | |
| | | | | Apr-Sep | 0.38 ** | Jul-Aug | 0.33 ** | | | Dec | 0.24 * | | |
| | | | | Jan-Oct | 0.38 ** | May-Oct | 0.33 ** | | | JUL | 0.24 * | | |
| | | | | Mar-Nov | 0.38 ** | Jun-Oct | 0.33 ** | | | | | | |
| | | | | Mar-Sep | 0.38 ** | Aug-Nov | 0.33 ** | | | | | | |
| | | | | Jun-Dec | 0.38 ** | Mar-Nov | 0.33 ** | | | | | | |
| | | | | Feb-Jun | 0.38 ** | Oct-Dec | 0.33 ** | | | | | | |
| | | | | Apr-Jul | 0.38 ** | Jun-Sep | 0.32 ** | | | | | | |
| | | | | May-Sep | 0.38 ** | Apr-Oct | 0.32 ** | | | | | | |
| | | | | Jan-Jul | 0.38 ** | Aug-Oct | 0.32 ** | | | | | | |
| | | | | Apr-Nov | 0.38 ** | Aug | 0.32 ** | | | | | | |
| | | | | Jul-Dec | 0.38 ** | May-Sep | 0.32 ** | | | | | | |
| | | | | May-Nov | 0.38 ** | Sep | 0.32 ** | | | | | | |
| | | | | Aug | 0.38 ** | Jul | 0.32 ** | | | | | | |
| | | | | Jul | 0.37 ** | Sep-Nov | 0.32 ** | | | | | | |
| | | | | Jun | 0.36 ** | Nov | 0.31 * | | | | | | |
| | | | | Nov | 0.34 ** | Oct-Nov | 0.30 * | | | | | | |
| | | | | Apr | 0.31 * | Feb | 0.29 * | | | | | | |
| | | | | DEC | 0.31 * | Oct | 0.29 * | | | | | | |
| | | | | Mar | 0.30 * | May | 0.27 * | | | | | | |
| | | | | Sep | 0.29 * | Jun | 0.26 * | | | | | | |
| | | | | NOV | 0.27 * | | | | | | | | |
| | | | | Jan | 0.26 * | | | | | | | | |
| | | | | Oct | 0.25 * | | | | | | | | |

| | |
|---|---|
| * | p < 0.05 |
| ** | p < 0.01 |
| *** | P < 0.001 |

**Appendix B-6:** Correlation results for monthly and seasonal climate variables over the combined study area. All values were positive.

| Temperature | | Precipitation | | PDSI | | PHDI | | NAO | | AMO | | EA | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation | Month(s) | Correlation |
| Jan-Feb | 0.47 *** | Dec | 0.32 ** | Dec | 0.39 ** | Dec | 0.31 * | Jan-Feb | 0.43 ** | NOV | 0.39 ** | JUL | 0.27 * |
| Jan | 0.41 *** | Feb | 0.30 * | Feb | 0.39 ** | Feb-Dec | 0.29 * | Feb | 0.36 ** | OCT-NOV | 0.38 ** | | |
| Feb | 0.34 ** | | | Feb-May | 0.37 ** | Apr-Dec | 0.29 * | Jan | 0.34 * | SEP-NOV | 0.37 ** | | |
| | | | | Feb-Jun | 0.37 ** | Mar-Dec | 0.29 * | | | AUG-NOV | 0.36 ** | | |
| | | | | Feb-Aug | 0.37 ** | May-Dec | 0.29 * | | | OCT-DEC | 0.36 ** | | |
| | | | | Feb-Jul | 0.37 ** | Nov-Dec | 0.28 * | | | SEP-DEC | 0.36 ** | | |
| | | | | Feb-Dec | 0.36 ** | Jun-Dec | 0.28 * | | | AUG-DEC | 0.36 ** | | |
| | | | | Feb-Mar | 0.36 ** | Feb-Nov | 0.28 * | | | JUL-NOV | 0.36 ** | | |
| | | | | Jan-Aug | 0.36 ** | Jul-Dec | 0.28 * | | | OCT | 0.36 ** | | |
| | | | | Jan-Jul | 0.36 ** | Apr-Nov | 0.28 * | | | SEP | 0.33 ** | | |
| | | | | Jan-Jun | 0.36 ** | Mar-Nov | 0.28 * | | | AUG | 0.32 ** | | |
| | | | | Feb-Sep | 0.36 ** | Feb-Oct | 0.28 * | | | DEC | 0.31 * | | |
| | | | | Feb-Sep | 0.36 ** | Aug-Dec | 0.27 * | | | JUL | 0.30 * | | |
| | | | | Jan-Sep | 0.36 ** | May-Nov | 0.27 * | | | Nov | 0.29 * | | |
| | | | | Jan-May | 0.36 ** | Feb-Sep | 0.27 * | | | Dec | 0.29 * | | |
| | | | | Feb-Apr | 0.36 ** | Apr-Oct | 0.27 * | | | Sep | 0.28 * | | |
| | | | | May | 0.35 ** | Mar-Oct | 0.27 * | | | JUN | 0.27 * | | |
| | | | | Feb-Nov | 0.35 ** | Sep-Dec | 0.27 * | | | MAY | 0.26 * | | |
| | | | | Nov-Dec | 0.35 ** | Jun-Nov | 0.27 * | | | Feb | 0.25 * | | |
| | | | | Apr-Dec | 0.35 ** | Oct-Dec | 0.27 * | | | | | | |
| | | | | May-Dec | 0.34 ** | Apr-Sep | 0.27 * | | | | | | |
| | | | | Mar-Nov | 0.34 ** | Jul-Nov | 0.27 * | | | | | | |
| | | | | Apr-Nov | 0.33 ** | May-Oct | 0.27 * | | | | | | |
| | | | | Mar-Dec | 0.33 ** | Mar-Sep | 0.27 * | | | | | | |
| | | | | Jun-Dec | 0.33 ** | May-Sep | 0.27 * | | | | | | |
| | | | | Jun | 0.32 ** | Feb-Aug | 0.27 * | | | | | | |
| | | | | Apr | 0.31 * | Jul-Sep | 0.26 * | | | | | | |
| | | | | Aug | 0.31 * | Jun-Oct | 0.26 * | | | | | | |
| | | | | Mar | 0.31 * | Jul-Oct | 0.26 * | | | | | | |
| | | | | Jul | 0.30 * | Jul | 0.26 * | | | | | | |
| | | | | Nov | 0.28 * | Feb | 0.26 * | | | | | | |
| | | | | Jan | 0.26 * | Aug-Nov | 0.26 * | | | | | | |
| | | | | DEC | 0.25 * | Sep | 0.25 * | | | | | | |
| | | | | Sep | 0.24 * | Nov | 0.25 * | | | | | | |
| | | | | | | Aug | 0.25 * | | | | | | |

| | |
|---|---|
| * | p < 0.05 |
| ** | p < 0.01 |
| *** | P < 0.001 |

**Appendix C-1:** Stand composition of canopy-class trees (> 5 cm dbh) at Gold Mine Trail. Three 20 m x 50 m plots were inventoried at the site.

| Species | Basal Area (m2/ha) | Stem # per Site (total 3 plots) | Density (stems per ha) | Dominance (BA / .3 ha) | Relative Density (%) | Relative Dominance (%) | Importance [(RDn + RDm)/2] |
|---|---|---|---|---|---|---|---|
| *Acer rubrum* | 7.4 | 31 | 103.2 | 24.51 | 11.03 | 8.07 | 10 |
| *Carya tomentosa* | 7.5 | 12 | 40.0 | 25.02 | 4.27 | 8.23 | 6 |
| *Magnolia fraseri* | 0.1 | 2 | 6.7 | 0.17 | 0.71 | 0.06 | 0 |
| *Nyssa sylvatica* | 4.6 | 60 | 199.8 | 15.30 | 21.35 | 5.03 | 13 |
| *Oxydendron arborea* | 5.1 | 42 | 139.9 | 16.92 | 14.95 | 5.57 | 10 |
| *Pinus echinata* | 14.2 | 11 | 36.6 | 47.35 | 3.91 | 15.58 | 10 |
| *Pinus rigida* | 2.3 | 2 | 6.7 | 7.62 | 0.71 | 2.51 | 2 |
| *Pinus strobus* | 13.4 | 25 | 83.3 | 44.54 | 8.90 | 14.66 | 12 |
| *Pinus virginiana* | 0.2 | 1 | 3.3 | 0.82 | 0.36 | 0.27 | 0 |
| *Quercus alba* | 13.4 | 27 | 89.9 | 44.70 | 9.61 | 14.71 | 12 |
| *Quercus coccinia* | 8.7 | 26 | 86.6 | 29.02 | 9.25 | 9.55 | 9 |
| *Quercus montana* | 6.6 | 16 | 53.3 | 21.99 | 5.69 | 7.24 | 6 |
| *Quercus velutina* | 4.4 | 12 | 40.0 | 14.70 | 4.27 | 4.84 | 5 |
| *Tsuga canadensis* | 3.4 | 14 | 46.6 | 11.25 | 4.98 | 3.70 | 4 |

**Appendix C-2:** Stand composition of canopy-class trees (> 5 cm dbh) at Rabbit Creek Trail. Three 20 m x 50 m plots were inventoried at the site.

| Species | Basal Area (m2/ha) | Stem # per Site (total 3 plots) | Density (stems per ha) | Dominance (BA / .3 ha) | Relative Density (%) | Relative Dominance (%) | Importance [(RDn + RDm)/2] |
|---|---|---|---|---|---|---|---|
| *Acer rubrum* | 8.6 | 50 | 166.5 | 28.64 | 14.93 | 7.75 | 11 |
| *Ilex opaca* | 0.1 | 2 | 6.7 | 0.27 | 0.60 | 0.07 | 0 |
| *Nyssa sylvatica* | 1.2 | 18 | 59.9 | 4.12 | 5.37 | 1.12 | 3 |
| *Oxydendron arborea* | 1.3 | 6 | 20.0 | 4.19 | 1.79 | 1.13 | 1 |
| *Pinus rigida* | 9.8 | 8 | 26.6 | 32.60 | 2.39 | 8.82 | 6 |
| *Pinus strobus* | 54.7 | 115 | 383.0 | 182.36 | 34.33 | 49.35 | 42 |
| *Pinus virginiana* | 10.6 | 20 | 66.6 | 35.35 | 5.97 | 9.57 | 8 |
| *Quercus alba* | 0.5 | 1 | 3.3 | 1.68 | 0.30 | 0.45 | 0 |
| *Quercus coccinia* | 5.8 | 7 | 23.3 | 19.45 | 2.09 | 5.26 | 4 |
| *Quercus montana* | 9.6 | 22 | 73.3 | 32.16 | 6.57 | 8.70 | 8 |
| *Quercus rubra* | 0.1 | 1 | 3.3 | 0.19 | 0.30 | 0.05 | 0 |
| *Quercus velutina* | 1.2 | 4 | 13.3 | 3.84 | 1.19 | 1.04 | 1 |
| *Tsuga canadensis* | 7.4 | 81 | 269.7 | 24.67 | 24.18 | 6.67 | 15 |

**Appendix C-3:** Stand composition of canopy-class trees (> 5 cm dbh) at Pine Mountain. Three 20 m x 50 m plots were inventoried at the site.

| Species | Basal Area (m2/ha) | Stem # per Site (total 3 plots) | Density (stems per ha) | Dominance (BA / .3 ha) | Relative Density (%) | Relative Dominance (%) | Importance [(RDn + RDm)/2] |
|---|---|---|---|---|---|---|---|
| *Acer rubrum* | 6.0 | 26 | 86.6 | 20.01 | 8.64 | 7.46 | 8 |
| *Betula lenta* | 0.1 | 1 | 3.3 | 0.40 | 0.33 | 0.15 | 0 |
| *Carya glabra* | 0.1 | 4 | 13.3 | 0.31 | 1.33 | 0.11 | 1 |
| *Carya tomentosa* | 0.3 | 3 | 10.0 | 0.87 | 1.00 | 0.32 | 1 |
| *Diospyros virginiana* | 0.7 | 2 | 6.7 | 2.47 | 0.66 | 0.92 | 1 |
| *Nyssa sylvatica* | 6.4 | 90 | 299.7 | 21.27 | 29.90 | 7.93 | 19 |
| *Oxydendron arborea* | 0.4 | 5 | 16.7 | 1.26 | 1.66 | 0.47 | 1 |
| *Pinus echinata* | 6.9 | 5 | 16.7 | 23.01 | 1.66 | 8.58 | 5 |
| *Pinus pungens* | 0.4 | 1 | 3.3 | 1.33 | 0.33 | 0.49 | 0 |
| *Pinus rigida* | 5.7 | 10 | 33.3 | 18.95 | 3.32 | 7.06 | 5 |
| *Pinus strobus* | 7.2 | 29 | 96.6 | 23.95 | 9.63 | 8.93 | 9 |
| *Pinus virginiana* | 12.8 | 47 | 156.5 | 42.62 | 15.61 | 15.88 | 16 |
| *Quercus coccinia* | 1.6 | 7 | 23.3 | 5.47 | 2.33 | 2.04 | 2 |
| *Quercus marylandica* | 0.3 | 3 | 10.0 | 0.86 | 1.00 | 0.32 | 1 |
| *Quercus montana* | 25.1 | 46 | 153.2 | 83.75 | 15.28 | 31.21 | 23 |
| *Quercus pallustrus* | 0.6 | 1 | 3.3 | 1.98 | 0.33 | 0.74 | 1 |
| *Quercus rubra* | 2.5 | 2 | 6.7 | 8.42 | 0.66 | 3.14 | 2 |
| *Quercus velutina* | 2.3 | 12 | 40.0 | 7.74 | 3.99 | 2.89 | 3 |
| *Tsuga canadensis* | 1.1 | 7 | 23.3 | 3.67 | 2.33 | 1.37 | 2 |

**Appendix C-4:** Depth of duff layer at sampling plots for each study site. Duff depth was measured at six locations across each plot (site n = 18). Duff is defined as material that is below loose leaf litter, but above mineral soil.

| Site | Duff Depth Range (cm) | Duff Depth Average (cm) |
|---|---|---|
| Gold Mine Trail - Plot A | 2–18 | 8.3 |
| Gold Mine Trail - Plot B | 1–6 | 2.8 |
| Gold Mine Trail - Plot C | 5–9 | 6.0 |
| GMT Average = 5.7 cm | | |
| | | |
| Rabbit Creek Trail - Plot A | 4–7 | 5.4 |
| Rabbit Creek Trail - Plot B | 3–9 | 5.5 |
| Rabbit Creek Trail - Plot C | 3–6 | 4.9 |
| RCT Average = 5.3 cm | | |
| | | |
| Pine Mountain - Plot A | 3–10 | 7.0 |
| Pine Mountain - Plot B | 2–13.5 | 6.4 |
| Pine Mountain - Plot C | 3–6 | 4.5 |
| PMT Average = 6.0 cm | | |

**Appendix D-1:** Correlation results for climate reconstructions with each other.
**A**) AMO, **B**) NAO, **C**) NIÑO-3, **D**) PDO, **E**) NHTMP, **F**) PDSI. Native American Period = 1697–1834, European Settler Period = 1835–1934, Full Period = 1697–2006. Actual sample number analyzed varies by the length of overlap between the variables. Significance is indicated by * (P < 0.05), ** (P < 0.01), and *** (P < 0.001).

**A) Atlantic Multidecadal Oscillation**

| Native American Period | | | | | European Settler Period | | | | | Full Period | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI |
| NAO | -0.25 | 0.004 ** | 138 | -0.37... -0.08 | NAO | -0.18 | 0.075 | 100 | -0.36... 0.00 | NAO | -0.16 | 0.0066 ** | 294 | -0.27... -0.05 |
| PDO | -0.05 | 0.532 | 138 | -0.22... 0.14 | PDO | -0.04 | 0.714 | 100 | -0.22... 0.18 | PDO | -0.07 | 0.2685 | 294 | -0.17... 0.06 |
| NHTMP | 0.02 | 0.778 | 138 | -0.16... 0.22 | NHTMP | 0.23 | 0.022 * | 100 | 0.00... 0.39 | NHTMP | 0.20 | 0.0006 *** | 294 | 0.09... 0.32 |
| PDSI | 0.18 | 0.037 * | 138 | 0.01... 0.32 | PDSI | -0.07 | 0.465 | 100 | -0.29... 0.14 | PDSI | 0.08 | 0.1997 | 294 | -0.04... 0.19 |
| NIÑO3 | -0.11 | 0.190 | 138 | -0.28... 0.07 | NIÑO3 | -0.11 | 0.265 | 100 | -0.31... 0.11 | NIÑO3 | -0.10 | 0.1087 | 282 | -0.23... 0.03 |

**B) North Atlantic Oscillation**

| Native American Period | | | | | European Settler Period | | | | | Full Period | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI |
| AMO | -0.25 | 0.004 ** | 138 | -0.37... -0.08 | AMO | -0.18 | 0.075 | 100 | -0.36... 0.00 | AMO | -0.16 | 0.0066 ** | 294 | -0.27... -0.05 |
| PDO | -0.07 | 0.427 | 138 | -0.25... 0.09 | PDO | -0.06 | 0.588 | 100 | -0.24... 0.14 | PDO | -0.04 | 0.5247 | 295 | -0.16... 0.07 |
| NHTMP | 0.09 | 0.316 | 138 | -0.11... 0.27 | NHTMP | 0.12 | 0.254 | 100 | -0.08... 0.31 | NHTMP | 0.09 | 0.1126 | 298 | -0.03... 0.20 |
| PDSI | 0.15 | 0.088 | 138 | -0.01... 0.31 | PDSI | 0.16 | 0.114 | 100 | -0.04... 0.32 | PDSI | 0.20 | 0.0005 *** | 305 | 0.09... 0.31 |
| NIÑO3 | -0.02 | 0.776 | 138 | -0.21... 0.15 | NIÑO3 | 0.04 | 0.670 | 100 | -0.14... 0.25 | NIÑO3 | -0.03 | 0.6241 | 282 | -0.15... 0.08 |

**C) Northern Hemisphere Temperatures**

| Native American Period | | | | | European Settler Period | | | | | Full Period | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI |
| NAO | 0.09 | 0.316 | 138 | -0.13... 0.25 | NAO | 0.12 | 0.254 | 100 | -0.08... 0.33 | NAO | 0.09 | 0.1126 | 298 | -0.01... 0.20 |
| AMO | 0.02 | 0.778 | 138 | -0.15... 0.20 | AMO | 0.23 | 0.022 * | 100 | 0.03... 0.40 | AMO | 0.20 | 0.0006 *** | 294 | 0.09... 0.31 |
| PDO | -0.06 | 0.467 | 138 | -0.23... 0.08 | PDO | -0.12 | 0.235 | 100 | -0.29... 0.09 | PDO | -0.08 | 0.1719 | 295 | -0.18... 0.03 |
| PDSI | 0.14 | 0.114 | 138 | -0.02... 0.29 | PDSI | -0.09 | 0.400 | 100 | -0.26... 0.10 | PDSI | 0.04 | 0.4621 | 298 | -0.06... 0.15 |
| NIÑO3 | 0.01 | 0.937 | 138 | -0.18... 0.19 | NIÑO3 | 0.12 | 0.235 | 100 | -0.08... 0.30 | NIÑO3 | 0.03 | 0.5817 | 282 | -0.08... 0.15 |

**D) El Niño/Southern Oscillation**

| Native American Period | | | | | European Settler Period | | | | | Full Period | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI |
| NAO | -0.02 | 0.776 | 138 | -0.21... 0.16 | NAO | 0.04 | 0.670 | 100 | -0.14... 0.23 | NAO | -0.03 | 0.6241 | 282 | -0.14... 0.08 |
| AMO | -0.11 | 0.190 | 138 | -0.29... 0.06 | AMO | -0.11 | 0.265 | 100 | -0.31... 0.12 | AMO | -0.10 | 0.1087 | 282 | -0.22... 0.03 |
| PDO | 0.33 | 0.000 *** | 138 | 0.15... 0.49 | PDO | 0.21 | 0.041 * | 100 | 0.02... 0.35 | PDO | 0.28 | 0.0000 *** | 282 | 0.16... 0.39 |
| NHTMP | 0.01 | 0.937 | 138 | -0.18... 0.19 | NHTMP | 0.12 | 0.235 | 100 | -0.08... 0.32 | NHTMP | 0.03 | 0.5817 | 282 | -0.08... 0.15 |
| PDSI | -0.02 | 0.866 | 138 | -0.20... 0.17 | PDSI | 0.05 | 0.600 | 100 | -0.15... 0.26 | PDSI | -0.01 | 0.8787 | 282 | -0.15... 0.12 |

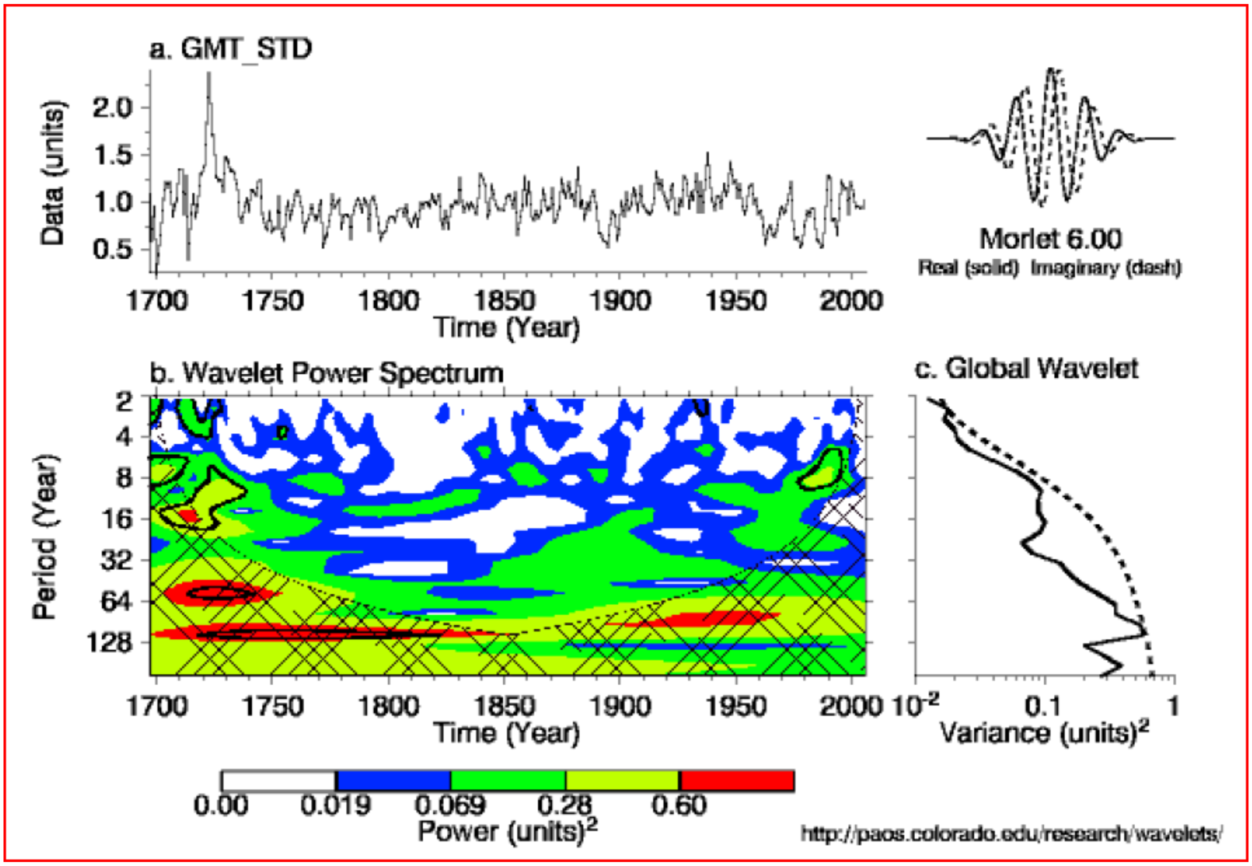
**E) Pacific Decadal Oscillation**

| Native American Period | | | | | European Settler Period | | | | | Full Period | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI |
| NAO | -0.07 | 0.427 | 138 | -0.25... 0.10 | NAO | -0.06 | 0.588 | 100 | -0.23... 0.14 | NAO | -0.04 | 0.5247 | 295 | -0.16... 0.07 |
| AMO | -0.05 | 0.532 | 138 | -0.22... 0.14 | AMO | -0.04 | 0.714 | 100 | -0.22... 0.18 | AMO | -0.07 | 0.2685 | 294 | -0.17... 0.05 |
| NHTMP | -0.06 | 0.467 | 138 | -0.23... 0.08 | NHTMP | -0.12 | 0.235 | 100 | -0.29... 0.09 | NHTMP | -0.08 | 0.1719 | 295 | -0.18... 0.02 |
| PDSI | -0.09 | 0.285 | 138 | -0.27... 0.08 | PDSI | 0.00 | 0.981 | 100 | -0.18... 0.20 | PDSI | -0.06 | 0.2774 | 295 | -0.18... 0.05 |
| NIÑO3 | 0.33 | 0.000 *** | 138 | 0.15... 0.49 | NIÑO3 | 0.21 | 0.041 * | 100 | 0.01... 0.35 | NIÑO3 | 0.28 | 0.0000 *** | 282 | 0.16... 0.38 |

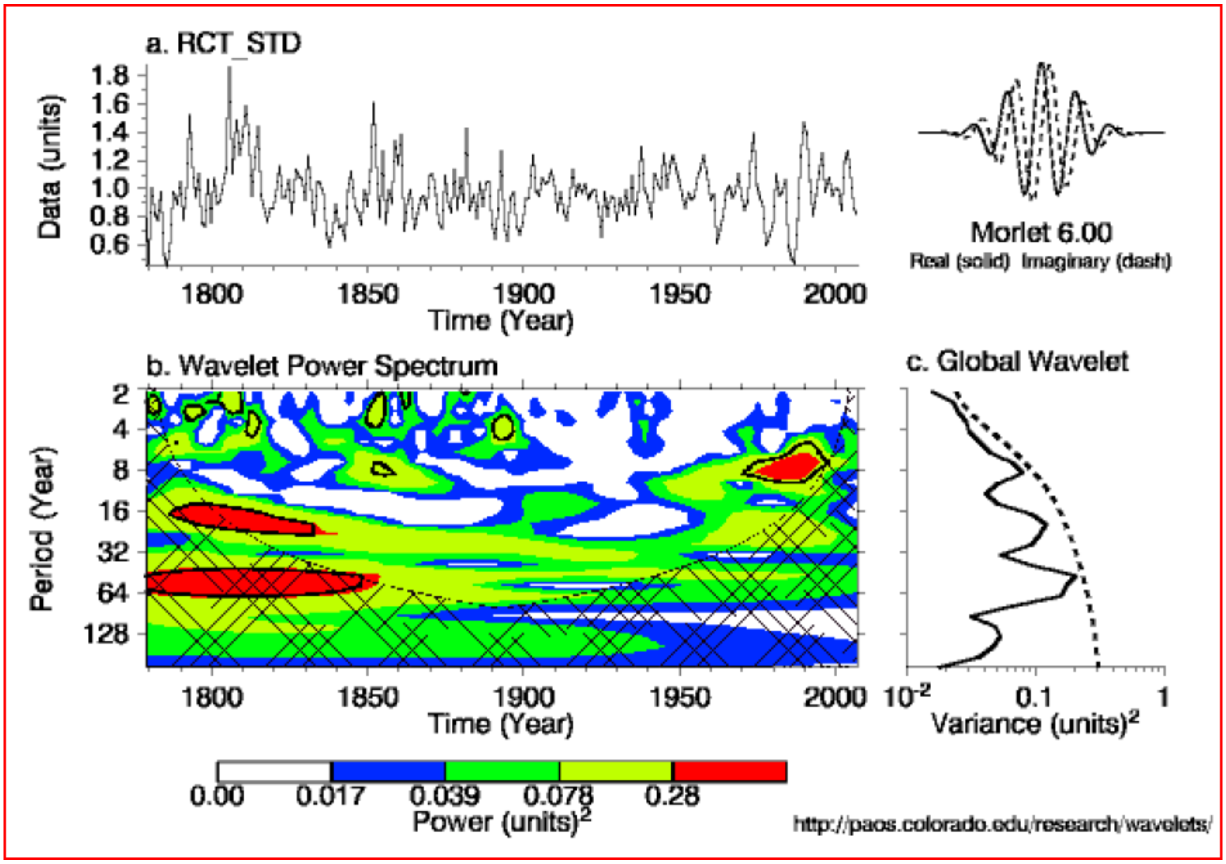
**F) Palmer Drought Severity Index**

| Native American Period | | | | | European Settler Period | | | | | Full Period | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI | | Corr. | P-value | Number | 95% CI |
| NAO | 0.15 | 0.088 | 138 | -0.01... 0.32 | NAO | 0.16 | 0.114 | 100 | -0.04... 0.34 | NAO | 0.20 | 0.0005 *** | 305 | 0.09... 0.30 |
| AMO | 0.18 | 0.037 * | 138 | 0.01... 0.33 | AMO | -0.07 | 0.465 | 100 | -0.29... 0.13 | AMO | 0.08 | 0.1997 | 294 | -0.05... 0.18 |
| PDO | -0.09 | 0.285 | 138 | -0.26... 0.10 | PDO | 0.00 | 0.981 | 100 | -0.19... 0.18 | PDO | -0.06 | 0.2774 | 295 | -0.18... 0.05 |
| NHTMP | 0.14 | 0.114 | 138 | -0.02... 0.29 | NHTMP | -0.09 | 0.400 | 100 | -0.26... 0.10 | NHTMP | 0.04 | 0.4621 | 298 | -0.06... 0.15 |
| NIÑO3 | -0.02 | 0.866 | 138 | -0.20... 0.17 | NIÑO3 | 0.05 | 0.600 | 100 | -0.15... 0.26 | NIÑO3 | -0.01 | 0.8787 | 282 | -0.14... 0.13 |

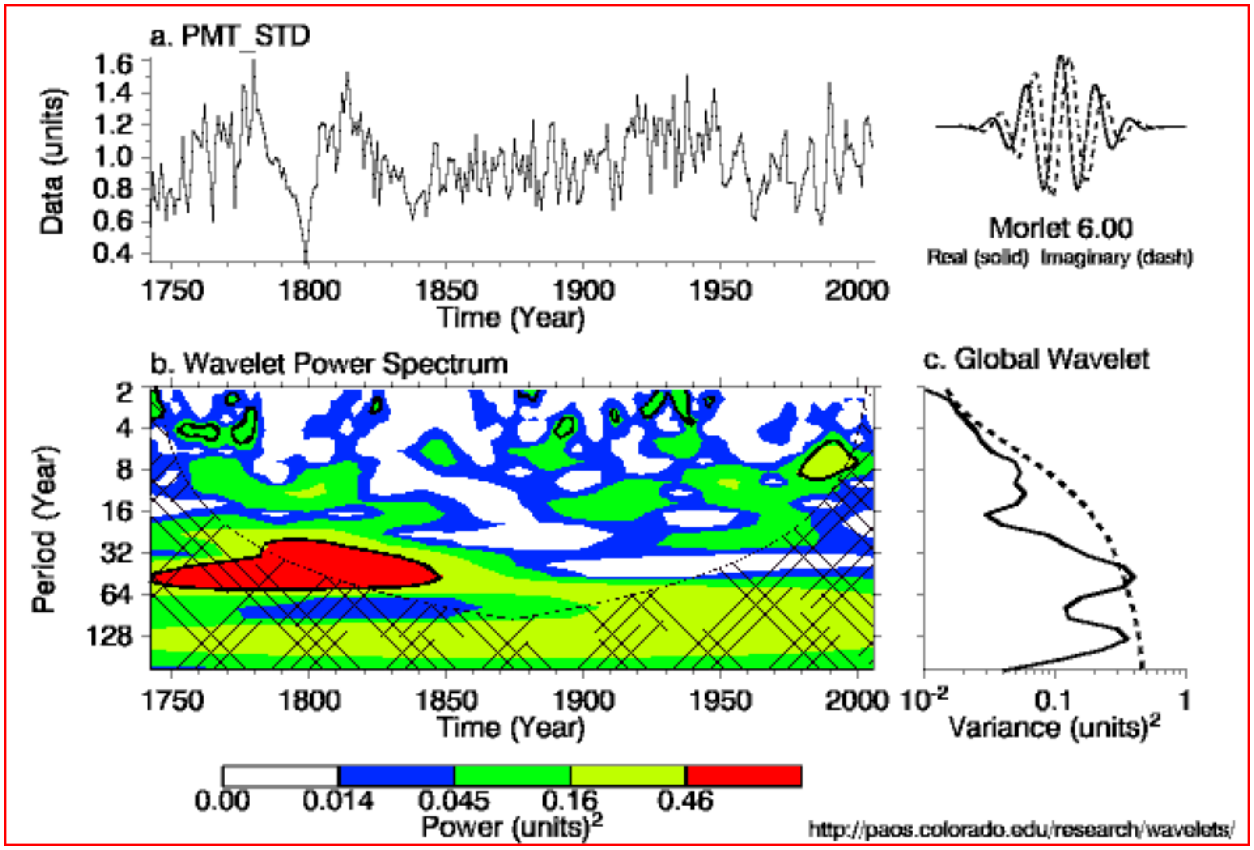
**Appendix D-2**: Wavelet Analysis for Gold Mine Trail standardized chronology. a) The chronology index, b) wavelet power spectra for the chronology, with black lines indicating 5% significance level, c) the global wavelet power spectrum. Crosshatched area represents the cone of influence. Analysis used the Morlet wavelet and zero-padded series (Torrence and Compo 1998). Concentrations of spectral power are around periods of 2–4, 5–20, 56, and 112 (the last two in C.O.I.)



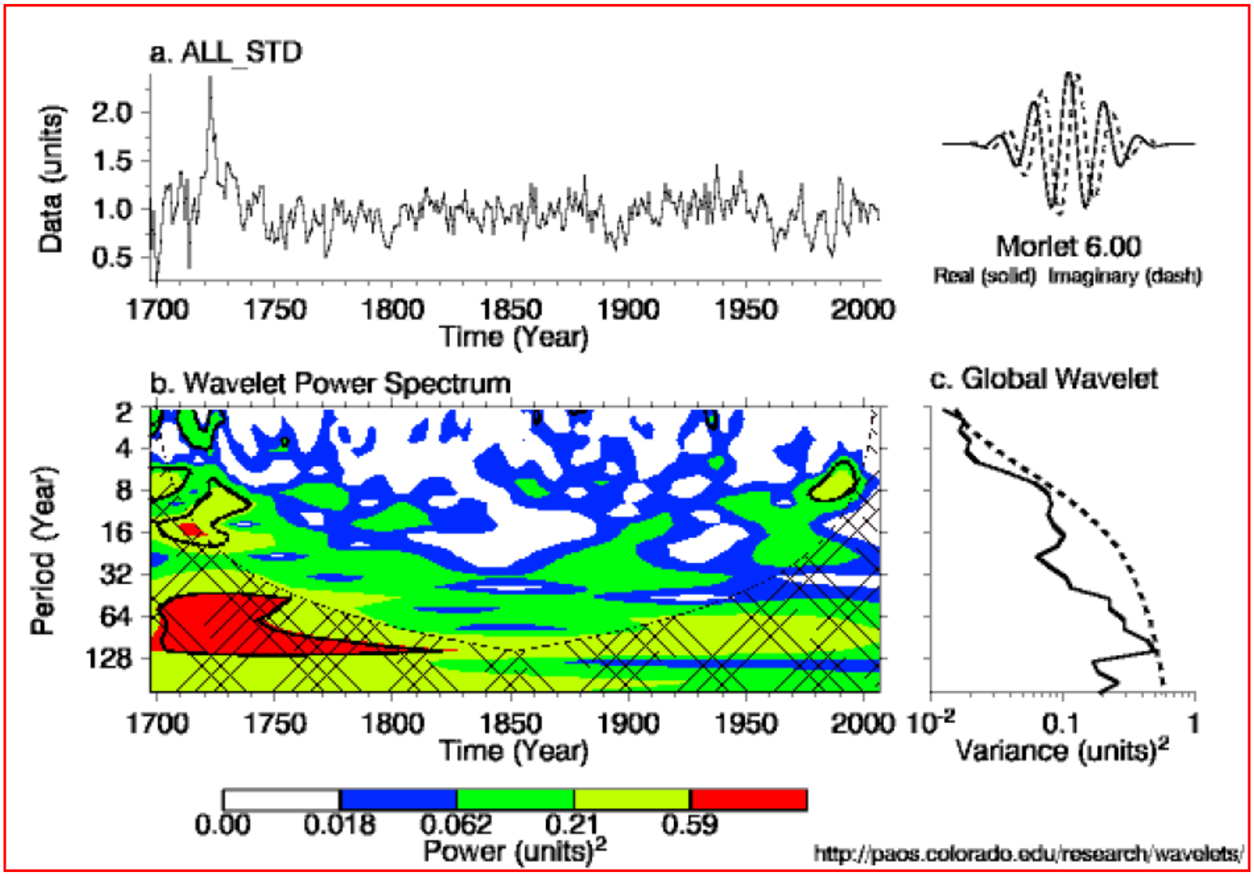
**Appendix D-3**: Wavelet Analysis for Rabbit Creek Trail standardized chronology. a) The chronology index, b) wavelet power spectra for the chronology, with black lines indicating 5% significance level, c) the global wavelet power spectrum. Crosshatched area represents the cone of influence. Analysis used the Morlet wavelet and zero-padded series (Torrence and Compo 1998). Concentrations of spectral power are around periods of 2–10, 12–24, and 48–64 (in C.O.I.)



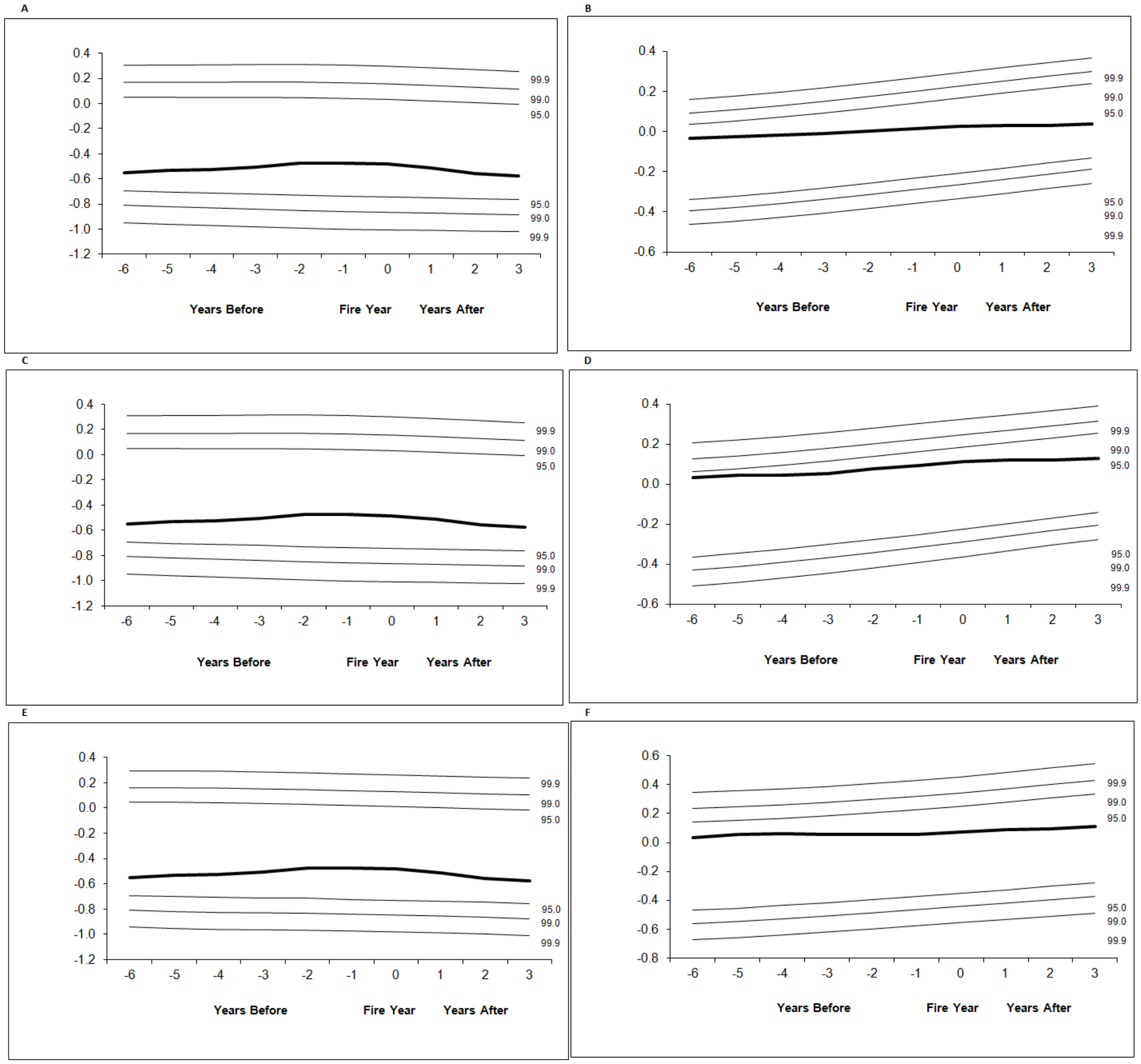
**Appendix D-4**: Wavelet Analysis for Pine Mountain standardized chronology. a) The chronology index, b) wavelet power spectra for the chronology, with black lines indicating 5% significance level, c) the global wavelet power spectrum. Crosshatched area represents the cone of influence. Analysis used the Morlet wavelet and zero-padded series (Torrence and Compo 1998). Concentrations of spectral power are around periods of 2–10 years and 24–64 years (partially in C.O.I.)



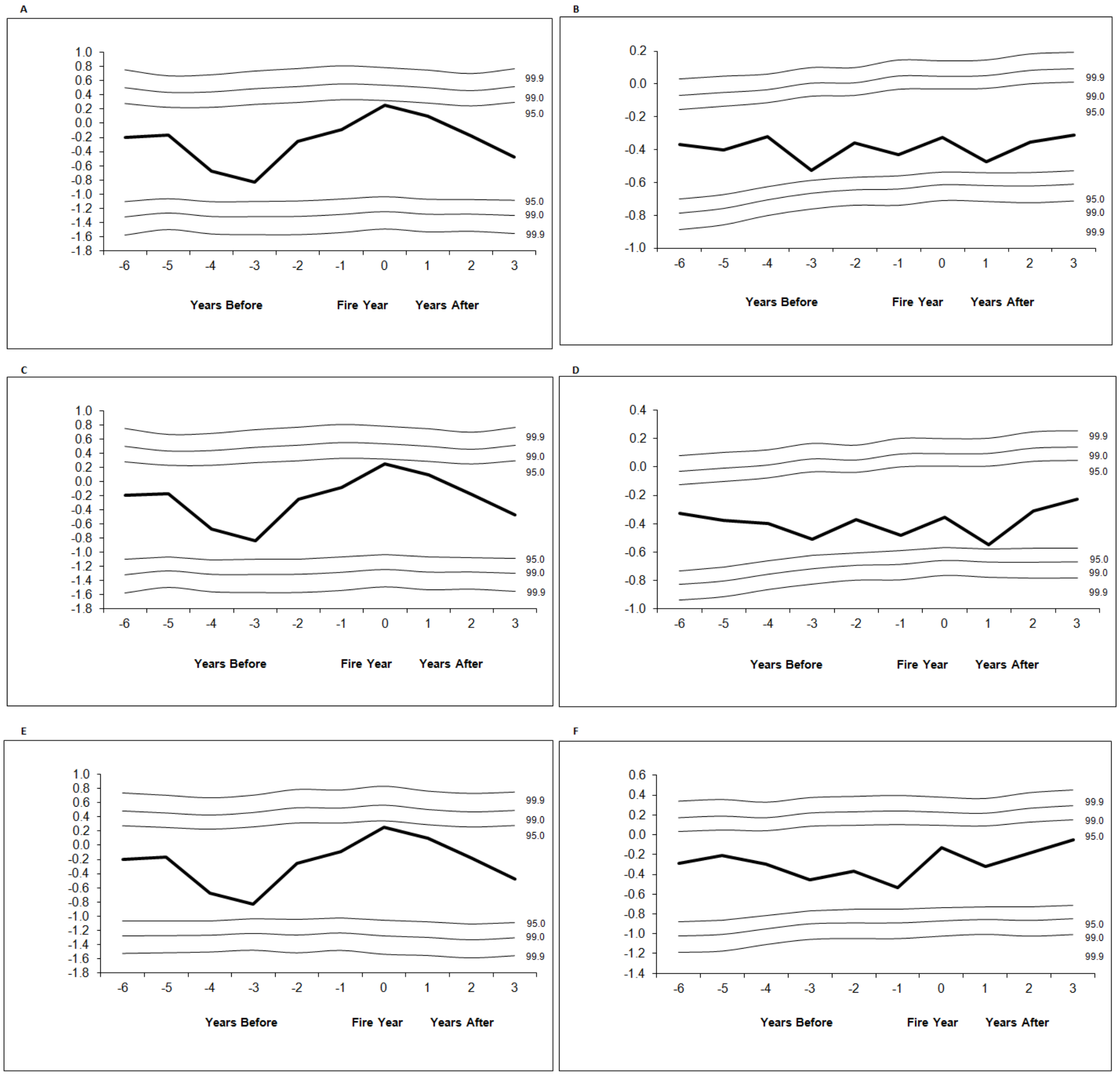
**Appendix D-5:** Wavelet Analysis for Regional (ALL) standardized chronology. a) The chronology index, b) wavelet power spectra for the chronology, with black lines indicating 5% significance level, c) the global wavelet power spectrum. Crosshatched area represents the cone of influence. Analysis used the Morlet wavelet and zero-padded series (Torrence and Compo 1998). Concentrations of spectral power are around periods of 2–20 years, and 48–112 years (in C.O.I.)



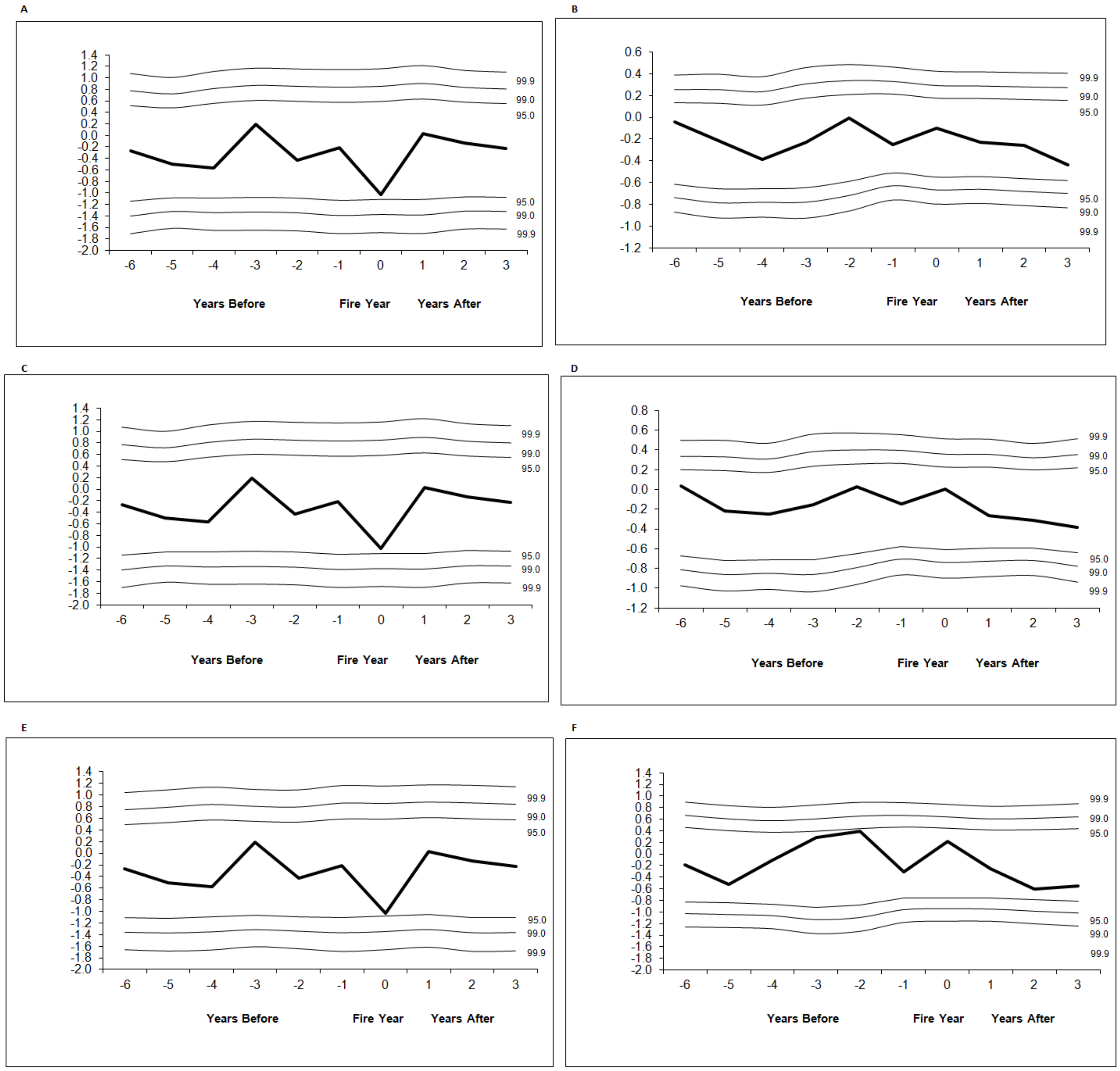
**Appendix D-6**: Superposed Epoch Analysis of Gold Mine Trail fires and Atlantic Multidecadal Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. Confidence intervals are given above and below. AMO reconstruction by Gray *et al*. 2004. No significant relationship was found between the variables.



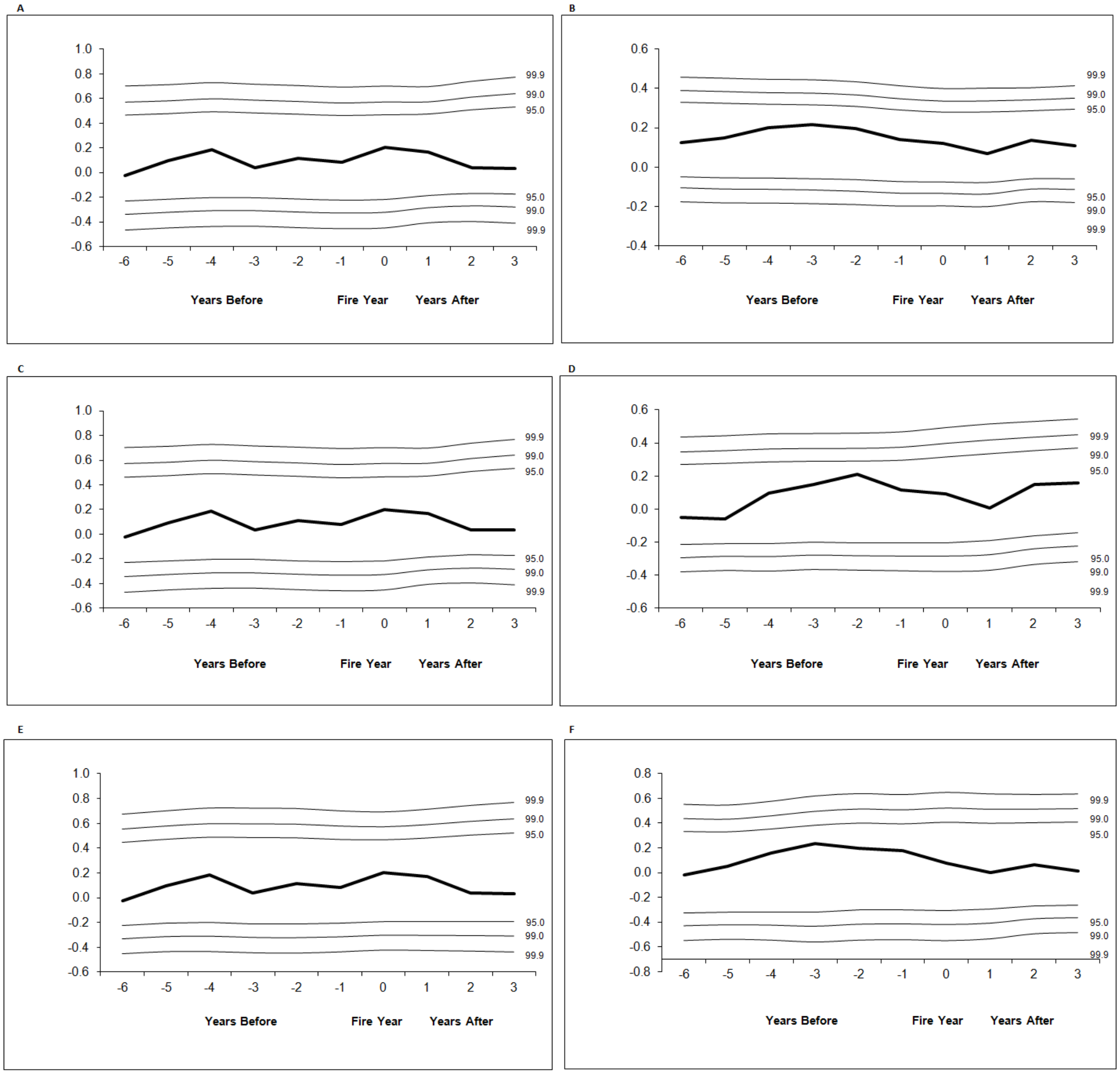
**Appendix D-7**: Superposed Epoch Analysis of Gold Mine Trail fires and Northern Hemisphere Temperatures. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NHD1 reconstruction by Briffa *et al*. 1998. No significant relationship was found between the variables.



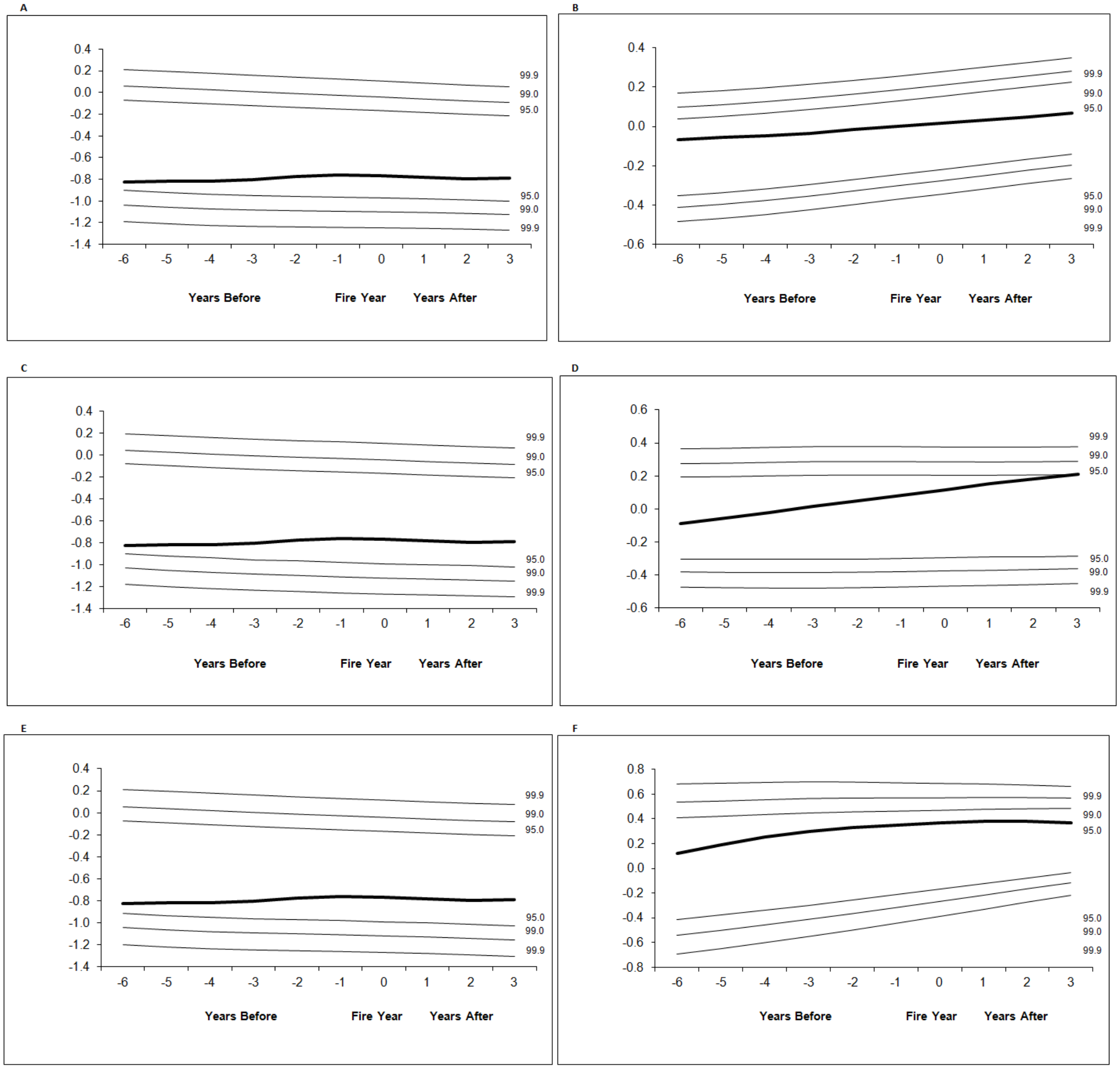
**Appendix D-8**: Superposed Epoch Analysis of Gold Mine Trail fires and Palmer Drought Severity Index. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. PDSI reconstruction by Cook et *al*. 2004. No significant relationship was found between the variables.



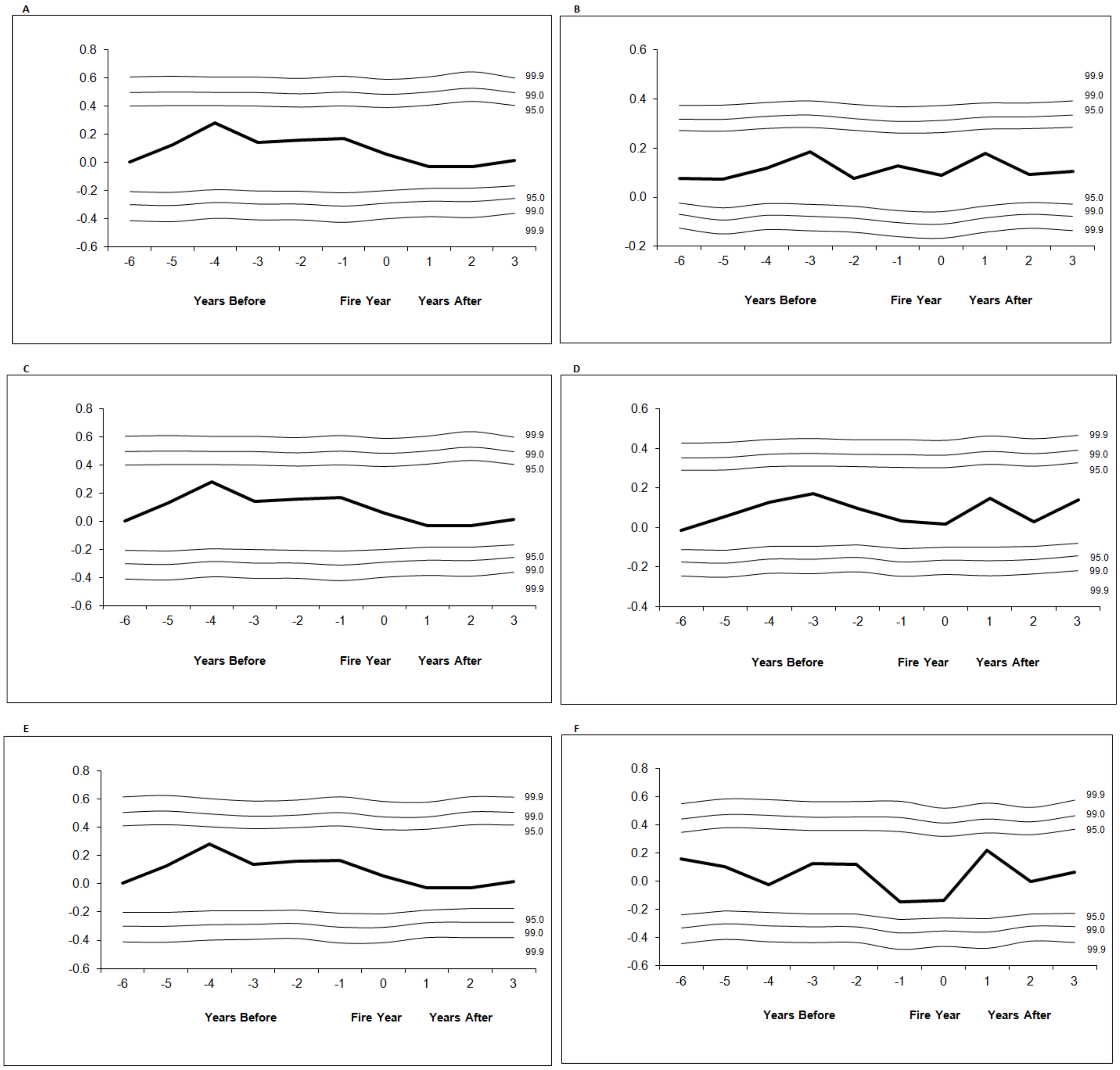
**Appendix D-9**: Superposed Epoch Analysis of Rabbit Creek Trail fires and Pacific Decadal Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. PDO reconstruction by Biondi *et al*. 2001. No significant relationship was found between the variables.



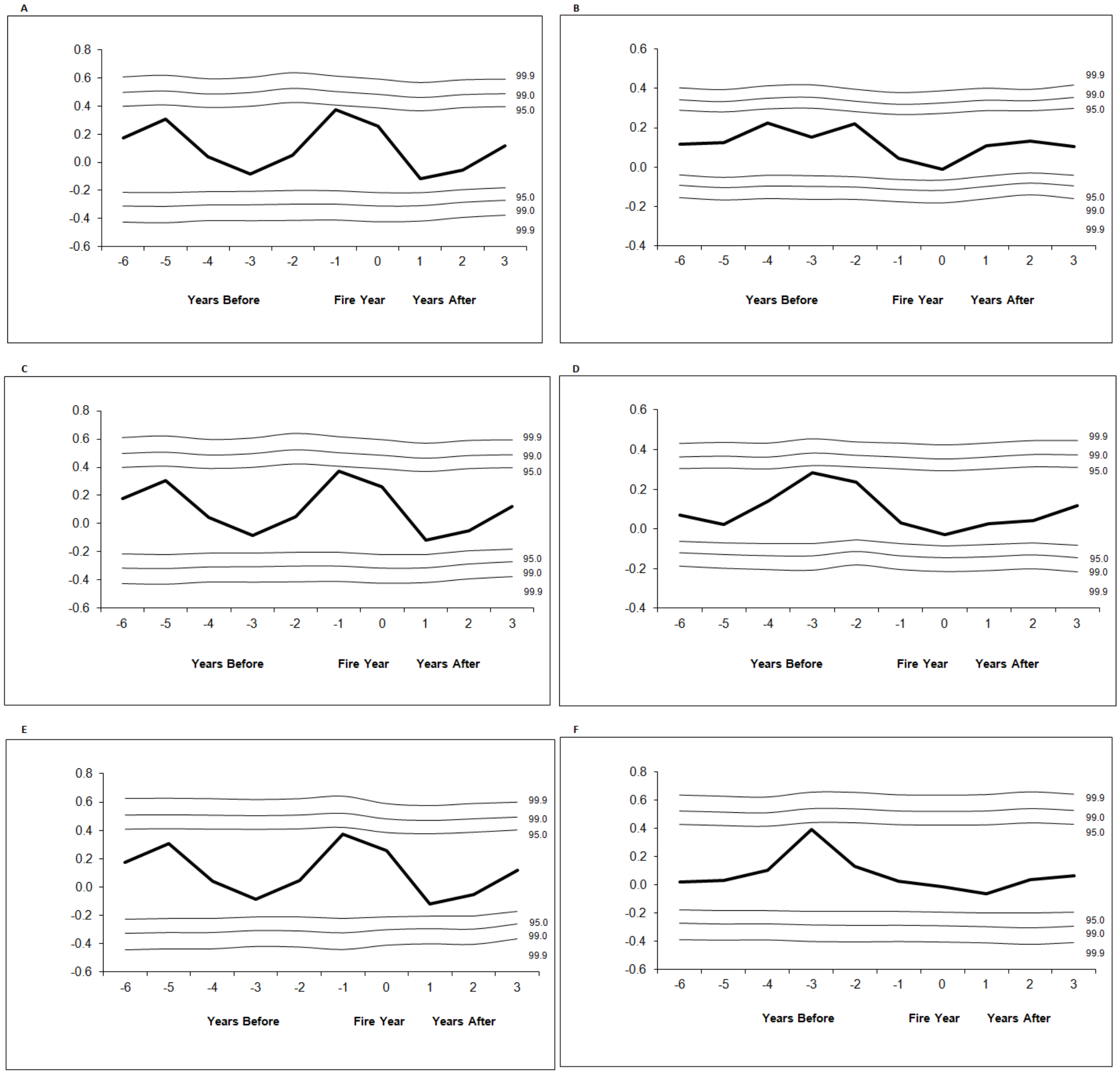
**Appendix D-10**: Superposed Epoch Analysis of Rabbit Creek Trail fires and Atlantic Multidecadal Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. AMO reconstruction by Gray *et al*. 2004. No significant relationship was found between the variables.



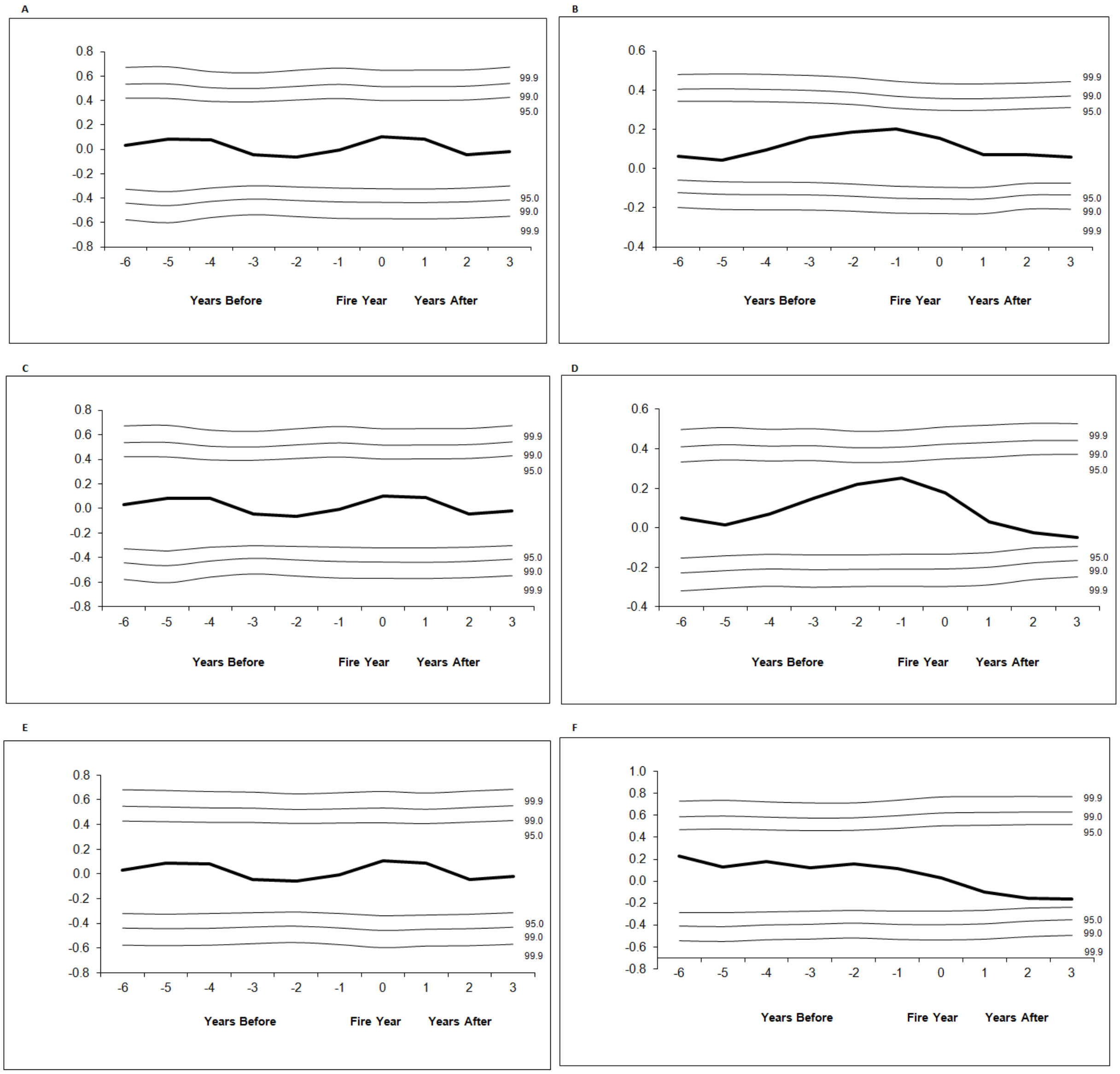
**Appendix D-11**: Superposed Epoch Analysis of Rabbit Creek Trail fires and El Niño-Southern Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NIÑO-3 reconstruction by Cook 2000. No significant relationship was found between the variables.



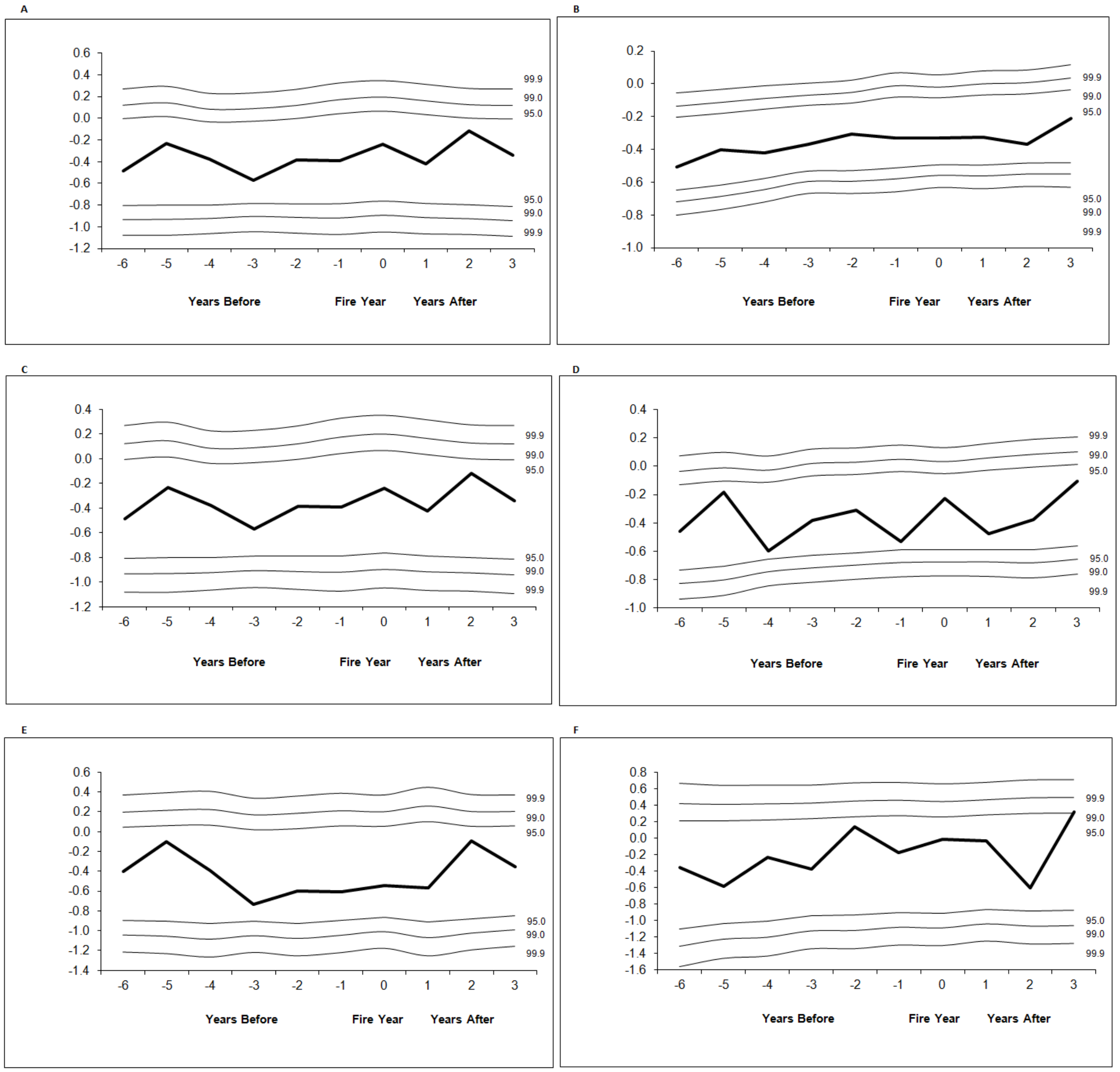
**Appendix D-12**: Superposed Epoch Analysis of Pine Mountain fires and El Niño-Southern Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NIÑO-3 reconstruction by Cook 2000. No significant relationship was found between the variables.



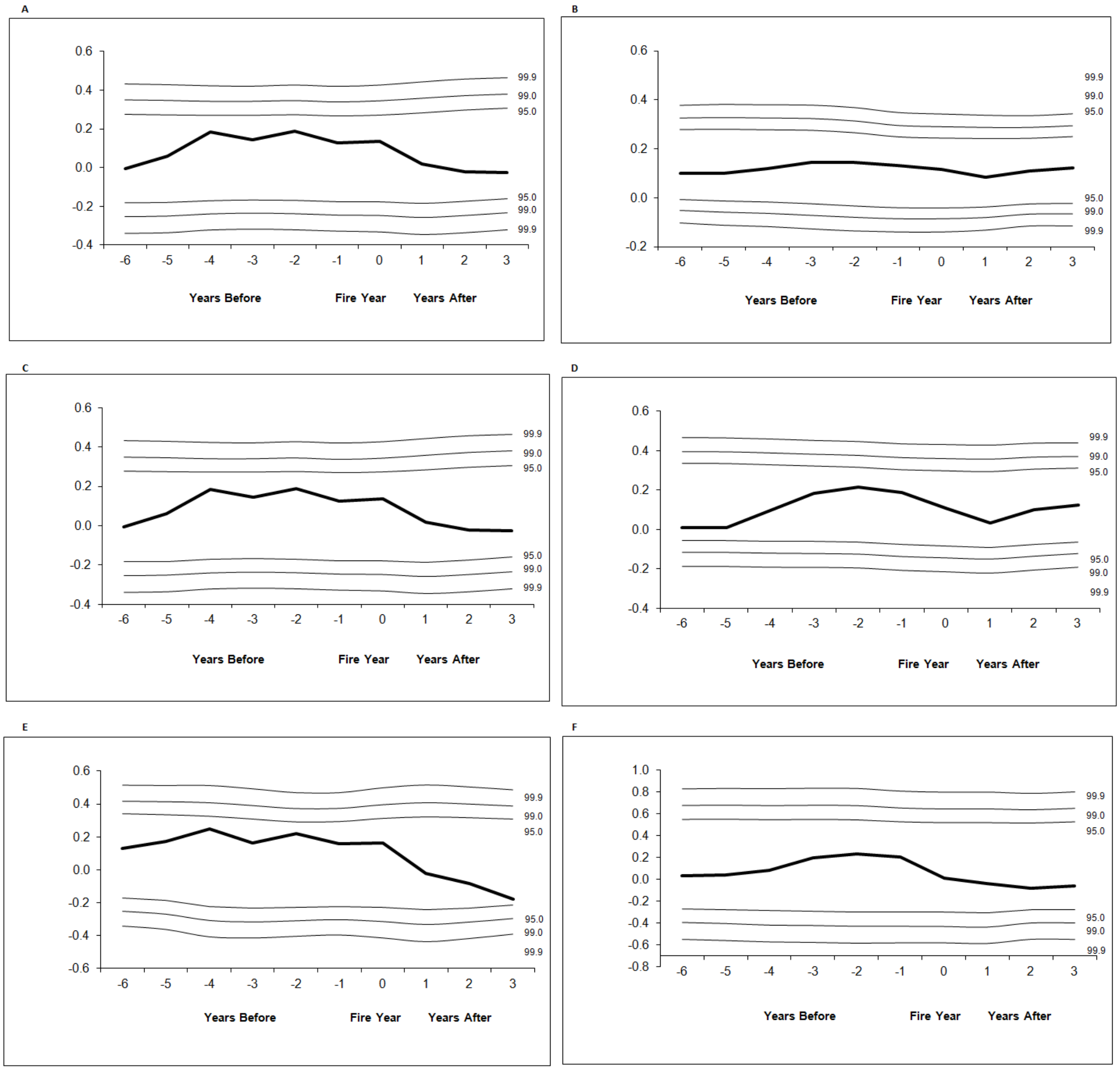
**Appendix D-13**: Superposed Epoch Analysis of Pine Mountain fires and Pacific Decadal Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. PDO reconstruction by Biondi *et al*. 2001. No significant relationship was found between the variables.



**Appendix D-14**: Superposed Epoch Analysis of Regional fires and Northern Hemisphere Temperatures. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period, C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period, E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. NHD1 reconstruction by Briffa *et al*. 1998. No significant relationship was found between the variables.



**Appendix D-15**: Superposed Epoch Analysis of Regional fires and Pacific Decadal Oscillation. A) All-scarred class, Pre-settlement Period, B) All-scarred class, Settlement Period C) 10%-scarred class, Pre-settlement Period, D) 10%-scarred class, Settlement Period E) 25%-scarred class, Pre-settlement Period, G) 25%-scarred class, Settlement Period. Dark line is mean value of the climate variable at each year prior, during, and after the fire. PDO reconstruction by Biondi *et al*. 2001. No significant relationship was found between the variables.



# VITA

Lisa Battaile LaForest started her current life in Austin, Texas during the late 1960s. While growing up with her family, she also resided in California, New Mexico, and Virginia, while spending summers in Colorado and Oaxaca, Mexico. A love of science, animals, and the outdoors led her to pursue a B.S. in Biology from George Mason University in 1997. She went on to earn an M.S. in Environmental Studies from Longwood University in 2004. Her thesis was titled, "Effects of Shelterwood Timber Harvesting on Understory Vegetation, Soil Nutrients, and Environmental Factors in a Virginia Piedmont Forest 3–5 Years Post-harvest." In and around those degrees, Lisa worked eleven years in a support role at a pharmaceutical testing laboratory in Vienna, Virginia, and three years in quality assurance at a manufacturing and distribution facility for aquarium fish supplies and exotic pet products in Blacksburg, Virginia. In the fall of 2004, she began a Ph.D. program in Geography at the University of Tennessee, Knoxville, and took the scenic route through graduate school until finishing in 2012. Her specialty areas were Biogeography and Environmental History/Landscape Change. Lisa's dissertation work on "Fire Regimes of Lower-elevation Forests in Great Smoky Mountains National Park, Tennessee, U.S.A." allowed her to spend many field hours in the beautiful mountains with entertaining and intelligent colleagues, in addition to numerous hours in the best-smelling laboratory (the Laboratory of Tree-Ring Science) on the U.T. campus. Lisa is looking forward to sharing everything she learned along the way with anyone who will listen.